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Food Systems, Climate Change Adaptation and Human Health in Australia

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Abstract:

Nutritious, safe, affordable and enjoyable food is a fundamental prerequisite for health. As a nation, Australia is currently classified as food secure with domestic production exceeding domestic consumption of most major food groups. However, the viability of the Australian food system sits counter to the continued presence of a stable and supportive climate. For Australia to adapt to climate change it is essential to implement evidence-based research and policy that will increase the adaptive capacity and resilience of Australia's vulnerable food and health sectors, while also considering the implementation of transitional, transformational, and mitigation strategies to ensure long term sustainability. This discussion paper reviews the current state of science to reveal key issues and gaps in the fields of human health and food systems research, with implications for Australia's capacity to adapt to climate change. It uses a food systems approach to identify observed and potential climate change impacts along the food chain and highlights the direct and indirect pathways to health outcomes. The paper represents a collaborative work bringing together expertise from leading Australian researchers and policy-makers in the fields of health and food, as part of a series being developed by the National Climate Change Adaptation Research Network for Human Health and builds on the National Adaptation Research Plan on Human Health (Nicholls 2009).

Key words: climate change adaptation, food security, human health

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Introduction

Food is a fundamental prerequisite for health. It provides energy and nutrients essential for the human body's growth, development, repair and functioning. The Australian population has a nutritional health profile commensurate with other Western OECD countries in both positive and negative dimensions. Most Australians have available (albeit not equally accessible) a relatively abundant, diverse, cheap, and safe food supply; yet diet-related behaviours contribute significantly to the burden of disease: for example, inadequate fruit and vegetable consumption contributes 3% (AIHW 2010). Among the ten leading causes of death, 4 have a strong dietary component: namely coronary heart disease, Type 2 diabetes, stroke and colon-rectal cancer. Type 2 diabetes is predicted to become the leading cause of death in 2013 (AIHW 2010).

The viability of the Australian food system is dependent on the continued domestic and international presence of a stable and supportive climate and related adequate environmental resources. However, evidence is growing that the Earth is warming and that global warming will affect both our food supply and health. Recorded evidence of current climate change reveals an increase in global atmospheric concentrations of greenhouse gases, carbon dioxide, methane and nitrous oxide since 1750 as a result of human activities (Forster et al 2007). These effects have contributed to an increase in total temperature by 0.76 degrees over the twentieth century (Trenberth et al 2007), leading to water expansion and melting of glaciers and ice caps; and in consequence, sea-level rise (Lemke et al 2007). Other impacts from climate change include changed rainfall patterns, the increased frequency of extreme weather events and water-stressed regions where people do not have access to safe and reliable water supplies (Costello et al 2009).

Climate change is high on the public policy agenda in Australia and around the world, recognized as the single largest threat to global food security and population health (Cohen et al 2008; McMichael and Butler 2009). The World Health Organisation (WHO 2005) identifies global environmental hazards to food and human health that could be exacerbated by climate change as: loss of biodiversity, changes in hydrological systems and freshwater supplies, land degradation, and stresses on food-producing systems.

Australia's history demonstrates that it is a resilient nation with the capacity to deal with extreme weather events (Stokes and Howden 2010). Since the 1950s, the national food system has undergone dramatic changes: there are fewer farms but they are larger, more specialized, corporatized, use more irrigation, chemical and machinery inputs, while fewer young people work in agriculture (Larsen et al 2008). Australia's food system is and has always been in a state of constant change - influenced by a confluence of tastes, technologies, trade and changing environments - shifting from the monotonous menus of colonial settlers

to today's multi-cultural menus of endless novelty (Pritchard and McManus 2000; Symons 2007). This sophisticated food system and diet are integrated into the global marketplace, both influencing and being influenced by global economic and environmental flows, while providing a relatively good nutritional health profile for the average Australian.

Australia must continue to build a food-secure, healthy nation with a food supply that is safe, sufficient, nutritious, diverse, affordable and ultimately resilient for all people at all times regardless of the weather. This discussion paper reviews the current state of science and policy to reveal key issues and gaps in the fields of human health and food systems research, constraining Australia's capacity to adapt to climate change. It uses a food systems approach to identify observed and potential climate change impacts along the food chain and highlights the direct and indirect pathways to health outcomes. Potential future scenarios are also discussed in a context of impacts on food security and health. Although this paper specifically discusses adaptation, it recognizes that the food system is a substantial contributor of greenhouse gas emissions, and is therefore, also a cause of climate change necessitating mitigation strategies. This issue will be discussed in Part 5: The limits to adaptation.

The paper is part of a series being developed by the National Climate Change Adaptation Research Network (ARN) for Human Health and builds on the recently published National Adaptation Research Plan (NARP) (McMichael et al 2009). It represents a collaborative work bringing together expertise from leading researchers and policy-makers in the fields of health and food from across Australia. Synergies exist between this document and others within the Health ARN discussion paper series, and across other NARPs, predominantly in the themes of Primary Industries (Barlow et al 2010), Water Resources and Freshwater Biodiversity (Bates et al 2010), Marine Biodiversity and Resources (Mapstone et al 2010), and Social, Economic and Institutional (Barnett et al 2009).

This paper offers an essential perspective to the climate change debate as it focuses on the under-explored intersection of the climate, food systems and health. It identifies critical links and feedback loops between these systems, which are often ignored. The paper also goes beyond analysis of the food production stage to report on the direct and indirect impacts of climate change on the entire food system, including distribution and consumption, with implications for population health.

Part 1: The conceptual approach

Climate change acts as a multi-determinant of both the food system and health risks and outcomes, and this section amplifies what is known about the interconnections between the two systems. The terms used throughout the paper

- climate change adaptation, mitigation and mal-adaptation, vulnerability, adaptive capacity and resilience - are defined in the next sub-section.

Climate change, pathways to health, and the food system

Scientists working in Australia generally accept that climate change will make the continent hotter, drier and lead to an increase in extreme weather events (Palutikof 2010; Barlow et al 2010; Bates et al 2010; Mapstone et al 2010; Barnett et al 2009; McMichael et al 2009). Climate change will have both direct and indirect impacts on population health (Nicholls 2009); and adapting to climate change will cause shifts in current health care priorities as research and resources are diverted to address new concerns (Blashki et al 2010; McMichael et al 2009).

According to Friel (2010), climate change will continue to affect the food system and health by contributing to impaired food quantity, quality and affordability in many countries, including Australia (see also McMichael et al 2007; FAO 2006; UNDP 2007). In Australia, climate events and trends — including fluctuating temperature, rainfall and humidity, and severe weather events, such as heat waves, floods, droughts and storms — will have direct health consequences through influencing plant and animal health and hence, the quantity and quality of food yields (Horton and McMichael 2008; Stokes and Howden 2010), while possibly increasing food-borne disease. For example, leading researchers identify that water shortages in Australia would contribute to greater incidences of food-borne infectious diseases such as gastroenteritis (Ebi et al 2007; D'Souza et al 2004). Indirect pathways between climate, food yields and nutritional standards include changes to ecosystem function and quality, such as increased levels of air and water pollution, soil and nutrient degradation (McMichael et al 2007). Other impacts include increased allergic diseases (Bunyavanich et al 2003; Beggs and Walczyk 2008), while the mental distress for vulnerable communities (such as farmers in drought-affected regions) is yet to be adequately accounted for (Berry et al 2010).

The food system is affected at multiple levels by climate change due to its multiple stages of production, processing, distribution and exchange, consumption and waste. At the 1996 World Food Summit, the Food and Agriculture Organisation (FAO) defined *food security* as when ‘. Since this declaration, the definition of food security has been extended to also recognize aspects of nutritional quality, social values and environmental stability. Figure 1 from the FAO contains a recent schematic showing the multiple contributors to a sustainable food supply.

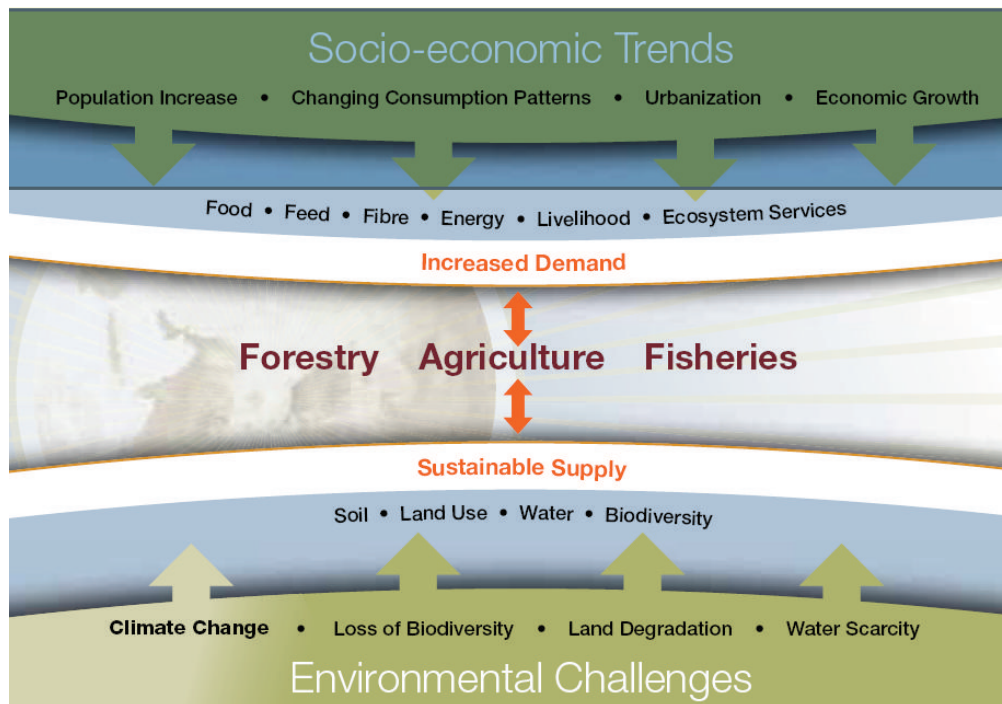


Figure 1 Profile for Climate Change. Source: FAO (2009)

The FAO has not only identified the importance of economic and environmental factors in a sustainable food system, but lists cultural issues, governance, technology, resource availability, climate change and population growth as co-determinants. It acknowledges critical connections and feedback loops existing both within and between the food system, climate and society in a way that is consistent with the thinking of ecologists. Ericksen (2008), for example, recognizes that a truly sustainable and secure food system looks beyond food production to consider climate change adaptation across the entire food chain, while also taking into account multiple scales (global, national and local), levels (temporal, institutional, and management), and time periods (short- and long-term implications).

Climate change adaptation, mal-adaptation, mitigation, vulnerability, adaptive capacity and resilience

To better understand how the food system and population health can adapt to climate change it is first important to define the terms. *Climate change adaptation* is understood here as the modification of current policies and practices to cope with unavoidable impacts from climate change (Kjellstrom and Weaver 2009). Adaptation exists in various forms, such as anticipatory and reactive, private and public, and autonomous and planned (Barnett et al 2009). Reactive adaptation is illustrated by heat wave early warning systems, while a planned strategy would entail growing more vegetation in cities to reduce the urban heat island effect (Pachauri et al 2007). Planned adaptations would also include the improvement or extension of existing policies and social functions.

Climate change adaptation can encompass a range of measures including incremental step wise change, to transitioning away from current practices, to transforming systems by introducing innovation. The first approach strives to increase resilience and reduce vulnerability within the current system in order to maintain the system. The implementation of a diversity of approaches, models and sources is thus a healthy sign of preparation to address a number of possible uncertain outcomes. Transitional approaches can involve re-locating production sites, harvesting different types of produce, or by implementing new farming methods. The third approach strives to introduce innovation into the system to restructure how food is currently produced, distributed and sold. Innovation supports change by taking risks. Introducing novelty into a system must be carefully considered as new factors could create potentially damaging results. Adaptive response strategies may be alternative or complementary, and vary in their degrees of risk-adversity, short- or long- applications, and in their degree of adaptive or mal-adaptive outcomes (Barlow et al 2010). *Mal-adaptation* is defined as adaptation that 'does not succeed in reducing vulnerability but increases it instead' (McCarthy et al 2001: 990).

By contrast, *climate change mitigation* represents actions instigated to reduce the root causes of climate change, thereby limiting over time the extent and cost of adaptation as well as forestalling the onset of catastrophic changes. Reducing greenhouse gas emissions through reducing red meat consumption is an oft-cited mitigation strategy. Both adaptation and mitigation are essential in an overall response to climate change (FAO 2009; Kjellstrom and Weaver 2009). However, for the purposes of this paper we focus on adaptation responses to climate change, and how vulnerable aspects of the food system can have their adaptive capacity strengthened so as to protect human health.

Before we proceed it is important to note that climate change affects people and sectors differently depending upon their state of *vulnerability*, defined by the Intergovernmental Panel on Climate Change (IPCC) (2007: 883) as 'the degree to which a system is susceptible to, and unable to cope with, adverse affects of climate change, including climate variability and extremes'. Vulnerability has three elements: exposure, sensitivity and adaptive capacity, and is not determined by climate alone (Barnett et al 2009). *Adaptive capacity* or *resilience* in turn, is defined as 'the general ability of institutions, systems and individuals to adjust to potential damages, to take advantage of opportunities and to cope with consequences' (Spickett et al 2007). If a system is resilient it is able to 'bounce back' from disturbances, 'while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change' (Pachauri and Reisinger 2007). Barnett (et al 2009:12) notes that adaptive capacity is context specific, changes over time, and importantly, is not necessarily equally distributed across society. Furthermore, although an individual or institution may have adaptive capacity, this may not occur due to the presence of economic, political and cultural barriers to action.

Part 2: Evidence of climate change on the food system and health

Overview

Domestic production of most major food groups in Australia equals or exceeds domestic consumption. This production/consumption balance remained largely unchanged between 1997-1999 and 2001-2003 (see Table 1). Specifically,

- Production of cereals, sweeteners, pulses, meat, milk and animal fats exceeded domestic consumption;
- Production of starchy root vegetables, vegetables, fruit and eggs equalled, or nearly equalled, domestic consumption; and,
- Production of seafood and vegetable oils did not meet domestic consumption (ABARE 2007; ABARE 2008).

However, in the last decade, there have been significant changes in the constitution of Australia's food supply with implications for reliable availability, accessibility and affordability of nutritious food. Australia's substantial food trade surplus decreased slightly with imports doubling to around \$9 billion in 2007-08. Dominant contributors to the import increase were processed foods, particularly flour and cereal food, wine, dairy products, beverages, fruit and vegetables, and 'other' processed foods (not elsewhere classified). Reduced grain and dairy exports explained most of the decline in exports; with smaller contributions from fresh/chilled fish, live animals and fresh/chilled horticultural produce. The decline in exports was largely as a result of climatic factors and fluctuating demand in key export markets such as Asia (ABARE 2007; ABARE 2002).

Table 1: Food balance sheets. Supply and consumption of major food groups in Australia. *Source:* Data from Australian Food Statistics (2002 and 2007 editions).

Table 1 Food balance sheets. Supply and consumption of major food groups in Australia.
Source: Data from Australian Food Statistics (2002 and 2007 editions)

Food group	Domestic production (kt)	Imports (kt)	Exports (kt)	Domestic consumption (kt) *	Production as % of consumption
Cereals, 97-99 avg	32,478	133	22,794	9,716	334%
Cereals, 01-03 avg	31,893	340	17,651	11,253	283%
Starchy roots, 97-99 avg	1,334	84	43	1,376	97%
Starchy roots, 01-03 avg	1,300	95	64	1,334	97%
Sweeteners, 97-99 avg	5,699	43	4,364	1,091	522%
Sweeteners, 01-03 avg	4,979	102	3,357	1,579	315%
Pulses, 97-99 avg	2,574	12	1,082	1,523	169%
Pulses, 01-03 avg	2,013	11	2,084	390	516%
Vegetables, 97-99 avg	1,790	189	247	1,740	103%
Vegetables, 01-03 avg	1,969	274	236	2,003	98%
Fruit, 97-99 avg	2,786	270	476	2,595	107%
Fruit, 01-03 avg	3,456	478	533	3,401	102%
Meat, 97-99 avg	3,469	25	1,508	1,986	175%
Meat, 01-03 avg	3,847	57	1,637	2,266	170%
Eggs, 97-99 avg	145	1	1	145	100%
Eggs, 01-03 avg	144	2	1	145	99%
Seafood, 97-99 avg	214	402	131	486	44%
Seafood, 01-03 avg	236	501	203	534	44%
Milk, 97-99 avg	9,842	365	5,528	4,759	207%
Milk, 01-03 avg	11,045	496	5,813	5,545	199%
Vegetable oils, 97-99 avg	351	213	111	449	78%
Vegetable oils, 01-03 avg	234	270	119	412	57%
Animal fats, 97-99 avg	725	20	585	160	453%
Animal fats, 01-03 avg	768	40	572	215	357%

Climate change and food production

Food yields are being impacted by adverse seasonal conditions (Campbell 2008a; Stokes and Howden 2010; McMichael et al 2007; ABARE 2002; Campbell 2009). Nearly all food products are considered vulnerable, albeit in varying degrees due to their exposure, sensitivity and capacity to adapt to changing bio-physical conditions (Stokes and Howden 2008). Australian industries grow 88% of vegetables and 85% of fruit consumed domestically (DAFF 2008). These intensive plant industries, which include horticulture, grow in tropical, sub-tropical, temperate and cool zones, with production often consuming large quantities of water. A wide variety of horticultural produce is highly vulnerable to climate change, especially those that are sensitive to heat stress, sunburn and wind, require winter chilling, lack water at critical periods, are susceptible to pests and disease, or are exposed to erratic weather, such as hailstorms (Barlow et al 2010; Stokes and Howden 2008).

Australia's land extensive plant industries produce grains, oil crops, rice and sugar cane, often in conjunction with livestock, through broad scale agriculture processes. Grains are grown in every state of Australia but are primarily located in a narrow curve running through central Queensland New South Wales, Victoria, down to South Australia and across to Western Australia. It is widely acknowledged that Australian agriculture is characterized by a history of adverse and variable weather conditions, as indicated by trends in rainfall over the Murray-Darling Basin (MDB): the nation's 'bread bowl' and foremost fruit and vegetable growing region. Figure 2 shows that the annual trend over the first half of the twentieth century was lower than the last fifty years, by about 50 millimetres on average or one and half month's annual rainfall (see Figure 2). The 1930-1946 period was particularly dry, as has been the 1998-2008 period.

The most recent drought in the MDB coincided with record high temperatures in southern Australia (Hennessy et al 2010).

However the significance of the latest drought concerns how Australian agriculture has changed appreciably since the 'dry' early decades of last century: most notably through the intensification of water-thirsty agriculture (lettuce, dairy, rice and viticulture). Within a context of water cap and trade regulations for farming and commodity groups which are more vulnerable to prolonged drying, the adaptation challenge for these farmers is at least more constrained than in the past.

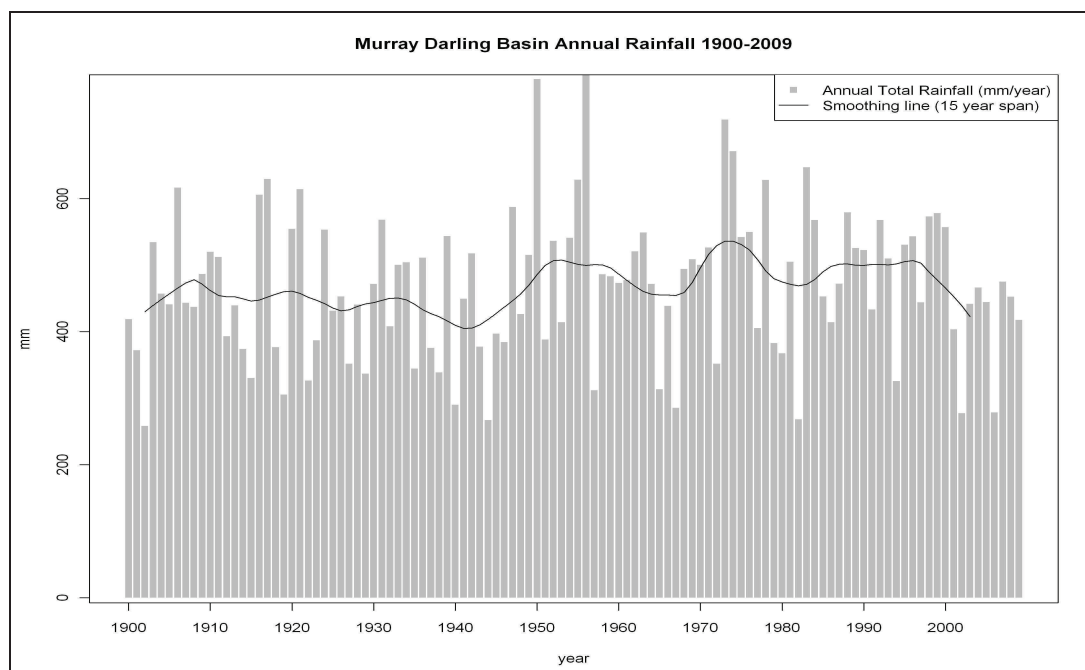


Figure 2 Murray Darling Basin Annual Rainfall 1900 – 2009. Source: Bureau of Meteorology

In all regions, grains are sensitive to climate with both wet and dry years causing substantial fluctuations in regional yield and grain quality. High rainfall can cause problems such as waterlogging, flooding, rain and hail damage, increasing pest and disease loads, with intermittent recharge of water to groundwater tables and associated leaching of nutrients (Stokes and Howden 2008). Alternatively, some irrigation is practiced to offset drought conditions, yet due to reduced water allocations, even irrigation is not resolving climate issues. Due to severe drought in the last decade, Australia, normally one of the world's largest grain exporters, has experienced two years (2001-02 and 2007-08) of net grain importing (Butler 2009).

Specific crops react differently to climate change. Sugarcane, a crop grown in areas of high rainfall, is estimated to be greatly impacted by water fluctuations (Stokes et al 2008), yet paradoxically benefits from climate change-induced increased carbon dioxide in the atmosphere (da Silva et al 2008). Rice, in contrast, produced under irrigation in the New South Wales Riverina and in small volumes in Victoria (ABARE and MAF 2006), is badly affected by drought and is expected to suffer drastically due to climate change impacts. Production plummeted 89% in 2009 to 17,600 tonnes on the back of significantly reduced plantings, while farmers are currently exploring other options to cope with losses (Australian Food Network 2009).

Regarding the broad acre livestock industry, prolonged drying and extreme weather events have an uneven effect on the price, seasonal availability and quality of most meats depending on their major sites of production. Models by

ABARE calculated that the 1994-5 drought reduced the gross value of farm production by as much as \$2.4 billion, mainly because of the impact on animal grazing conditions (Hogan et al 1995; White 2000). Sheep numbers have halved in the last two decades due to drought in concert with world markets, although beef numbers have increased in the same period (The Climate Institute 2009). Lesser rainfall in the sub-tropics make some new areas suitable for grazing cattle, yet the areas may still not be viable due to relatively higher costs of buying and transporting industrial feed to feedlot cattle. Climate change is also likely to exacerbate existing pastoral management challenges, such as pests, soil erosion, salination and acidification, including problems with animal nutrition and health, all impacting upon overall productivity (Stokes and Howden 2010).

The intensive livestock industries include dairy, beef and sheep feedlots, and poultry and piggeries. Dairy is the largest sector within the Australian intensive livestock industry, representing one third of production behind beef and wheat. For dairy, again drought, in addition to factors of national market deregulation, foreign direct investment and supermarket control of milk supply chains, have combined to affect the balance of trade between domestic and imported volumes of milk and dairy products. The intensive nature of dairy production calls for significant consumption of materials, energy, water and grains for fodder. Higher temperatures and lower rainfall in some regions will continue to see dairy herds decrease in areas requiring longer and more costly supply chains, while in higher rainfall regions, such as Tasmania and New Zealand, dairy may benefit from warmer conditions and be able to expand their herds. However, dairy cows are also likely to suffer due to heat stress, which may result in reduced milk yields.

In terms of fish stock quantities and resilience, climate-induced marine environmental change for coral reef habitats is among the most significant. The quality and diversity of these habitats are being eroded through a mix of factors, including warming and acidifying seas and decreased carbonate accretion on coral reefs due to increases in carbon dioxide in the oceans, with the latter further compromising the corals' resilience to reproduce and to withstand wave energy (Hoegh-Guldberg et al 2007; Munday et al 2008; Mapstone et al 2010). Australia is a significant net importer of fish. The global market provides about 164 million tons; three quarters of which comes from marine waters and the remainder from inland water systems, with the latter consisting of capture fisheries (2/3 of this fish) and aquaculture systems (1/3). However, '70% of world fish stocks are estimated to be fully exploited, overexploited, or recovering from a period of depletion' (Brander 2007: 19709). In Australia, between 2002-03 and 2007-2008, the catch of tuna, abalone, scallops and oysters was steady, rock lobster experienced a modest, steady decline, prawns showed a modest decline, and 'other fish' (the type eaten by the majority of the Australian population) has seen variable declines (DAFF 2009).

The adverse impact of seasonal conditions on farming is demonstrated by 84% of Australian agricultural businesses reporting that they had experienced

droughts, severe frosts, hail, severe storms, floods, or an increase in seasonal variability during the 2007–08 season. Almost one third reported using financial reserves and/or taking on increasing liabilities in response to adverse seasonal conditions (ABS 2008). Australia, normally one of the world's largest grain exporters, has experienced two years (2001-02 and 2007-08) of net grain importing due to severe drought (Butler 2009). Farmer vulnerability was illustrated during the 2009 Victorian heat wave which resulted in production losses of 50-90% of raspberry, blackberry and blueberry crops, 20-25% of orchard crops (apples and late season apricots) and 60-80% of strawberries in the Port Phillip region (DPI 2009).

Climate change and food processing

Food processing is Australia's largest manufacturing industry with total sales of approximately \$66 billion, 21% of which are exports, employing about 205,000 people (ABARE 2009; TISN 2006; DAFF 2004). Examples of processing centres include canneries for fruit and vegetables, abattoirs to process meats; and various factories that grind flour to make bread, that husk rice, turn milk into cheese, yoghurt and ice cream; process tea; juices; confectionary; biscuits and cakes; and many more complex snacks and meals with various ingredients and processing stages. Basic resources required for food processing include: available raw produce and transport to the processing plant; a suitable location and premises for processing with access to adequate workers and raw material; and, a high level of hygiene and temperature control; as well as transport to move produce from factory to point of sale.

Processing may be affected by climate change either directly through extreme weather events or indirectly along the food chain through declining good quality food inputs. Under conditions of prolonged changed climatic conditions reliable supply chains may become no longer viable (Larsen 2010). Products such as rice may only be available in wetter years and processing mills may not be viable with inconsistent supplies (Gaydon et al 2010). The costs of 'doing business' are already increasing under fluctuating weather conditions as experienced by rising prices for water, energy and transport, requiring higher investments in logistics systems to ensure appropriate standards of hygiene and temperature control to minimize spoilage and waste (ABARE 2002; Morgan 2009).

Australia is already subject to strict regulation and checks to ensure a high level of hygiene and temperature control during processing and manufacture. With possible climate change impacts occurring in food production and processing, such measures will become even more important. As many climate change concerns for processing are actually projections of what could happen in the near or distant future, further discussion of this sector is located in 'Part 3: Possible future scenarios'.

Climate change and distribution

Distribution refers to how, when and to whom, food is transported and distributed. Distribution systems enable movements of: agricultural inputs, such as fertilisers and fuels, to farms; primary produce and other materials to processing; and primary produce and processed foods to export, distribution centres, wholesalers, retailers and other outlets. The journeys that people make to access food can also be considered part of the food distribution system.

Australia's food supply is delivered using a variety of modes and routes. There are over 810,000 kilometres of roads and 44,000 kilometres of rail in Australia. Road transport is by far the dominant freight mode for food (for human and animal consumption) within Australia, both by total volumes carried (94.7% travels by road) and by tonne-kilometres (86.8%). Interstate sea freight is significant between Victoria and Tasmania, rail is used primarily for bulk movement of commodities that have low value per tonne, such as grains and sugar. Other food and live animals make up only 3-5% of the goods moved by rail (ABS 2004).

Food for human and animal consumption accounted for 22% of tonne-kilometres travelled as Australian road freight and 14% of the tonnes in 2000 (ABS 2002). Road is the dominant transport mode largely due to the short shelf life and highly perishable nature of many food products, which makes timing critical (Larsen 2010). Inclusion of broader food-related categories (cereal grains and live animals) brings food related freight to a total of 29.7% of the tonne-kilometres and 23.3% of the total freight weight carried by road in Australia (ABS 2002). Any major disruption to road freight in Australia will have a significant impact on the movement and cost of food. For analysis of food supply vulnerabilities associated with distribution systems, it may be appropriate to also consider the indirect food freight task associated with fertilisers and petroleum products as they are critical inputs into the current agricultural system - fertilisers make up 16% of the tonnes moved on Australia's roads.

Food for human and animal consumption travels as solid bulk (20%), liquid bulk (19%), containerised (19%) and other (packaged and palletised goods) – 44% (ABS 2002). 95% of cereal grains travel as solid bulk, and almost 100% of live animals travel as 'other' (ABS 2002). These commodities are affected differently in terms of the perishability and vulnerability to different events. For example, liquid bulk (such as milk) is more vulnerable to transport disruption than many packaged or palletised goods that have already undergone processing.

An example of where extreme weather events have affected key points of movement and exchange, such as ports and major highways, is when the 2009 floods in Tablelands (QLD) made transport of fruit and vegetables unfeasible along the Bruce Highway. Up to \$10 million worth of fresh fruit and vegetables in cold rooms and sheds were stored in cut-off coastal areas (The Cairns Post

2009). Flooding of key roads could have a significant consequence on the short term accessibility for some local regions (Bureau of Transport and Regional Economics 2004). However, as many vulnerabilities represent foreseeable impacts in the near or semi-distant future, they will be discussed in more detail in 'Part 3: Possible future scenarios'.

Climate change and exchange

Exchange refers to the interface between a food supply and food's end-users and consumers. The most typical form of transaction is between sellers and buyers in the commercial marketplace. However depending on household economic circumstances, cultural traditions and issues of food access, individuals may obtain food through other forms of exchange, including: bartering of surplus between friends, family and neighbours; 'gifting' through charity-run 'community kitchens'; and gleaning and other forms of non-commercial and non-reciprocal food appropriation such as dumpster diving (Edwards and Mercer 2007). The sphere of commercial exchange becomes redundant when households self-provision from the home or community garden, or from edible urban gardens where produce is freely available: a contemporary form of gleaning (Dixon et al 2009). Chippendale in inner Sydney has become a model urban garden, supplying small volumes of herbs and fruit to passers-by. New forms of exchange are emerging in Australia, with climate change as one of multiple driving factors. Food that is produced and distributed and exchanged through local, community-based channels does not come under the scrutiny of food regulators and may pose food-borne safety risks through herbicide use or poor refrigeration and handling. These food chains are complementary to the mainstream, industrial and commercial food system and to the food exchange activities of non-government organizations and charity kitchens. How climate change may alter the mix of food chains is not known, although climate change has been documented as placing additional stress on existing social system inadequacies including income and employment (Friel et al 2008).

Climate change and food consumption

Climate change related disruptions in food production, processing and distribution will increasingly result in reduced food availability, affordability, and accessibility. Such disruptions can, in turn, influence dietary practices, food intake and nutritional status, with implications for food security and a range of diet-related health outcomes (Kettings et al 2009).

Numerous factors - such as sufficient money for food; access to retail outlets that offer desirable, affordable commodities; the possession of adequate food storage and cooking facilities; access to culinary practices appropriate to one's cultural identity; and having the personal skills, knowledge and time to prepare nutritionally balanced meals - all influence the social distribution of food, nutrition security, and chronic disease risk (Friel and Conlon 2004; Friel and Baker 2009).

Like other risk factors for chronic diseases, food insecurity is most prevalent among socially disadvantaged groups. Energy-dense, highly processed foods, with their hidden salts, sugars and fats, are major contributors to dietary imbalances that result in diet-related disease (WHO and FAO 2003). Australian evidence suggests a strong link between poverty, food insecurity and obesity in developed countries - the risk of obesity is 20-40% higher for women who are food insecure (Burns 2004). In Australia, the cost of a diet adhering to the national health guidelines consumes about 40% of the disposable income of welfare-dependent families, compared to 20% for an average income household (Kettings et al 2009). Climate change related food price increases will hit the poorer households hardest. Indigenous and non-indigenous rural and remote Australians often source their food from the community store, where available food is expensive relative to the national average and to the incomes of community members. Transporting food to remote regions also increases prices while reducing fresh food availability, and possibly, nutritional standards.

A range of global and domestic influences has led to rising food prices in recent years affecting food manufacturing input costs and output prices. Key drivers include higher energy and other input costs, adverse climatic influences undermining agricultural production, and growing demand for food in developing nations. While raw agricultural commodities have generally increased in price, they often represent only a small proportion of the costs of meeting first-world consumer needs for affordable, tasty, convenient, and safely processed foods year-round. As yet, there is no comprehensive assessment of climate change impacts on Australian food prices. However, modelling exercises based on the current Australian drought provide some indication that the cost of fruit and vegetables has increased more than the consumer price index, while highly processed foods have fallen (Queensland Health 2006). Another report indicates that drought alone is responsible for increasing prices across all food groups by 12% between 2005 and 2007, while vegetables showed the most pronounced increase in the consumer price index (Quiggin 2010). Sheales and Gunning-Trant (2009) explain recent fruit and vegetable price volatility as the result of 'seasonal factors'.

Climate change, nutrition quality and foodborne disease

In terms of nutrition, degraded soils and lack of water may reduce the quality of produce, particularly affecting perishable, fresh foods. These foods contain micro-nutrients which with insufficient consumption lead to acute deficiencies of vitamin C, folate and other B vitamins, with significant negative health impacts for pregnant women (Brand-Miller et al 2008). In relation to the macro-nutrient composition of certain foods, it is reported that increasing atmospheric carbon dioxide levels could reduce crop protein content by 20% as plants lose the ability to absorb nitrate from agricultural soils (Bloom et al 2010).

Climate change also increases the incidence of food-borne diseases. The most common food-borne disease in Australia is infectious gastroenteritis, which is caused by different pathogens. About a third of all gastroenteritis cases in Australia is due to food, numbering a total of about 5 million cases each year. Deaths are rare but can occur in the elderly and immuno-compromised (Hall 2005).

Pathogens can enter the food system at any point between paddock to plate. Some pathogens then replicate in food, especially under warm conditions. At the primary production stage pathogens may appear due to use of manure, irrigation or runoff as indicated in Figure 3.

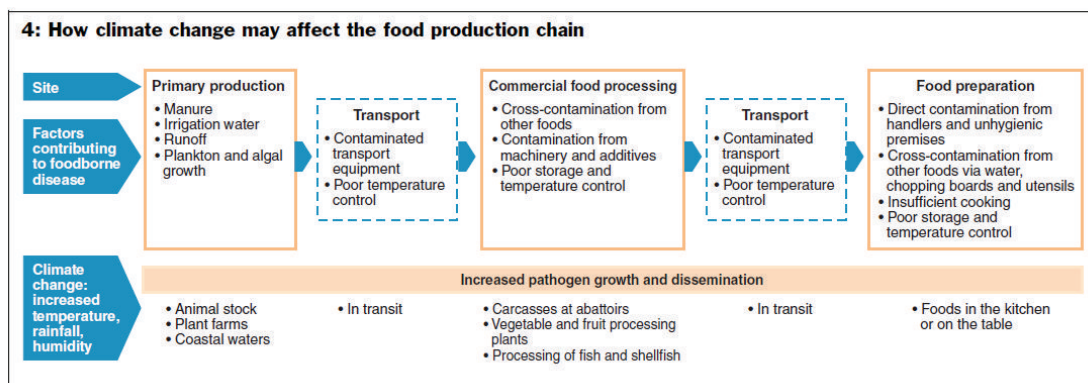


Figure 3 How climate change may affect the food production chain. Source: D'Souze and Kirk 2002

Naturally occurring and man-made toxins and chemicals used in production and processing are also potential sources of illness. Toxins are already found in foods in Australia linked to warmer climates including ciguatoxins and histamines from contaminated fish. For seafood, changes in sea temperature can affect plankton and algae growth and consequently cause the growth of microorganisms such as *Vibrio cholera* (Sedas 2007). Natural toxins are already found in fish in warmer, northern parts of Australia, including the ciguatoxins and histamines, and this reach is likely to extend southwards with climate change (Tester et al 2010).

Another example are the carcinogenic and hepatotoxic mycotoxins, including aflatoxins, that are produced by fungi growing in stored grains and nuts in hot humid conditions. Potential man-made chemical contaminants of food include heavy metals such as mercury and lead, dioxins, and pesticides and organic fertilizers. Heavy metals are sometimes found in predatory fish in particular, and in the past, detectable levels of dioxins have been found in the Australian population in low doses (Edwards et al 2001). Concerns about safety also extend to the introduction of technologically-advanced foods, such as genetically modified and functional foods and nanotechnology.

As the climate warms and as weather patterns become more erratic, liver cancer through aflatoxin contamination (World Cancer Research Fund and American Institute for Cancer Research 2007) may become an increasing problem. These fungal metabolites contaminate cereals and pulses, with dry, hot conditions increasing risk of contamination during crop growth, whereas the harvesting and storage of mature crops are at risk of contamination during wet conditions (Cotty and Jaime-Garcia 2007). Industrial chemical contaminants of food can also be a human health issue due to increased use of pesticides required as plant and animal diseases change in response to changed climate (Webb and Whetton 2010). Fertilizers are also likely to be increasingly used as soil nutrients are depleted in part through over-grazing, and also through soil loss, due to hot winds and torrential rains (Stokes, Crimp et al 2010).

Climate change and waste

Climate change impacts stand to exacerbate current food waste issues that exist along each stage of the food chain. For example, food may be wasted during production as there would be less worker availability for harvest on hot days, while increasing temperatures ripen some foods sooner causing a glut during processing in addition to food losses from extreme weather events. Heat waves could increase food spoilage directly or require more refrigeration – in turn adding pressure to stressed electricity systems (and greenhouse emissions). The impacts of climate change on electricity networks are already in evidence in Australia. During heat waves, peak demand for air-conditioning has caused system brown-outs and black-outs, while during the 2003 heat wave in France, 25-30% of food businesses were found to have inadequate cold storage capability (Létard et al 2004 cited in IPCC 2007). Some regions in Australia may also lack sufficient refrigerated capacity to deal with primary production in increasingly hot conditions: insufficient pre-cooling facilities (Rural Industries Research and Development Corporation 2004) and shortages of refrigeration trucks in peak seasons have already been identified (Food Chain Intelligence 2010). A loss in food quality standards from difficult weather conditions may be unappealing to consumers, resulting in less food sold or consumed, ending up in the rubbish bin. Food waste is already a prominent issue in Australia. Australian households throw out more than \$5 billion worth of food each year, \$250 worth per person in NSW (Baker et al 2009). However, food waste data is not publicly available in Australia for other parts of the food chain, such as from farmers' fields and orchards, and the processing and retail sectors (Morgan 2009). Food waste symbolically compounds existing issues within the current food system, which are further exacerbated by climate change.

Part 3: Possible future scenarios

Part 2 has discussed the direct and indirect impacts on health of climate change through the various stages of the food system. Much of the required knowledge remains as yet uncharted. This section builds on what we know from Part 2 to explore possible consequences from prolonged and more extreme climate change on the food system and health if timely adaptation and mitigation measures are not introduced.

Change or reductions in the food supply

The future possibility of a significant change in, or lack of, food supply is endorsed by DAFF in a submission to the Senate *Inquiry into food production in Australia* (2009a), where it forecast falls between 2006 and 2050 in wheat (up to 13%), sheep, beef and dairy (up to over 18%) and sugar, if no mitigation or adaptation measures are put in place. A similar study conducted by Australian Bureau of Agricultural and Resource Economics states that Australia will see reductions in exports of key agricultural commodities of 11-63 % by 2030 and 15-79 % by 2050. These estimates are based on warming scenarios of 1.0°C by 2030 and 0.8-2.8°C by 2050 relative to 1990 temperatures (Gunasekera et al 2007).

Producers whose agricultural systems depend on the kind of rainfall they have been getting since 1946 will experience enormous adjustment pressures if the dry conditions of the 1930s and 1940s return (refer again to Figure 2). One response to declining productivity is to relocate production and processing sites to more suitable growing areas. It is important to remember that such investment and re-investment is a feature of Australia's agricultural system. During the relative moistness of the late 1860s and 1870s, farmers went north of Goyder's Line in South Australia, only to find the dryness returned in the 1880s, forcing them back south again.

Likewise, the Marine NARP (see Mapstone et al 2010) and other sources predict that despite uncertainty about the precise speed of climate change relative to the past, the next 50 years will see the conditions under which coral reefs and mangroves have survived over the past half-million years alter rapidly (Hughes et al 2003). There appears to be some consensus that already fragile status of coral reef habitats combined with human fishing systems and other human activity in and around the corals has set up conditions for making these habitats more susceptible to future climate change effects (Perry et al 2010; Hughes et al 2003).

The intensive production of animals sensitive to heat, namely poultry and pigs, requires increased cooling and water systems, with additional costs likely to undermine the viability of smaller to medium-size producers.

Severe disruption to the distribution system

Australia has one of the most concentrated food supplies of any country, being dominated by two large supermarket chains. These organisations operate with such efficiency that their logistic chains hold only a few weeks' supplies (cited in Haug et al (2007)). The food logistics system is built around the principle of 'just-in-time' movement of freight reducing inefficiency under normal circumstances but which leaves no margins in the event of a disaster - Australia lacks food reserves in the event of a major disruption (Lederman and Lederman 2008; Palmer 2009). Disruptions to distribution systems due to flooding in Queensland and northern New South Wales and South Australia over the 2009-2010 summer prevented citizens from accessing food for up to a week (ABC News 2010).

All Australians are affected during severe weather events, although it is the lower-income households who are less likely to have stockpiles of food or be easily able to restock. Household stockpiling for any extended time brings risk of nutrient deficiencies, as extended reliance on a pantry of processed foods can lead to acute deficiencies of vitamin C, folate and other B vitamins (Brand-Miller et al 2008). In emergency situations, lower-income households are less likely to have stockpiles of food or be easily able to restock following power loss and spoilage. Following Hurricane Katrina, the shops that were not damaged or closed ran out of stock very quickly affecting the eating habits of poorer populations (Palmer 2009).

Change in location of production

One response to declining productivity is to re-locate production and processing sites, and to re-route transport to where there are available resources. However, interdependence between processing, production and markets may spawn other consequences, such as the loss of local markets, jobs, and a decline in support industries (Everingham et al 2002; Muchow et al 2000)

Where particular food supply chains are heavily dependent on transport infrastructure, changing growing conditions may introduce significant relocation costs. Upgrading of roads and rail links to new production areas may be required. However, with unpredictable and constant climate change, relocation of major facilities may still not be a secure investment over the long term. Increased frequency and severity of extreme rainfall events will cause increased flooding, which can both block and cause long term damage to road, rail, bridge, airport, port and tunnel infrastructure. Ports and coastal infrastructure are particularly at risk from storm surges; sea level rise will add to the problem. Increased storm damage, as well as gradual decline through heat stress and sea level rise, is

likely to increase the cost of transport infrastructure maintenance and replacement (DSE 2006).

Changes in shopping behaviour

In the short-term, consumers may respond to a changed climate in a range of ways. In a context of price rises associated with climate pressures on food yields, and as a consequence of spending more on energy consuming climate adaptive services (such as household cooling and the use of air-conditioned motor cars), people on low incomes may shift consumer purchasing towards produce that has a lower cost per calorie. These are likely to be foods that are high in fats, salts and sugars thus exacerbating health risks. A move away from home prepared foods in favour of meals prepared by the food services sector, may also take place in the interests of saving money, using less energy and water in food preparation. Householders may also choose to save water by not having vegetable gardens, while there is evidence that those who grow their own are more likely to consume more fruit and vegetables (Alaimo et al 2008). Each response poses greater dependence on market availability.

There are other potential early responses to increasing temperatures, storms and other 'wild weather' events which may not be healthy. For example, shopping routines may change favouring one-stop shopping at major supermarkets; internet shopping; or more home delivery of pizzas and other fast foods (Banwell et al 2009). Any motor vehicle dependent shopping option – that is those involving consumers' cars, and supermarket and fast food chain delivery vans – reduces opportunities for incidental physical activity. These food procurement decisions will impact people's health differently according to their gender, age, lifestyle, and for those with special needs, for example, people who are ill, migrants, or elderly.

However, there are also more healthy plausible responses. Where there is enough land and rainfall, householders may return to, or start to, grow their own foods, either individually or as part of community schemes. Environmentally-friendly foods – those that emit fewer greenhouse gases, and/or require less water, industrial feed, and fertilisers - may become popular; for example, kangaroo, poultry and pigs which feed on organic waste and forage, and vegetarian farmed fish (ABS 2008; SNFA 2009). Likewise, locally produced food may be further advocated as a way to reduce oil dependency and promote greater sustainability (Larsen et al 2008; Gaballa and Abraham 2008).

Responses to food safety

In relation to climate change and food safety concerns, a number of business decisions are also conceivable. Moving to new locations may compromise safety during storage and transport, especially if refrigeration is less available or fails

due to overload of the electricity grid. Some growers may choose to store products if the supply chain is disrupted, leading to loss of product quality, shelf life, and possible spoilage. More chemicals may be used to counter changed plant and animal diseases or, alternatively, increased prices of chemicals may inhibit their use, instead encouraging the application of organic inputs. In addition, a shift to acquiring food from offshore locations may introduce subsequent health risks due to less stringent food regulations and monitoring in other countries. Shortage of fertile land could lead to planting on toxic soils, increasing the risk of people eating food of lesser quality that may be contaminated. All these circumstances necessitate stringent and comprehensive measures to ensure food safety in times of climate change. These tentative scenarios highlight the variety and degree of inter-connectedness and complexity of feedback loops between climate change, the global and Australian food systems and health. Understanding the interrelationships between producer and consumer behaviours and structural reform drivers is critical if Australia is to foster a sustainable and healthy food system.

Part 4: Adaptive response strategies: Australia's current responses

The preceding scenarios are indicative of the variety of connections, and the degree of complexity of feedback loops, that can tip standards of food supply and health in either a positive or negative direction. Australia's current responses to climate change at the intersection of food and health are addressed in this section.

In general, Australian responses for addressing food-related health adaptations to climate change are in their infancy and are un-coordinated. At the national government level, there are federal programs concerning climate change in general (the Department of Climate Change and Energy Efficiency and the National Climate Change Adaptation Research Facility), and agricultural issues more specifically (such as Australia's Farming Futures program, the Water for the Future program, and various CSIRO initiatives). Regarding health and food specifically, the Australian Dietary Guidelines are currently being revised with the new version expected to reflect dietary recommendations that are based on principles of not just nutrition, but also of environmental sustainability and social equity. The Victorian government's Sustainability Fund established the Victorian Eco-innovations Lab in 2007, in part to advise the government on sustainable food systems. While in 1999, the South Australian Food and Health Policy recognized that 'a high quality food supply is dependent on ecologically-sustainable agricultural practices... The quality and variety of food produced has an impact on the health of the population' (DHS 1998).

At the same time, public health coalitions and cross-sectoral coalitions have released visions for a national food and nutrition policy with a focus on

sustainability and health at its centre (PHAA 2009; DAA and PHAA 2009; Friends of the Earth Adelaide 2010). Non-government agencies, most notably the Australian Conservation Foundation and Doctors for the Environment, have sponsored research into climate change and sustainable food systems (Horton and McMichael 2008). The National Heart Foundation is currently supporting a food sensitive urban planning and design initiative, which will include reference to the impacts of climate change (Larsen and Barker-Reid 2009).

Food and beverage processing is Australia's largest manufacturing sector (DAFF 2009). Industry has responded to climate change impacts in the food area by advocating for genetically-modified and functional (nutritionally-enhanced) foods, and the application of nanotechnology, which can embed both natural and man-made materials with characteristics to adapt to climate change conditions (Dawe et al 2002; Scrinis and Lyons 2010). The resulting products are presently expensive and rely on consumer acceptance if they are to address nutritional deficiencies, while their contribution to environmental toxicity is yet to be determined. Fundamentally, a reliance on highly industrial foods does not tackle the underlying structural problems or nutritional equity of the current food system (Dixon et al 2009).

Improvements in transport, processing and preservation technologies now enable food retailers to source a growing range of products from large global suppliers. At the same time, supermarkets are positioning themselves as industry leaders in social and environmental sustainability through corporate social responsibility policies, triple bottom line reporting and ethical traceability schemes (Hattersley and Dixon 2010). Supermarkets are among the earliest adopters of the novel global audit, the Hazard Analysis Critical Control Point measures, intended to monitor the management of food safety hazards along commodity chains.

Farmers are on the frontline of climate change. According to Kurukulasuriya and Rosenthal (2003, cited in Heyhoe 2007), agriculture's track record of adaptation to climatic variability allows a measure of confidence that continued adaptation is possible. Further, there is political support for climate risk management as part of usual business practice with government programs promoting farmers' capacity to manage risks (Lockie and Higgins 2007). Existing farm-level practices and technologies are already available that suit low-end adaptation purposes. The options include changes to the timing or location of cropping activities, shifting to varieties or species with increased heat and drought tolerance, water harvesting and conservation, integrated pest management, and enterprise diversification and climate forecasting (Howden et al 2007). Howden et al (2007) suggest these adaptation practices work best under low to moderate warming conditions (<2 C), and are likely to be less effective under greater temperature rise. Given that climate change related challenges are likely to intensify over time, questions are raised regarding how much variability can be accommodated using existing farm

management strategies and technologies. More profound structural adjustment or technological change may well be required (Stokes et al 2010).

Finally, grassroots community responses have begun to emerge in urban areas, with householders and communities establishing new forms of production and distribution (Donati et al 2009). Although seemingly meagre set against the sheer scale of the formal economy, these pockets of change reveal patterns of community understanding and concern, ideas and innovation that have potential to grow (Edwards unpub).

The urban re-location of food growing, if well managed, could boost certain fresh food supplies while complementing rural crops, in addition to encouraging new urban food-related services, introducing urban food models and a change in roles from consumer to producer for citizens. Urban agriculture could also reduce vulnerability to food supply disruptions or extended emergency supply situations by providing diverse sources of perishable food supply nearby and relieving pressure on farming on the urban fringe, which is particularly vulnerable to the impacts of increasing population size and peak oil (Mason and Knowd 2010).

Incremental adaptive change can be effective in building resilience within vulnerable sectors and populations, such as by introducing diversity and flexibility within the food system. Examples of resilience strategies include increasing diversity of food production to increase the likelihood of harvest even in unpredictable conditions, changing planting dates and varieties to more resilient crops and systems, and looking for opportunities for low-input agricultural techniques (including organic systems) as these have been found to be particularly 'resilient and productive' (Larsen et al 2008).

Part 5: The limits to adaptation

Climate change poses risks to many things of importance to people, including their health, employment, families, communities, and food preferences. For adaptation to be effective, individuals' and communities' diverse goals, needs, values, cultures, capacities, and institutions, need to be understood and aligned to enable or constrain responses. However, there are bio-physical, economic, social, health and governance limits to adaptation.

Water shortages are probably the key bio-physical limiting factor for Australia, as exemplified by the near collapse of the Murray-Darling Rivers system to the detriment of the dairy and horticulture industries reliant on it for irrigation (Edwards unpub). With state governments asserting their rights over the river system to supply urban households with drinking water, there is likely to be a high level of disputation between jurisdictions and between alternative land uses (Palutikof 2010).

As recognized in the Primary Industries NARP (Barlow et al 2010), if production systems do not begin to adapt or transform in response to changing climate conditions now, the costs of production are likely to increase as producers attempt to reduce the effects of climate change on their systems, or as they seek to substitute inputs to compensate for temporally scarce resources, such as water or pasture. Hence, even adaptation, the first step to addressing climate change, will require substantial investments by farmers, governments, scientists and development organizations, all of whom face many other demands on their resources (Lobell et al 2008). Other business risks that farmers face include fluctuations in commodity prices, interest rates and exchange rates, the availability and cost of labour, competing and potentially unsympathetic land uses. Singly and combined, these are all likely to affect farmers' adoption of new practices and their allocation of resources.

Current assessments are likely to substantially underestimate costs due to overlooking some sectors, only partially covering others, and due to unforeseen costs from mal-adaptation (Parry et al 2009). If agricultural systems do not adapt in time or to an appropriate extent, the costs of production will increase, competing against other business opportunities (Lobell et al 2008), and placing greater reliance on overseas sources of food: many of which are also impacted on by climate change.

Farmers have to be in good health themselves to practice adaptive strategies (Berry et al 2010). In a recent analysis, women and young farmers were the farmers more likely to report poor health, isolation from support and social systems, and low social capital. These factors combine to create reduced capacity to adjust to climate change pressures⁷¹

Good governance is essential if an effective and equitable approach to adaptation is to be realized. For example, UK research shows that consumer capacity to respond to climate change is limited without industry and government support (SDC 2006). As Barnett (2009) recognises, regardless of the risks, places, and groups involved, adaptation is at its core a social issue.

The *Social, Economic and Institutional Dimensions* NARP Discussion Paper (see Barnett 2009) encourages the implementation of both adaptation and mitigation plans because 'if no efforts were made to address climate change through mitigation actions, then eventually the impacts of climate change would become so great that adaptation would be impossible'. Effective mitigation will save Australia money, time, health, energy, resources, socio-political stress, and prevent the loss of unique natural resources. A dual strategy requires federal government leadership nationally and internationally, with strong input from business, non-government sectors, and citizens.

The limits to adaptation necessitate the implementation of mitigation to save money, time, energy, resources, socio-political stress, and the planet. This united

approach requires federal government support, as expressed by Garnett (2008:78): 'It is also critical that adaptation and mitigation measures are combined... The need to balance food security with lower emissions pathways – is perhaps the major challenge for decision-makers'. However, what is optimal for managing climate risk in the long-term may not be optimal for individual enterprises in the short to medium-term due to competing pressures, the availability of resources, and management capability. Further, high levels of uncertainty regarding the actual level of risk presented by future climate change relative to historic levels of variability may make it difficult for even the best managers to calculate the relative costs and benefits of various investment decisions. Such risks magnify the challenge of mitigating climate impacts and maintaining or improving agricultural productivity.

One widely debated mitigation strategy for which consumers must take a lead concerns the reduction of red meat consumption: the IPCC recognizes agricultural production as the single biggest contributor to the food system's total emissions, with the livestock sector being the largest agricultural sector contributor (FAO 2006a; Smith et al, 2008, Bellarby et al, 2008). If Australians significantly reduced their red meat consumption, they would also significantly improve their health, reducing incidences of ischaemic heart disease, some cancers (see McMichael et al, 2007) and possibly also reduce obesity.

Part 6: Research questions

This paper has described what is known about the connections and multiple feedback loops between climate and the food system, and how such changes can significantly alter food security outcomes in unprecedented and unexpected ways. The timing of changes will be important. In the Australian context, Stokes and Howden (2008) recognize that although some productivity may peak by the middle of this century, it is more likely that negative impacts will 'lag behind' becoming apparent later on. The changes in supply – affecting food quantity, quality and affordability – have flow-on effects to other parts of the food chain in addition to affecting population health. These interlinkages are among the most pressing for future research.

Other research questions raised throughout this paper include:

How are existing climate adaptation and mitigation management practices likely to influence food production and distribution? What are the key sources of adaptive capacity and can these be improved?

When do normal price and other mechanisms not occur to right the system over an adequate timeframe? What are the limitations of that adjustment? Do those limitations imply reasons for concern? What are the policy implications?

When is the right time, and best way, to move from one level of adaptation to the next? In what contexts should different levels of adaptation occur at the same time?

Where will climate change impacts on food safety and quality be observed, and what measures can be implemented to reduce such risk? How can the health of vulnerable populations be protected? In particular what of the mental health of farmers and the impacts of greater heat stress for food processing labourers?

How important and viable are diverse farms to Australian food security? What are their relative efficiencies and environmental impacts? What potential nutritional improvements could occur in food sources due to changed production methods? Which methods make a difference and for which foods?

Which Australian crops should no longer be grown in Australia due to climate change? What are the social, economic, health, food security and environmental implications if these crops shift overseas?

How can food production be better integrated into Australian cities? How could current urban agricultural zones be protected? What are the best models to suit urban conditions, and what contribution could urban agriculture make to food security?

How can food systems be better realigned with public health and environmental sustainability?

Conclusion

This paper describes what is known about the impacts of climate change on the food system and its implications for population health, with a focus on Australia. From this review, key issues and knowledge gaps are revealed. There is evidence that weather conditions are affecting the production, processing, distribution, consumption and waste of the entire food system, with particularly vulnerable subsystems identified as fresh fruit and vegetables, intensive livestock, and seafood. Associated health impacts include reduced food availability and affordability of these nutrient-rich foods, higher incidences of foodborne diseases and food safety concerns, and greater socio-economic and mental stress associated with loss of jobs in the domestic food system. These issues particularly threaten the poor, Aboriginal people and non-indigenous Australians living in rural and remote regions, farmers, and people living in coastal communities, in addition to impacting upon the health of the Australian population as a whole in varying degrees.

Stokes and Howden (2008) argue that the relatively moderate direct impacts from climate change in the near term should not lead to an underestimation of

future challenges or to a deferral of the policy decisions and management actions that will be needed to address them. Equally, it is critical that adaptation to policy decisions taken over the next three decades does not encourage mal-adaption to future climate impacts (see also Howden et al 2007). Hence, policy decisions and management actions are needed in the short-term to improve both mitigation and adaptation (such as by taking action now to enhance adaptive capacity in the longer term). Additionally, innovative approaches are likely to be required in order to compensate for both calculated risks and possible unforeseen impacts of climate change. As recognized in the Primary Industries NARP (Barlow et al 2010), 'perhaps the most fundamental research need is to enable stakeholders to better understand the nature of the climate change response they should be considering: incremental, systems or transformational'.

Australia, to date, has taken only incremental steps to adapt to climate change. Such actions may seem sufficient at this early stage of onset, yet when the impact from complex feedback loops and other issues such as latent climate change present and persist, new strategies of transitional and transformative adaptive models, in addition to mitigation strategies, will require urgent implementation. Rather than suffer 'analysis paralysis' (Barnett 2009), this paper recommends immediate policy and action, while cautioning against mal-adaptation. Such action could consist of developing adaptation and mitigation plans that prioritize vulnerable industries and populations to increase resilience, whilst trialing mid- to long- term transformational strategies to ensure a sustainable, secure and healthy food system overall. Australia, with its unique landscape and natural resources, history and global position, is in an excellent position to become a leader in addressing climate change through taking action to adapt and transform its food system.

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