Resilient Food Supply Chains

Summary

Key policy messages
Climate change will make it more challenging to deliver the NAP2 outcome on ensuring a resilient food supply chain. In the absence of adaptation, this is most likely to be felt through greater price volatility with associated costs, rather than as supply availability. While there are already activities in place to manage these risks, the potential size of climate change effects indicates that there would be benefits in scaling up responses, particular with a role for Government to remove the barriers to enable and encourage private sector adaptation, and to encourage a higher level of resilience along supply chains.

What is the outcome?
Food system resilience (also known as food supply chain resilience) is defined by Global Food Security (GFS2018) as the system's capacity to maintain a desired state of food security when exposed to stresses and shocks. The 2nd National Adaptation Programme (Defra, 2018), has a specific action to "**Ensure a food supply chain which is resilient to the effects of a changing climate**". This considers both domestic and international food supply chains.

This case study focuses on the NAP2 action above (the outcome) and considers how climate change could affect food supply chain resilience. It also assesses the potential adaptation options to maintain and enhance resilience, and thus ensure the outcome is achieved.

It is highlighted that there are already activities in this area. In the 2018 Cabinet Office Resilience Sector Plans (Cabinet Office, 2018), the Government set out how it and the sector will work together to ensure the resilience of food supply. This builds on recent research into the resilience of food supply (with the Food Chain Emergency Liaison Group) and building resilience in supply chains to extreme weather events. Furthermore, food supply is included as one of the 13 Critical National Infrastructure sectors. NAP2 sets out that Defra produces an annual Sector Resilience plan and is currently carrying out a review of the UK Food Security Assessment, due to be published in 2019. Climate change will be considered and highlighted as a risk (and possible opportunity) in this review. It is also noted that the impact of Brexit will have very large consequences for this sector, but as these are extremely difficult to predict currently, we have not considered the impact of Brexit on the outcome.

How does climate change affect the outcome, in a 2 vs 4°C pathway?
The UK imports food from over 180 countries (which comprises around 50% of food consumed) and this ensures that absolute UK food supply is resilient to supply interruptions from specific countries and from disruption to domestic UK production – although this does leads to new risks (Defra, 2017b; Defra, 2018). Current climate risks for the food supply chain primarily arise from extreme events (Tröltzsch et al., 2018), and these risks are generally managed in the short term by rationing through price or quantity and in the long term by supply diversification and switching sources of supply (UK Foresight, 2011).

Climate change will affect the productivity of food production (supply), and patterns of extreme events, and so it will potentially affect the delivery of the outcome (a resilient food supply chain). These impacts could include (UK Food security Assessment, 2010; Porter et al., 2014; GSF, 2012; 2018):

- Negative impacts on food prices from effects on production in domestic and global food markets.
- Changes in production of primary food produce, both from changes in agro-climatic shifts, but also from changes in the patterns of extremes. The literature generally reports that these changes will be modest for 2°C of warming, but are generally negative (for many regions) above this. This

means there will be major differences between 2 and 4°C futures. These effects may also arise from changes in pest and disease prevalence and range, impacts on food manufacturing, etc.
- Damage to facilities, buildings, equipment and products involved in the food production process, including loss of water and power for production;
- Disruption to the transportation of raw materials, labour, capital or finished goods and services associated with the food supply chain.

Climate change could lead to a 20% (mean) food price rise in 2050 globally, but with a large range from 0% to 60% (Nelson et al., 2014) across the models. - yield losses and price impacts rise more sharply in later years under higher warming scenarios. However, this needs to be translated into food supply chain effects. In the short to medium term (to 2040), the potential impacts vary most strongly with climate uncertainty (i.e. the 10th to 90th range from UKCP18, Lowe et al., 2018) and are likely to be dominated by extremes and shocks. For example, Allianz Global Corporate & Specialty (2012) estimates that 70% of damages by extreme weather events are linked to supply chain and procurement risks, such as disruptions and delays in delivery. Allianz Global Corporate & Specialty (2012) estimates that 70% of damages by extreme weather events are linked to supply chain and procurement risks, such as disruptions and delays in delivery. Beyond this time, i.e. after 2050, the impacts are projected to vary strongly with the future emission path (i.e. 2 vs 4°C). However, the risks from climate change to the food supply chain in England are likely to manifest themselves in the price levels of food products rather than their physical availability. Our expert judgement is that although there are market mechanisms currently in place to mitigate the effects of food price hikes and volatility, the short-term economic and social costs from climate related disruption could be significant.

Compared to other risks, there is much less lock-in invested in global supply chains, because of the potential to shift to alternative suppliers over the relative short-term (although there is high lock-in risk for producers, because of land-use change). However, there are a number of threshold risks that are associated with food supply chains and recent studies have considered climate and socio-economic tipping points could have significant effects on UK food production areas, as well as on food security.

What are the economic costs of climate change, i.e. the effect on the outcome?

Ray et al. (2015) estimated that, globally, for substantial areas of the global breadbaskets, climate variability accounts for roughly a third of the observed yield variability. In the context of the outcome and the short-term policy focus, it is likely that there could be short-term price increases as a result of such national or international extreme weather events, but these will be of short duration. Recent historical examples in the global wheat market provide evidence of such effects, with short-run (< 1 year) price increases of 40% (JRF, 2016b) observed for major shocks in 2006-2008 and 2010-11. This level of impact gives an indication of possible levels for future periods. These events are likely to result in greater price volatility with associated costs both for the consumer (in periods of higher prices) and producer (where prices are uncertain leading to less investment in agricultural productivity), and have been observed in UK analysis (JRF, 2016b). In principle, such costs could be quantified using macro-economic simulations, and under alternative climate scenarios; in practice, to date, these have not been undertaken.

What are the potential additional adaptation options to address these impacts?

As highlighted above, there are already actions being taken to build the resilience of food supply chains (Defra, 2018; CCC, 2017). Most of the focus has been on the private sector. Businesses will take adaptation actions when the benefits of doing so outweigh their (private) costs (Cimato and Mullan, 2010), however, the great complexity of supply chains and their multi-staged processes, coupled with the uncertainty around climate change impacts, indicates that the private sector might struggle to take all appropriate actions. The Government could therefore play a role in removing some of the barriers to enable and encourage private sector adaptation, as well as ensuring a higher level of resilience along supply chains, e.g. for infrastructure. Since many supply chains have international dimensions, there is a role for a multi-national co-ordinated regulatory structure in the food commodity markets that are most vulnerable to climate-related supply-side shocks. As a further example, under the auspices of the current Food Sector Resilience Plan, Government could further encourage the development and up-take of insurance instruments that protect both domestic and international actors in food supply chains. Finally, open trade policies could be pursued in order to encourage diversification of suppliers of critical food commodities/products.

The case study has identified a range of adaptation options that might be effective in reducing food supply chain impacts and building resilience. It is highlighted that these adaptation options may be undertaken by a range of actors, both domestically and internationally. These include early low and no-regret options, as well as the need to make sure infrastructure and land-use decisions are climate-smart. It also includes a greater focus on adaptive management, research and learning. For the latter, one early priority is to identify possible hot spots (regions/countries which already show vulnerability to weather events and food production and transport disruptions), and how these might change under longer-term 2^{o}C vs. 4^{o}C pathways. This would help understand the scale of future vulnerability of the UK market under different scenarios, and provide a stronger rationale for action.

What are the benefits and potential costs of adaptation?
There are some aspects of climate change risks and responses that have been quantified for food supply chain resilience, but there is little information on the associated costs and benefits (in aggregate). However, for each identified measure, we identify some key features of the economic data required. This is highlighted as an area for future case study analysis.

Step 1. What is the objective and outcome?

The 2nd National Adaptation Programme (Defra, 2018), has a specific key action to "Ensure a food supply chain which is resilient to the effects of a changing climate". The NAP2 states that food supply is one of the 13 Critical National Infrastructure sectors[1], and identifies that the current review of the UK Food Security Assessment (to be published in 2019) will explicitly consider climate change as a risk and opportunity.

This case study focuses on the action above (the outcome) and considers how climate change could affect the delivery of food supply chain resilience. It also assesses the potential adaptation options to maintain and enhance resilience, and thus ensure the outcome is achieved.

Food system - or supply chain – resilience is defined by Global Food Security (2018) as "the system's capacity to maintain a desired state of food security when exposed to stresses and shocks", and encompassing:

- Robustness (The ability of the food system to resist disruptions to desired outcomes);
- Recovery (the ability of the food system to return to desired outcomes following disruption, and;
- Re-orientation **(**the ability of food system actors to accept alternative outcomes following disruption).

Climate risks can be seen as being one of a number of factors that have the potential aspects of food supply chain resilience, the others including trade disruption, terrorist and cyber-attacks, and political disturbance in source, transit or the destination country. We define the food supply chain as a food system – a generic example of which is sketched below. The value of the food supply chain in the UK is estimated to be £111 billion (Defra, 2017), equating – on a pro rata basis – to £92.5 billion for England.

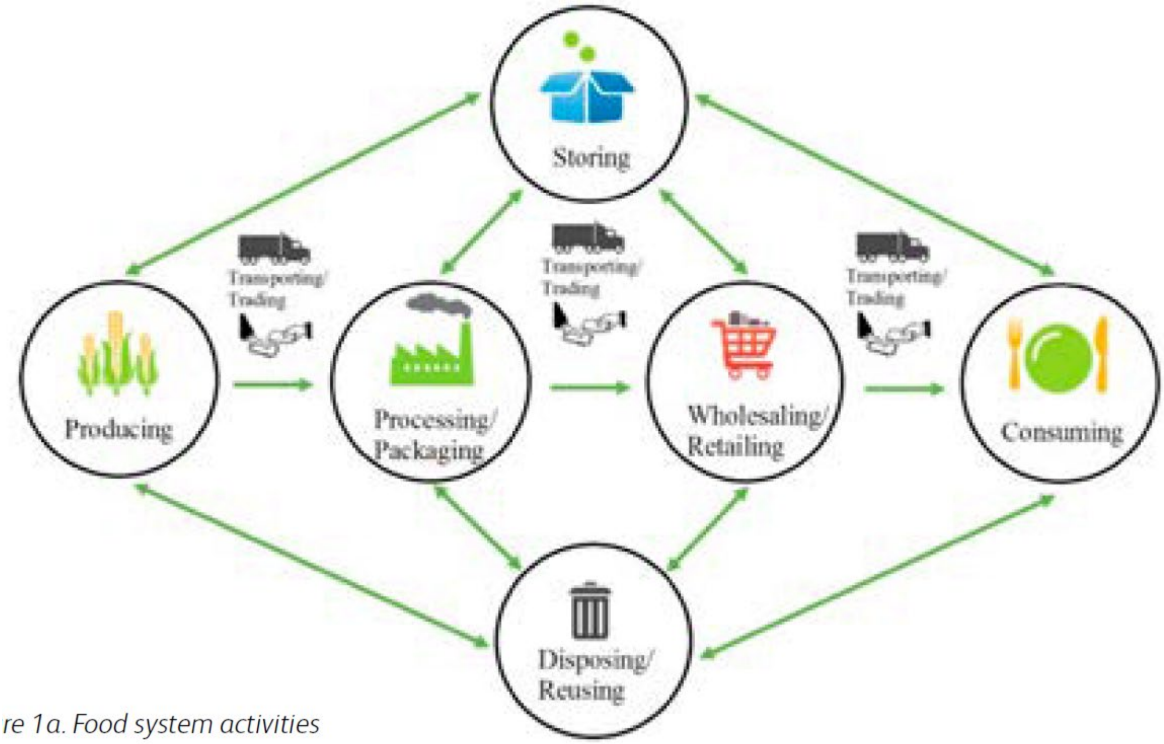


Figure 1 Food System Activities. Source Global Food Security (2018)

[1] Centre for the Protection of National Infrastructure, Critical National Infrastructure. Available at: https://www.cpni.gov.uk/critical-national-infrastructure-0

It is recognised that these supply chains may or may not have an international dimension. The figure below highlights that 50% of the food consumed in the UK is produced in the UK whilst 30% comes from the rest of the EU, with the rest from other world regions.

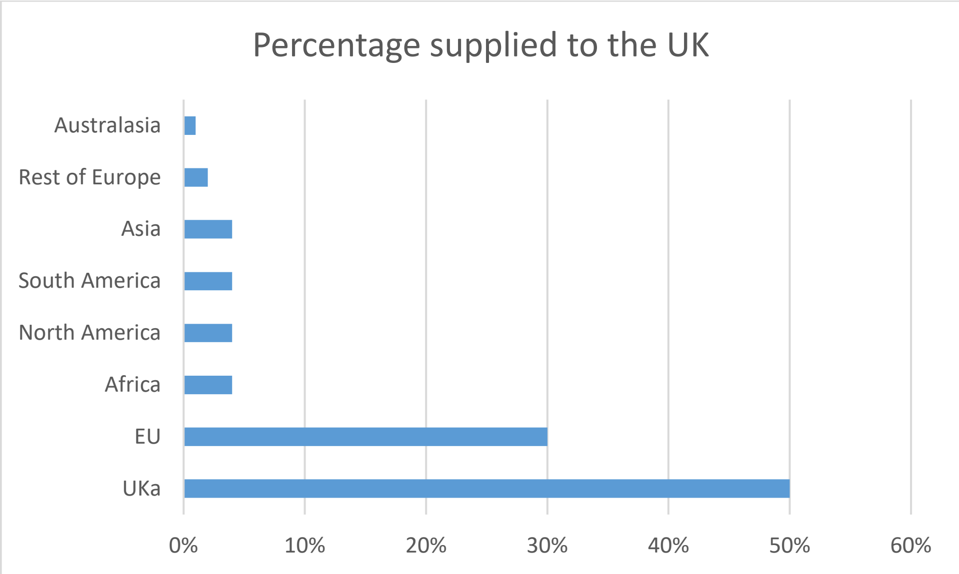


Figure 2 Origins of food consumed in the UK 2017 Source: Defra (2017)

However, there are major differences between food commodities, for example, a much higher % of fruit and vegetables is imported.

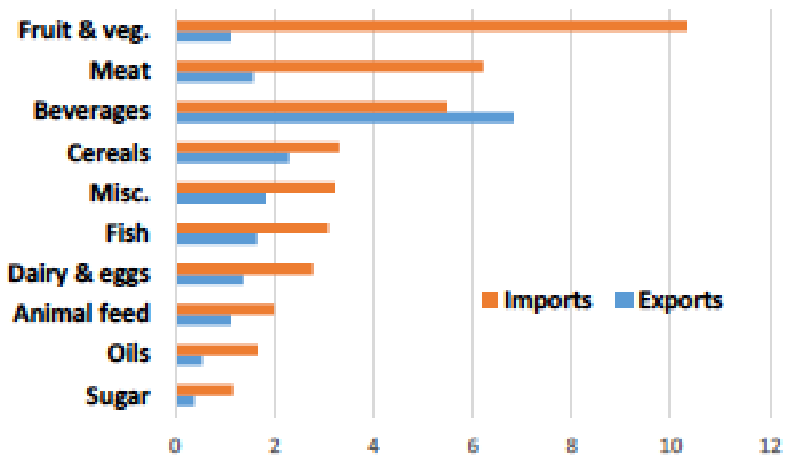


Figure 3 UK Food exports and imports (£ billions)

Source: Agriculture in the United Kingdom, 2016, Defra, 2016 in POST (2017).

As reported in the NAP2 (Defra, 2018), the UK imports food from over 180 countries and Defra reports that this openness ensures that UK food supply is considered to be very resilient to supply interruptions from specific countries and also from disruption to domestic UK production (Defra, 2018). In particular retailers and large food service operators have -in the past- been able to switch sources of supply rapidly if required, as demonstrated during a range of crises including severe weather, transport disruption and Industrial Action (Defra, 2018). However, it is also the case that high import dependency can increase risks. For example, a spell of unusually cold and stormy weather in Southern Spain in January/February 2017 resulted in there being both physical rationing and a trebling of purchases and prices of iceberg lettuces and broccoli in English supermarkets for the following two months.

As shown above, in 2016, the EU accounted for most (70%) of the food imported to the UK and received most (60%) of the food exported from the UK (POST, 2017). Further, there are certain sectors of the food market where the UK is heavily dependent on just a few countries for imports (POST, 2017):

- The UK heavily relies on imports of fruit and vegetables, with just two countries (Spain and the Netherlands) accounting for 69% of imports of fresh vegetables and four countries for 44% of fresh fruit imports.
- The UK also depends on animal feed imports for livestock production, particularly in the poultry and pig sectors, with the bulk of its imports of soy beans coming from Argentina and Brazil.

Through their international supply chains, distribution networks and global markets, UK businesses are exposed to the risks of extreme weather around the world. Climate change is expected to increase the risk of weather-related disruptions, particularly for supply chains and distribution networks that involve more vulnerable countries (Defra, 2018).

Defra produces an annual Sector Resilience plan and is currently carrying out a review of the UK Food Security Assessment (which was last fully updated in 2010). This is due to be published in 2019 (which was a commitment in the NAP2). As reported in the NAP2, climate change will be considered and highlighted as a risk (and possible opportunity) throughout the 2019 review.

Since the last UK Food Security Assessment (2010), Defra has commissioned some work on food supply security. In 2013, Professor Chris Elliott, Director of the Global Institute for Food Security at Queen's University Belfast, led an independent review into the integrity and assurance of food supply networks. However, the review focussed mainly on food crime prevention, and did not take climate change risks into consideration, although the review identified a 'red flag' concerning the need for coordinated intelligence to highlight areas of weather-related risks (HM Government, 2014, page 115).

In the 2018 Cabinet Office Resilience Plan (Cabinet Office, 2018), it is stated that the Government and the sector will continue to work together to ensure the resilience of food supply. This will include:

- Building on recent research into the resilience of food supply with the Food Chain Emergency Liaison Group to respond to and recover from maritime transport disruption resulting from a major coastal flooding event;
- Building resilience in supply chains to extreme weather events.

It is also noted that the impact of Brexit will have very large consequences for this sector. Defra has been working with the food industry sectors, across Government and with the Devolved Administrations, to undertake contingency planning for a range of EU exit scenarios, including a no-deal scenario. However, as it is extremely difficult to predict the outcome of Brexit discussions currently, we have not considered the impact of Brexit on the outcome.

Step 2. How does climate change affect the outcome, in a 2 vs 4°C pathway?

Climate change has the potential to lead to major effects in the agriculture and food sector, particularly to production, with potentially negative effects (e.g. from lower rainfall or increasing variability) but also potentially positive effects (e.g. from CO_2 fertilization, or extended growing seasons) from changes in mean weather variables, as well as changes in the risks of extreme events, shifts in the range and prevalence of pests and disease, etc. These will lead, in turn, to effects on aggregate production, supply chains, prices and trade. There are also possible risks to food security and the breakdown of food systems (Porter et al., 2014).

For food supply chains, most of the focus has been on extreme weather events. These potential risks have been reported (see UK Food security Assessment, 2010) by:

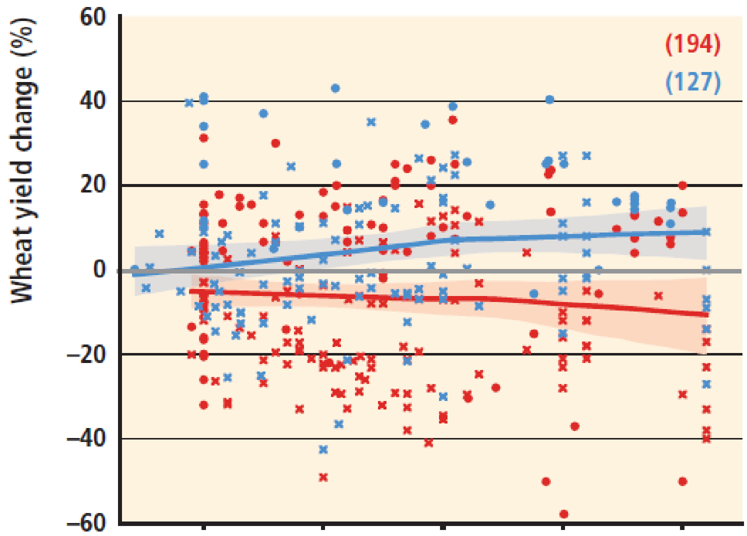
- Changing conditions affecting the extraction and/or production of raw materials to be used in food and manufacturing processes. This includes damage to crops, livestock, and fisheries from temperature stresses, extreme events, increases in pests and spread of disease. These may lead to temporary or long-term reductions in agricultural product yields.
- Increased climatic stress on natural resources (particularly water) and biodiversity, which threatens productivity in various regions. For instance, productivity of horticulture could be affected in water-stressed regions such as the Middle East and North Africa
- Greater risks to harvests from variable weather, drought and pests, leading to potentially more volatile supplies and prices
- Rising temperatures generally are likely to improve yields in the shorter term in the northern hemisphere, but threaten yields in other, developing regions
- Damage to facilities, buildings, equipment and products involved in the food production process, including loss of water and power for production.
- Disruption to the transportation of raw materials, labour, capital or finished goods and services. More frequent extreme weather events in the UK will test business continuity planning and infrastructure resilience. Coastal flooding can affect ports and agricultural land use.
- Ocean acidification adding to pressure on marine stocks.

The table below presents some examples of the potential impacts on agricultural production domestically and/or internationally that result from extreme weather events, and the effects on supply chain resilience. It is expected that the majority of extreme weather events that currently affect production – and other parts of the supply chain – will become more intense and/or more frequent under climate change scenarios.

There are major differences in the potential scale of effects between 2 and 4°C pathways, but most of the literature on this has focused on the general impacts of climate change on food production (Porter et al, 2014) using crop models. At the global level, most of these studies report that climate change impacts will be modest for 2°C of warming, but rise strongly above these levels, with major impacts in 4°C scenarios. For example, figures 4 and 5 give a summary of the projections in the literature, with regard to wheat production in temperate and tropical world regions. Comparison of the two regions shows that tropical regions are more vulnerable to temperature increases, even when adaptation is included. In temperate regions, yield falls are 5% and 7% in 2°C and 4°C pathways in the absence of adaptation. In tropical regions, however, yield falls are 5% and 35% in 2°C and 4°C pathways. It is a broadly similar, though less severe, pattern for maize whilst rice yields are more vulnerable in temperate regions in a 4°C pathway, perhaps reflecting more severe water constraints.

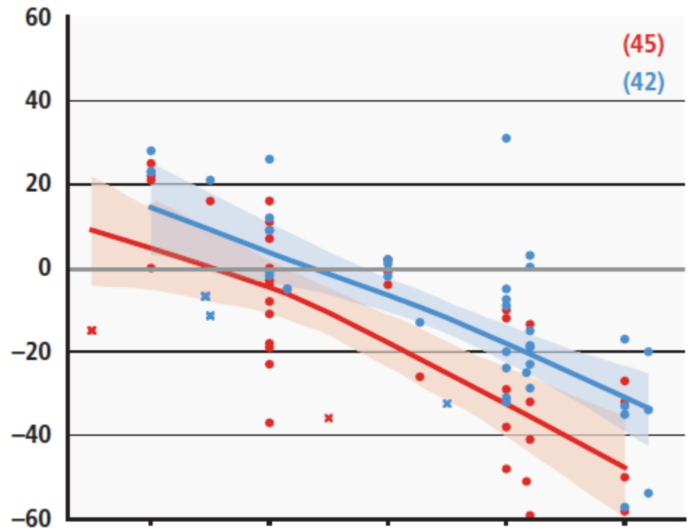
At the European to UK scale, the results of crop modelling studies tend to show a strong distributional pattern in Europe, with productivity gains in the North and losses in the South (Iglesias et al., 2012; Ciscar et al. 2014): the changes in the UK tend to be modest, although studies often report productivity benefits (at 2°C of warming) falling back to current levels under 4°C).

Figure 4. Wheat yield responses to temperature and adaptation in World Temperate regions, without (red) and with (blue) adaptation



Source: Porter et al. (2014)

Figure 5. Wheat yield responses to temperature and adaptation in World Tropical regions, without (red) and with (blue) adaptation



Source: Porter et al. (2014)

There are also a set of economic models that feed crop model results into wider economic analysis, for example using Computable General Equilibrium models, to allow analysis of the impact at scale and across the economy, for example, how changes in agricultural production affects prices and how changes in the agricultural sector cascade through to other sectors of the economy. These models can then be used to look at possible adaptation responses, particularly with respect to trade. For example, Szewczyk et al (2016) undertook a more detailed analysis of Europe (as part of a global study), and investigated the effects by region. The study found benefits in the UK & Ireland, followed by Northern Europe and the Central Europe North regions. These differences reflect the initial size of impacts as well as the potential for substitution (especially for agriculture). These studies highlight that looking only at crop yield projections is inadequate to derive reliable conclusions about the scale of climate change impacts and adaptation. They find that international linkages through trade and commodity prices have a major influence on the effectiveness of resilience planning. Indeed, they project that trade can address most of the potential downside risks in Europe. However, the trade assumptions in models are considerable (they assume frictionless trade).

Table 1. Summary of examples of weather impacts on agricultural production

Climate stressor	**Direct impacts**	**Indirect impacts on food supply chain**
Rainfall	Affects productivity Impedes access: • Delayed mechanised activity including applying fertiliser, and plant protection products • Reduced time livestock on land • Mechanised activity on wet ground increases compaction Affects pollination Increases disease risk Waterlogging reducing growth Lodging of crops	• Lost yield • Delayed agricultural activity, reduced yields, reducing quality, increased costs (e.g. feed bills for livestock kept indoors, drying costs for damp grain etc) • Land left unharvested • Potential increase in waste food due to impact on consumer choice/behaviour • Higher harvesting cost • Land abandonment (due to reduction in field capacity days)
Heavy precipitation and flooding	• Impedes access • Erodes soil, washes away nitrogen and other inputs • Removes plants, lodges plants • Reduces growth • Livestock loss	• Short term yield loss • Long term yield loss • Loss of yield, replacement planting • Yield/forage loss • Lost yield
Heat/drought	• Increased stress • Heat stress (e.g. pre-sheering in sheep) • Reduction in forage requiring supplementary feeding •	• Lost yield and quality
High wind	• Lodging of crops • Loss of leaves/blossom in fruit • Closure of UK/other ports • Impacts on farm buildings, fences, hedges	• Lost yield • Interrupts international supply chain • Increased repair bills
Snow/ frost/ hail	• Access to forage for livestock causing condition loss, abortion, death • Frost damage (e.g. horticulture) • Crop damage	Lost yield
Weather impacting on pests/ diseases	• Wind aiding migration of insects from the Continent and transmitting • Disease impacts due to particularly favourable conditions for pests	Lost yield
Weather/ air quality interaction	• Hot still weather interacting with air pollution causes increases in ground level ozone which pollutes plant metabolic activity	Lost yield
Ocean acidification	• Reduced fish stock, particularly shellfish	Lost yield

Source: Derived from Global Food Security (2012)

More importantly, most of these crop and economic models focus on slow onset climate change, looking at change in agro-climatic suitability. The main focus to date has been on medium to long-term productivity changes and studies have not analysed inter-annual price fluctuations, e.g. from extreme weather events (Tröltzsch et al, 2018). There has also been less coverage of what happens when yields and prices diverge away from market equilibria.

There is also high uncertainty with the information, and this can influence the outcomes. This was demonstrated by analysis on the global impacts of climate change on agriculture undertaken in the Agricultural Model Inter-comparison and Improvement Project, (AGMIP), reported in Rosenzweig et al (2013) and Nelson et. al. (2014). This compared the outputs of seven economic models – three economy-wide (general equilibrium) models and four agricultural market-specific (partial equilibrium) models – from simulations that use the yield output to 2050 for a common climate scenario (RCP8.5) and a common reference socio-economic scenario for population and GDP (SSP2). The model inter-comparison used seven scenarios of biophysical crop yield changes under climate change – based on a combination of five different crop models and two general circulation models. This found that climate change could lead to a 20% (mean) food price rise in 2050 globally, but with a large range from 0% to 60% (Nelson et al., 2014) across the models. Yield losses and price impacts rise more sharply in later years under higher warming scenarios.

There is much less evidence on the impacts of climate change on supply chains. The COACCH project (2018), conducted a knowledge synthesis and gap analysis on climate impact analysis, economic costs and scenarios in Europe. The main findings of this review on food chains can are reported as follows:

- There have been some studies of supply chain and procurement risks, focusing on disruptions and delays in delivery and transport due to extremes (Lühr et al., 2014). Lühr et al. (2014) refer to two studies which analyse disruptions of production in general: Allianz Global Corporate & Specialty (2012) estimates that 70% of damages by extreme weather events are linked to supply chain and procurement risks, such as disruptions and delays in delivery; and only 30% of damages are dedicated to direct physical damages of the production sites. A study by PriceWaterhouseCoopers (2008) determined that 60% of companies affected by production disruptions show a reduction in turnover and rate of return in the following year. The average return on assets declines by 5% and return on sales by 4%.
- There has also been analysis of supply chain risks using input output models (Wenz & Levermann, 2016) and the risks of climate change on embodied water in imports (Hunt et al., 2014).
- The ImpactChain project for Germany reports that imports from non-EU regions decline by up to 2.1% by 2050 under climate change and exports to non-EU regions decline by up to 0.3% (although this looks at all supply chains). Parts of these reductions are compensated by increased imports from and exports to EU regions, but this partial substitution is insufficient to avert a decline in German GDP and welfare (up to 0.4%).
- According to the literature, the indirect impacts of climate change transmitted by international trade are likely be as important for the European industrial sector as the direct climate impacts on production process (EEA, 2017).

In the UK, several studies have concluded that climate change impacts transmitted by international trade might represent a similar or even greater threat for some parts of the UK economy than domestic climate change impacts (UK Foresight, 2011; PricewaterhouseCoopers, 2013; West et al., 2015).

A further example for the UK is the study by West at al. (2015), which estimated yield changes for four studied commodities (maize, soy, wheat, rice) that show a special relevance for the UK economy. Across all four commodities, the models estimated potential long-term decreases in commodity availability in the countries involved in the UK supply chain of 20-30% under RCP8.5 (which simulates a 4°C degree path scenario), and up to ~10% decrease for some commodities under RCP2.6 (2°C degree path scenario).

However, as a wealthy trading nation, the impact on the food supply of the UK is likely to be in the form of price increases rather than loss of security of supply (UK Foresight, 2011). This is further investigated in the next step of the analysis.

Thresholds, tipping points and lock in

Compared to other risks, there is much less lock-in invested in global supply chains, because of the potential to shift to alternative suppliers over the relative short-term (although there is lot of lock-in for producers, because of land-use change).

However, there are a number of thresholds risks that are associated with food supply chains. The Global Food Security programme (2017) has considered potential environmental tipping points and reports that tipping points in environmental systems do occur and that they could have significant effects on food security. These could be associated with global climate tipping points (i.e. such as identified by Lenton et al. 2008). For Europe, the most important short-term climate tipping point is associated with artic summer ice sheet loss (Levermann et al., 2012). However, it is also highlighted that a large part of current UK imports are from Spain, and projected levels of warming in this country are much greater than the global average: Vautard et al 2014 project that for 2°C of warming globally, the Iberian peninsula might experience closer to 4°C of warming, and also experience increasing patterns of heat extremes. These tipping points could also arise from other factors, for example particular outbreaks of pests and diseases, affecting production areas, or involving restrictions on trade from affected areas. The study also provides an example of a potential tipping point in East Anglia with the degradation and loss of peat soils, creating conditions where widespread soil erosion may occur.

There is also the potential for large-scale socio-economic tipping points associated with major food production areas, which could be tipping points for short-term food security and food supply shocks.

Step 3. What are the economic costs of climate change, i.e. the effect on the outcome?

In recent years, there have been several periods of rapid food and cereal price increases following climate extremes in key producing regions, indicating a sensitivity of current markets to climate extremes, among other factors (Porter et al 2014). Some of these have transferred through to the UK.

Previous studies have mapped historical price patterns against weather events. World price trends are charted over the period, 1960 – 2018 in the figure below. The index in real prices shows that there has been an upward trend since 2000 that has included two significant spikes in 2006-2008 and 2010-11 (JRF, 2016). In the case of the first price spike, of 40%, weather shocks have been identified as a major factor, such as drought in Australia (2005–07) that reduced wheat production and trade. However, other contributory factors included policies to promote the use of biofuels, which increased demand for maize and vegetable oils. There were also contributory factors from the depreciation of the US dollar, upward pressure on prices for petroleum and fertilizer (because of the resource-intensive nature of their economic growth and increased demand for meat, and hence animal feed (FAO, 2011). The second price spike – also of 40% - is also attributed to many of the same factors, though the strongest determinant is thought to have been the effects of drought and wild-fires in Russia and Ukraine that reduced production of barley and wheat by 30% (Wegren 2011). BSR (2018) reports that in 2010, the drought in Russia delivered economic losses estimated at US$15 billion. Resulting export restrictions had the knock-on effect of contributing to global price increases. Similarly, recordbreaking temperatures in the U.S. over the summer of 2012 reduced corn supply and increased meat and dairy prices. Global food prices soared by 10 percent between June and July of that year.

Ray et al (2015) estimated that, globally, while some areas show no significant influence of climate variability, in substantial areas of the global breadbaskets, more than 60% of the yield variability can be explained by climate variability; and climate variability accounts for roughly a third (between 32 and 39%) of the observed yield variability.

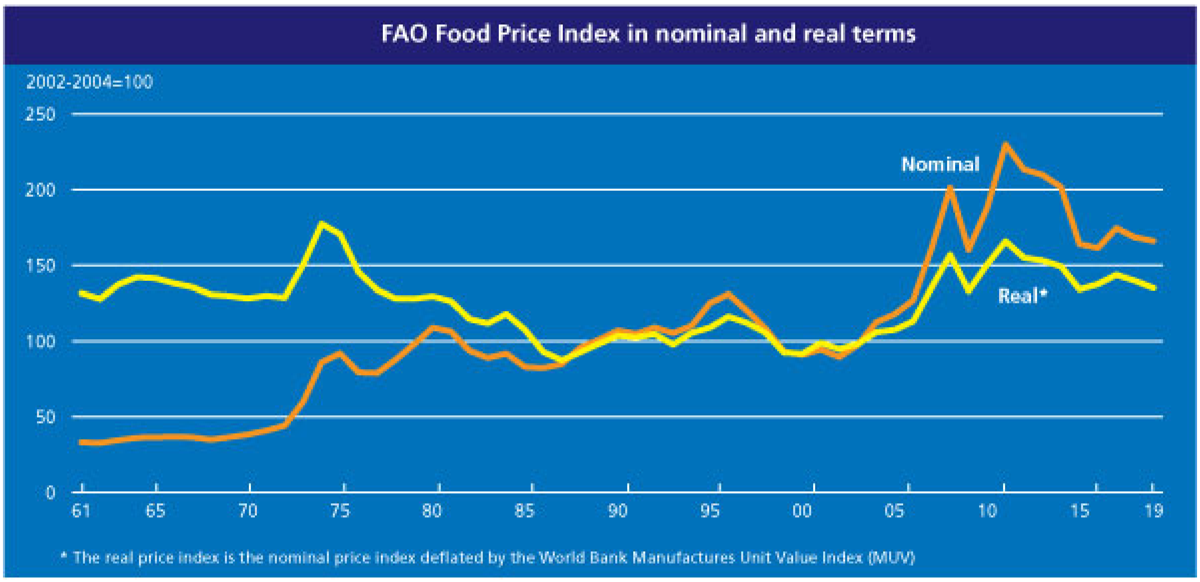


Figure 4 Global Food Price Index Trend – Real Prices (2002-2004 = 100). Note: Years 1961 – 2019 on x-axis; Price index on y-axis

As shown below, these global patterns are reflected to some extent in food prices in the UK.

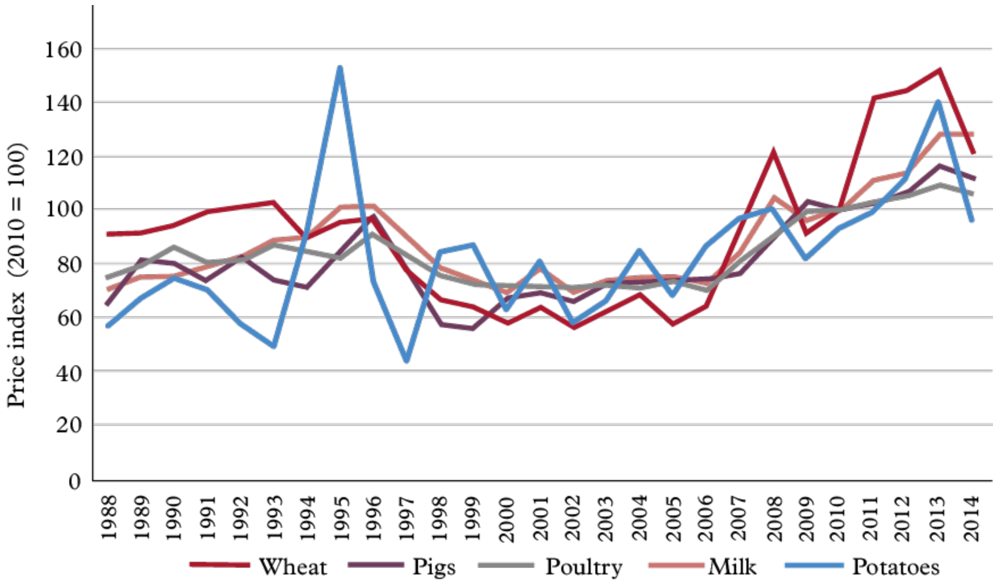


Figure 5 Real indexed prices for selected agricultural commodities (UK)

Source: Defra (2017)

JRF (2016) did explore the link between food price shocks and UK household expenditures, as reflected by changes in UK food prices. They found that whilst food prices rose at the same rate as overall consumer prices between 2001 and 2007, the increase in food prices between 2007 and 2011 was twice as high as that in all prices (26% compared to 14%). It is also interesting to note that although individual food products that are directly based on the cereals affected by the extreme weather events - such as bread, cereals and biscuits & cakes – increase at a similar rate (125%-133%), the meat and dairy are at least as high, (122% - 159%), reflecting the fact that cereals are used as an input for livestock. Those food products that have little relation to cereals – fruit, vegetables and alcohol – are fractionally lower (118% - 126%). These data suggest, implicitly, albeit weakly, that a global price – UK consumer price relationship may exist.

The wider pathways by which these mechanisms can occur is shown below (PwC, (2013). This indicates - in generic terms - a number of potential impacts of trade disruptions, including those in the food supply chain, to the economy. These occurrences are likely to have associated financial and economic costs.

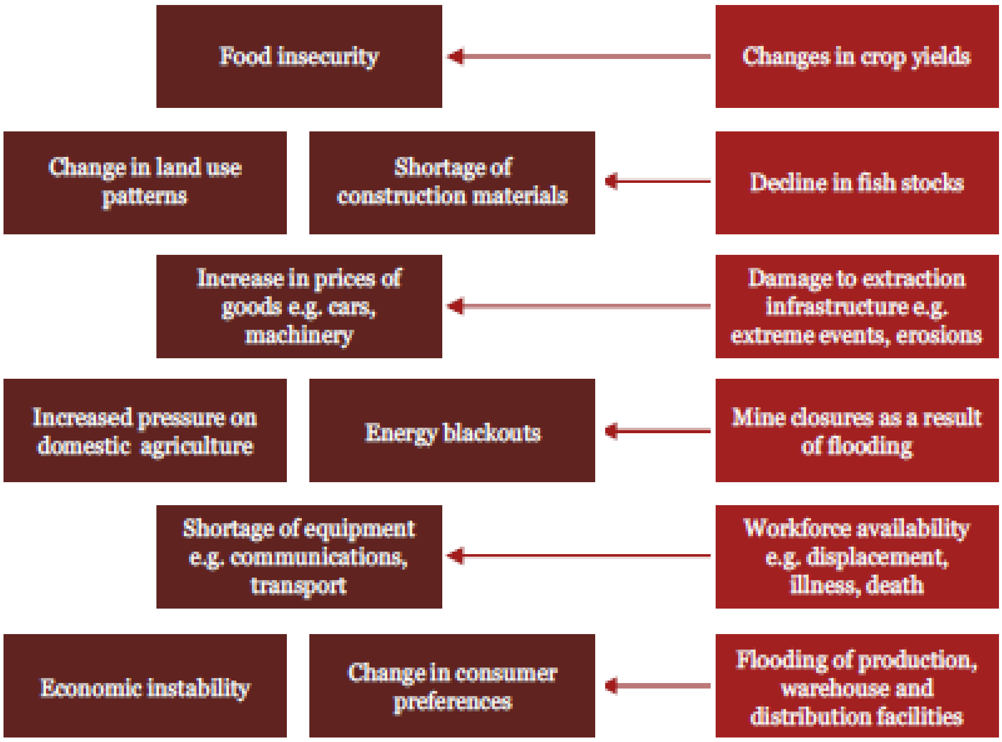


Figure 6 Examples of knock-on impacts from trade disruptions to the rest of the UK economy

Source: PwC (2013)

The future costs of climate change on food prices and food shocks are much more difficult to project. These impacts are challenging to map, as they will occur on a global scale, with impacts like to be more concentrated in some regions than others (developing countries more exposed and more vulnerable to climate impacts). However, what is clear is that impacts – and therefore the resulting costs - will be more significant under severe climate scenarios. These will have knock-on effects on the English businesses and consumers since prices of some food materials and products that they face will be higher. Whether these food price effects will have macro-economic consequences is unclear. Food currently comprises 8% of the basket of goods considered in calculating the monthly inflation rate; consequently, one would expect that a policy response would be considered only if a large proportion of food products had significantly higher prices, sustained for a period of many months. This seems unlikely in the event that the price increase is triggered by a single seasonal variation but more likely if the disruption is sustained over a longer period.

A meta-analysis of 1090 studies conducted by Porter et al. (2014) on yields (primarily wheat, maize, rice and soybeans) under different climate change conditions indicates that climate change may significantly reduce yields in the long run. Porter et al (2014) found that global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (high confidence).

In the UK, climate change-induced supply chain risks are likely to result mainly in higher market prices faced by households. This will be the case where there is some constraint in the supply of goods to market resulting from a climate risk. It is notable that – as indicated by the range of examples presented above – the extent of possible markets that may be impacted is very broad. Perhaps as a result of this breadth, the size of price impact has not been investigated in quantitative terms for the UK.

There have also been some studies that have looked at particular parts of food supply chains, notably transport. The UK Climate Change Risk Assessment 2017 Evidence Report (ASC, 2016) highlights a number of historical incidents where supply chain disruption has resulted from weather events, and cites that these are likely to become more frequent under climate change scenarios. These incidents include the fact that between 2006 and 2013, 24% of rail disruptions in England and Wales were attributed to weather-related incidents. The economic extent of international supply chains was emphasised by reporting that the value of UK imports rose from £150 billion in 1990 to £548 billion (nominal prices) in 2014 whilst exports increased from £139 billion in 1990 to £511 billion over the same time period.

On the basis of current climate projections, (Met Office, 2018; IPCC, 2014), more frequent climate-related extreme weather events are likely to occur in the UK and internationally. Thus, the recently observed trend of price spikes, and price volatility more generally[2], may be expected to be exacerbated to 2050 and beyond. As above, these spikes are likely to be more prevalent and more intense under 4°C pathways. However, in the short term (to 2040), the potential size of impacts vary more strongly with climate uncertainty (i.e. the 10th to 90th percentile range from the models for a given emissions scenario) and are dominated by extremes and shocks.

Finally, as highlighted above, whilst higher consumer prices may have impacts on household expenditure patterns, volatility may also have effects on producers. Price changes are generally assumed to be helpful in signalling to/from what economic resources should be allocated, however, they may lead to excessive investment and the risk of subsequent market crashes. Such behaviour is argued to misdirect real resources and increase the cost of technical innovation. Excessive volatility could also have social consequences by pushing marginal producers out of business, which might lead to consequences such as a gradual depopulation of regions.[3] At a more disaggregated level, CCC (2017), report that certain industries and sectors have considered the future implications of climate change on their international supply chains. For example, Seafish (2015) identified a number of future international risks and opportunities to the UK seafood industry resulting from air or sea temperature change, both at home and further afield. These risks and opportunities included projected changes in inputs such as species distribution, catch potential and production of fisheries elsewhere in the world,

[2] Defined as excessive variations in agricultural commodity prices over time

[3] Written evidence from Sir John Marsh (RPV0006) to The House of Lords Select Committee, European Union Committee: Responding to Price Volatility – creating a more resilient agricultural sector. 15TH Report of Session 2015-2016, 16th May 2016, HL Paper 146.

and risks to infrastructure from more intense and more frequent storms. No quantification was made of these impacts.

Step 4. What are the potential additional adaptation options to address these impacts?

As highlighted above, there are already actions being undertaken to enhance the resilience of food supply chains, and a UK Food Security Assessment is due to report later this year. Nonetheless, it is useful to look at the potential adaptation options that could help build resilience.

In the table below, we identify a range of adaptation options that might be effective in reducing potential impacts or make the UK food supply chain more resilient. It is highlighted that these adaptation options may be undertaken by a range of actors, both domestically and internationally. This list is indicative rather than comprehensive.

It is highlighted that food supply chains are led by the private sector, and thus there is an important issue to understand how to incentivise business to act. Businesses will take adaptation actions when the benefits of doing so outweigh their (private) costs. Companies will most likely focus on categories of high spend where climate change risks are perceived as the highest (hot spots), business-critical suppliers, or key raw materials that are not sourced directly. However, the great complexity of supply chains multi-staged process, coupled with the uncertainty around climate change impacts, suggest that the private sector might struggle to take the appropriate actions. The Government could therefore play a role in removing some of the barriers preventing private sector adaptation as well as ensuring a higher level of resilience along supply chains e.g. infrastructure.

CCC (2017) notes that the importance of generic supply chain resilience has been recognised by Government as an issue that requires support. Thus, in England, the Environment Agency has published guidance on managing risks from climate change to supply chains (Climate Ready, 2013). Self-reported data is available through, e.g., the Climate Disclosure Project. This suggests that some large multinational companies are managing the risks of disruption to suppliers but that there has been a focus on identifying alternative suppliers. CCC (2017) also report that large food retailers and manufacturers, including Tesco, Morrisons, The Co-operative, Waitrose, Marks & Spencer and Asda use weather data and forecasting services to reduce the risk of severe weather-related disruption along their supply chains and provide information on future demand trends. These and other large food retailers also engage with the Sustainable Supply Chain Initiative established and co-ordinated by the Consumer Goods Forum.[4]

As there are existing food supply shock risks, there would be benefits from no- and low-regret adaptation options that address current extreme risks, and these would build resilience to future increases under climate change.

There is also a need to better understand these risks, and enhanced monitoring and research is warranted, notably to identify possible hot spots (regions/countries which already show great vulnerability to weather events causing food production and transport disruptions) in the short-term (under the 10^{th} to 90^{th} percentile range in UKCP18) and in the long-term under a 2^{o}C vs. 4^{o}C degree scenario. This would help understand the scale of future vulnerability of the UK market under different scenarios, and provide a stronger rationale for action. Priority should be given to understanding future impacts on the production and availability of those food items which currently represent a large share of imports (fruit and vegetables, and meat).

[4] https://www.theconsumergoodsforum.com/initiatives/sustainable-supply-chain-initiative/

Based on the evidence that emerges, supply-side interventions could be designed, for example to increase domestic production in sectors such as horticulture and animal feed where the UK is heavily reliant on imports. Also, the uptake of new technologies to improve productivity could be promoted. Finally, on the demand-side, awareness campaigns to reduce food waste and encourage the consumption of British food could be pursued.

Table 2. Taxonomy of adaptation options in the food supply chain.

Climate change impact on food supply chain	Adaptation option/measure	Adaptation actor (public/private)
Changing conditions affecting the extraction and/or production of raw materials to be used in food and manufacturing processes	Development and adoption of climate resilient varieties; Adoption of farm-level climate-sensitive measures, e.g. water efficient irrigation systems; enhanced insurance coverage; More diversified supplier network. Information/advice services, including development of longer term weather forecasting services for producers Increasing domestic production in sectors such as horticulture and animal feed where the UK is heavily reliant on imports	Public and collective industry investments Private producers Private producers Public and collective industry
Damage to facilities, buildings, equipment and products involved in the food production process	Flood resistant property design; Enhanced insurance coverage	Private
Disruption to the transportation of raw materials, labour, capital or finished goods and services	Diversified supplier network; Resilient transport infrastructure requires a diverse range of entry points to be available that are well distributed nationally. Climate-resilient design, e.g. higher sea port coastal defences; Food storage facilities.	Private and public infrastructure investment
Negative impacts on food prices from effects on production in domestic and global food markets	Food storage facilities; Price regulation; Expanded/efficient trade provision; Food commodity hedging markets Encourage people to change their patterns of consumption, for example to eat more seasonal produce, to eat more British-produced food or to reduce meat consumption. Reduce household food waste, and food waste generated elsewhere along the food supply chain in manufacturing, in the hospitality and food service sector and in retail.	Private Public Public/private Private

Step 5. What are the benefits and costs of adaptation, including trade-offs?

Evidence from the previous steps, above, suggest that climate change may result in increased risks to food supply chain security or resilience. As a consequence, costs of food security are likely to rise. However, the multi-dimensional, multi-staged process by which these climate risks are manifested in the food supply chain, and the multi-actor range of responses, mean that any quantification of the benefits and costs of the adaptation measures of the type described above has not been undertaken to date. We do note, though, that individually, in England there does exist the knowledge and adaptive capacity to identify and weigh up the costs and benefits of the different adaptation measures either through the use of micro-economic or macro-economic methods in specific decision contexts. Whilst quantitative cost and benefit data are not yet collected, in Table 3, below, we provide an indicative sketch of these data and an indication of the possible features of economic efficiency indicators in the case of the individual adaptation measures.

Table 3.

	Adaptation option/measure	Adaptation actor (public/private)	Cost type	Benefit	Economic efficiency characteristics
Changing conditions affecting the extraction and/or production of raw materials to be used in food and manufacturing processes	Development and adoption of climate resilient varieties;	Public and collective industry investments	Capital investment in research programme Operational costs (5 yrs +)	Ensure market supply	Long lead-in time (> 5 years) Potential lock-in effects
	Adoption of farm-level climate-sensitive measures, e.g. water efficient irrigation systems	Private producers	Capital investment in equipment Operational costs (life-time of measures)	Ensure continued production	Short-term benefits though may require behavioural change of producer
	Enhanced insurance coverage	Private producers, Insurance companies	Operational cost to producer	Producer income loss mitigated	Constant low costs; occasional large benefits. Insurance market dependent on risk-cost trade-offs
	More diversified supplier network.	Private companies	Time investment in making/maintaining supply connections	Ensure market supply	Risk diversification benefits have to outweigh costs of network maintenance
	Information/advice services, including development of longer term weather forecasting services for producers	Public and collective industry investments	Capital investment in research programme Operational costs (5 years +)	Facilitates producer risk mitigation strategies	Efficiency relies on producers fully valuing information
	Increasing domestic production in sectors such as horticulture and animal feed where the UK is heavily reliant on imports	Private companies Public policy (exhortation, tariffs, etc.)	Capital costs if re-direct domestic agricultural producers	Domestic producers gain; foreign lose	Dependents on effectiveness of incentives
Damage to facilities, buildings, equipment and products involved in the food production process	Flood resistant property design;	Private	Capital costs	Ensure market supply	Site-specific. Depends on extent of reduced risk relative to increased cost
	Enhanced insurance coverage	Private	Operational cost to firm	Firm income loss mitigated	Constant low costs; occasional large benefits. Insurance market dependent on risk-cost trade-offs
Disruption to the transportation of raw materials, labour,	Diversified supplier network;	Private companies	Time investment in making/maintaining supply connections	Ensure market supply	Risk diversification benefits have to outweigh costs of network maintenance

capital or finished goods and services	Resilient transport infrastructure requires a diverse range of entry points to be available that are well distributed nationally.	Private and public infrastructure investment	Capital investment; Operational costs (life-time of infrastructure)	Ensure market supply	Long lead-in time (> 5 years) Potential lock-in effects
	Climate-resilient design, e.g. higher sea port coastal defences; Food storage facilities.	Private and public infrastructure investment	Capital investment; Operational costs (life-time of infrastructure)	Ensure market supply	Long lead-in time (> 5 years) Potential lock-in effects
	Food storage facilities;	Private infrastructure investment	Capital investment; Operational costs (life-time of infrastructure)	Ensure market supply	Long lead-in time (> 5 years) Potential lock-in effects
	Price regulation;	Public policy	On-going regulatory costs	Price stability encourages private producer investments	Planning advantages to be weighed against loss of incentives
	Expanded/efficient trade provision;	Public policy	Transactional costs of establishing new trade relations	Lower consumer prices	Trade efficiencies weighed against political economy (vested interests)
	Food commodity hedging markets	Private	Investment costs in establishing new markets	Lower consumer prices	Financial market maintenance against price efficiencies
Negative impacts on food prices from effects on production in domestic and global food markets	Encourage people to change their patterns of consumption, e.g. reduce meat consumption.	Public/private	Costs of information/campaign provision	Better informed consumers	Information provision costs weighed against informed consumers
	Reduce household food waste, and food waste generated elsewhere along the food supply chain	Public/private	Costs of information/campaign provision; behavioural/time costs of change in practices	Cost savings to producers/consumers	Information provision costs weighed against consumption cost savings

References

Allianz Global Corporate & Specialty (2012). Managing Disruptions: Supply chain risk: an insurer's perspective.

Adaptation Sub-Committee (2017). UK Climate Change Risk Assessment 2017 Evidence Report.

BSR (2018). Climate + Supply Chain. The business case for action. September 2018.

Cabinet Office (2018). Cabinet Office, Sector Resilience Plans. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/786206/20190215_PublicSummaryOfSectorSecurityAndResiliencePlans2018.pdf

Ciscar JC, et al (2014). Climate Impacts in Europe. The JRC PESETA II Project. JRC Scientific and Policy Reports, EUR 26586EN

Defra (2006) Food Security and the UK: An Evidence and Analysis Paper. Food Chain Analysis Group. December 2006.

Defra (2017) Agriculture in the UK.

Defra (2018). The National Adaptation Programme and the third strategy for climate adaptation reporting: Making the country resilient to a changing climate. July 2018. Department for Environment Food, and Rural Affairs. https://www.gov.uk/government/publications/climate-change-second-national-adaptation-programme-2018-to-2023.

EEA (2017). Climate Change, Impacts and Vulnerability in Europe 2016: An Indicator-Based Report.

FAO (2011) The state of food insecurity in the world 2011. http://www.fao.org/docrep/014/i2330e/i2330e03.pdf

Global Food Security (2012) Severe weather and UK food chain resilience. October 2012.

Global Food Security (2018) Exploring the resilience of the UK food system in a global context. Policy Brief.

Global Food Security programme (2017). Environmental tipping points and food system dynamics: Main Report.

HM Government (2014). Elliott Review into the Integrity and Assurance of Food Supply Networks – Final Report. A National Food Crime Prevention Framework July 2014. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/350726/elliot-review-final-report-july2014.pdf

Hunt, A. S. P., Wilby, R. L., Dale, N., Sura, K. and P. Watkiss (2014). Embodied water imports to the UK under climate change. *Climate Research*. 59:89-101. doi: 10.3354/cr01200.

JRF (2016). Climate Change Impacts on the Future Cost of Living (SSC/CCC004). Report to the Joseph Rowntree Foundation and the Project Advisory Group. https://www.climatejust.org.uk/resources/climate-change-impacts-future-cost-living

IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
Met Office (2018) UKCP18 Science Overview report November 2018.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. U. S. A. 105, 1786–93. https://doi.org/10.1073/pnas.0705414105

Levermann, A., Bamber, J.L., Drijfhout, S., Ganopolski, A., Haeberli, W., Harris, N.R.P., Huss, M., Krüger, K., Lenton, T.M., Lindsay, R.W., Notz, D., Wadhams, P., Weber, S., 2012. Potential climatic transitions with profound impact on Europe. Clim. Change 110, 845–878. https://doi.org/10.1007/s10584-011-0126-5

Luhr, O., Kramer, J-P., Lambert, J., Kind, C. and Savelsberg, J. (2014). Analyse spezifischer Risiken des Klimawandels und Erarbeitung von Handlungsempfehlungen fur exponierte industrielle Produktion in Deutschland (KLIMACHECK). _

Nelson, G., Valin, H., Sands, R., Havlík, P., Ahammad, H., Deryng, D., Elliott, J. et al. (2014). Climate Change Effects on Agriculture: Economic Responses to Biophysical Shocks. *Proceedings of the National Academy of Sciences* 111 9: 3274-79.

Parliamentary Office of Scence and Technology (2017). Security of UK Food Supply. POSTNOTE 556 June 2017.

Porter, J.R. et al. (2014). Food security and food production systems. In IPCC. 2014. Climate Change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report. of the Intergovernmental Panel on Climate Change, pp. 485–533. Cambridge, UK and New York, USA, Cambridge University Press.

PwC (2013) International threats and opportunities of climate change for the UK. Report for Defra.

PwC (2008): From vulnerable to valuable: how integrity can transform a supply chain.

Ray D.K. et al (2015). Climate variation explains a third of global crop yield variability. Nature Communications, 6:5989, DOI: 10.1038/ncomms6989. www.nature.com/naturecommunications

Rosenzweig, C., et al (2013). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. PNAS(ISI-MIP Special Feature). PNAS.

Seafish (2015) Climate Change Adaptation in UK Seafood: Understanding and Responding to Climate Change in the UK Wild Capture Seafood Industry

Tröltzsch, J et al, 2018. D1.2 Knowledge synthesis and gap analysis on climate impact analysis, economic costs and scenarios. Deliverable to the COACCH project. Available at www.coacch.eu

Wojtek Szewczyk, W and Ciscar, J.C (2016). Deliverable 8.2.1: Modelling autonomous adaptation with the CAGE-GEME3 model. Deliverable of the Econadapt Project. Available at https://econadapt.eu/sites/default/files/docs/Deliverable%208_2%20approved%20for%20publishing.pdf. Accessed October 2018.

UK Foresight (2011). International Dimensions of Climate Change. Final Project Report BIS/11/1042. London: UK Government Office for Science. https://www.gov.uk/government/publications/international-dimensions-of-climate-change.

Vautard, Robert Andreas Gobiet, Stefan Sobolowski, Erik Kjellström, Annemiek Stegehuis, Paul Watkiss, Thomas Mendlik, Oskar Landgren, Grigory Nikulin, Claas Teichmann, Daniela Jacob (2014). The European climate under a 2°C global warming. Environment Research Letters. ERL-9 034006. doi:10.1088/1748-9326/9/3/034006

Wegren, S. K. (2011) Food Security and Russia's 2010 Drought, Eurasian Geography and Economics, 52:1, 140-156.

Wenz, L., and Levermann, A. (2016). Enhanced Economic Connectivity to Foster Heat Stress-Related Losses. *Science Advances* 2: 6.

West, C., S. Croft, E. Dawkins, R. Warren, and Price, J. (2015). Identifying and Exploring Key Commodity Chains at Risk from Climate Impacts. In AVOID2. WPF3: The Impact of Weather Extremes on Agricultural Commodity Prices.