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Climate change impact on global commodity supplies and the value of domestic crops

Teixeira E and Brown H

July 2012

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Teixeira E, Brown H

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THE NEW ZEALAND INSTITUTE FOR PLANT & FOOD RESEARCH LIMITED

Private Bag 92 169, Auckland 1142, New Zealand

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This report has been prepared by The New Zealand Institute for Plant & Food Research Limited (Plant & Food Research), which has its Head Office at 120 Mt Albert Rd, Mt Albert, Auckland.

This report has been approved by:

Hamish Brown

Team Leader, Systems Modelling Team

Date: 9 July 2012

Brent Clothier

Science Group Leader, Sustainable Production – Systems Modelling

Date: 9 July 2012

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This report reviews the methods used to estimate future global food supplies, demands and prices under different climate change (CC) and socio-economic scenarios. It then goes on to review the results from selected global food assessment studies. Finally, the implications of these findings in relation to the arable sector economy in New Zealand are discussed. The main insights from this report are as follows:

Global food supply in response to climate change:

- For most studies, negative impacts of climate change on global food supply are minor until the middle of the 21st century, but become important later in the century.
- The magnitude and timing of impacts differ among scenarios and studies, highlighting the significant uncertainties inherent to this type of study.
- Crop yield reduction due to global warming occurs earlier and is larger for high CO_2 emission scenarios, particularly when the CO_2 stimulation of crop photosynthesis is assumed ineffective.
- Climate change impacts are geographically heterogeneous. Larger CC negative impacts on crop yields are projected for tropical and sub-tropical countries.
- Countries in temperate areas (high latitudes) suffer lower yield reductions or show potential for higher yields, particularly at warming <2°C.
- Adaptation of crop management is shown to be important to minimise damage or harness opportunities driven by climate change.
- Results from current studies are limited in scope by not accounting for climate change effects on extreme events, rainfall variability (timing and intensity) and pest damage to crops.

Global food prices in response to climate change:

- Climate change is just one of many drivers of global food prices. Socio-economic and political drivers have strong leverage on world food prices.
- Without considering climate change, most “baseline” scenarios assume increasing food prices throughout the 21st century in response to greater demand from a larger and wealthier global population. Environmental limits are not fully accounted for.
- Dietary choices, driven by the awareness of health, social and environmental aspects of food consumption – particularly in wealthy countries – may have important impacts on *per capita* grain demands.
- The extent of the demand for food crops to produce biofuels (1st generation technology) has the potential to foster competition for land, water and other production resources - contributing to increase world food prices.

Future food prices are likely to increase in the long term in response to increasing food demand. Climate change also contributes to food price increase, depending on its suppression of crop yields. The extent and timing of this price increase, and the consequences to New Zealand producers, depends on the combination of the factors mentioned above. There is likely to be close correlation between socio-economic and climatic drivers of world food prices. To explore possible outcomes to the New Zealand arable sector, this report discusses two scenarios characterised by “low” and “high” magnitudes of price increase due to climate change:

- The “low” food price increase due to CC scenario is consistent with the IPCC B1 storyline in which the world is effective at mitigating and adapting to climate change impacts. We therefore assume that crop production and price changes are the lowest. The social changes that accompany this scenario include a larger liberalisation of agricultural trade and more even distribution of global wealth along with more responsible diet choices. This implies the stabilisation of global population, reducing overall food demand.
- The “high” food price increase due to CC scenario is consistent with the IPCC A2 storyline in which the world mostly carries on a “business-as-usual” basis without effective mitigation of greenhouse gasses emissions and climate change. We therefore assume larger negative impacts to global crop production and consequent increase in global food prices. Its socio-economic dimension depicts an uneven distribution of wealth, trade regulation to protect national interests and diet choices disconnected from environmental and social consequences. Regionalised increase in *per capita* food consumption in wealthy nations, and continued population growth, raise global food demand and food prices. The negative impacts of climate change on yields become more severe after 2050.

Possible implications to the New Zealand arable sector:

- commodity market. This is due to the openness of New Zealand economy, the country’s reliance on agricultural exports, limited government influence on prices, and a relatively small share of international markets. These conditions strongly link farm prices to world commodity prices.
- Under the “low” price increase due to CC scenario, global food production keeps pace with demand and prices respond mostly to socio-economic drivers. Changes in consumer preference may see a reduced demand for animal-based food products causing a shift from feed grain and forage production to more grain for food and processing. Economic incentive for alternative crops, e.g. grain legumes for human consumption of plant protein, may be created under this scenario. The value of seed production (herbage and horticulture) is likely to remain similar under this scenario given the specialised nature of the market.
- Under the “high” price increase due to CC scenario, New Zealand exports benefit from greater demand for animal protein (dairy and meat). Domestically, continued expansion of livestock production (respecting environmental limits) drives an increase in the demand for forage and feed grain. Higher grain prices in the global market intensify competition between grain and forage/feed production. This, together with higher prices of imported alternatives, increases prices for all crop types.

The two scenarios considered try to represent extremes of plausible outcomes. The extent of climatic and socio-economic changes (and subsequent food price changes) is likely to sit somewhere in between these two extremes. However, it is worth noting that if the *status quo* in terms of global emissions continues unchecked, major technological advances and socio-economic adjustments will be required to achieve the “low” scenario.

There are still important unknowns and uncertainties in global food assessment studies. For example, the likely impacts of CC on the frequency and magnitude of extreme events (e.g. foods, heat waves and severe droughts), impacts of sea level rise on urban and agricultural infrastructure, changes to seasonal rainfall patterns, and on-crop damage caused by pests and diseases are not yet addressed in these studies.

Teixeira E and Brown H

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For further information please contact:

Edmar Teixeira

The New Zealand Institute for Plant & Food Research Limited
Plant & Food Research Lincoln
Canterbury Agricultural and Science Centre
Private Bag 4704
Christchurch Mail Centre 8140
NEW ZEALAND
Tel: +64-3-325 9659
Fax: +64-3-325 2074
Email: edmar.teixeira@plantandfood.co.nz

1 Introduction

Climate change has an important impact on regional and global agricultural production. Global average surface temperatures have increased by 0.6 ± 0.2°C over the 20^{th} century, due to increases in atmosphere CO_2 and other greenhouse gases in part as a result of human activities (IPCC 2007b). For New Zealand, temperatures are projected to increase by 1–4°C by the year 2090 from baseline (1980–99) values, depending on the region and emission scenario considered (Reisinger et al. 2010).

The economic performance of the agricultural sector is sensitive to climatic changes in different ways. The yield and quality of food and feed crops respond to increases in atmospheric CO_2 and temperature, changes in rainfall (seasonal patterns and amounts), the frequency of extreme events (heat waves, storms and floods) and pest pressure. Both for New Zealand and overseas cropping regions, “direct” climate change impacts on plant photosynthesis, canopy development and yield losses were shown to be either positive or negative, depending on the location, the crops used, soil types, management and local adaptive capacity (e.g. Teixeira & Brown 2012; Tubiello et al. 2007b).

In addition to “direct” biophysical impacts on crop yields, climate change may also have substantial “indirect” impacts on the cropping sector, through global food markets effects. New Zealand has an open economy and crop farmers are fully exposed to commodity prices in the global market (Lattimore & Eaqub 2011). Therefore, it is possible that climate change impacts in other cropping regions worldwide will affect the economic performance of New Zealand farms through its influence on global market prices and trade.

In this report, we review the current knowledge covering projected impacts of climate change on global supply of key food commodities and explore possible implications for product values in the cropping sector in New Zealand.

2 Global food assessments – methods

The possible impacts of climate change of global food supply have attracted great scientific interest in the past 20 years. Although it is impossible to "predict" these future impacts, due to the complex nature of the food and climate systems, researchers have developed analytical methods to explore possible futures through "scenario analysis". These studies rely on a combination of techniques including the definition of sensible socio-economic scenarios and use of mathematical modelling to dynamically project climatic, bio-physical and economic aspects that influence the global food system (Reilly & Willenbockel 2010). Often, the motivation for this type of study is the need to evaluate risks of a "Malthusian" future, in which global food security is jeopardised due to insufficient food production and also to identify regional pockets of risk of hunger, which today still affects around 15% of the global population. In the following sections, we discuss important aspects of previous food assessment studies, their common insights and uncertainties regarding global food supply and prices in response to climate change.

2.1 Structure of global food assessment studies

The response of global food supply and prices to climate change is estimated with modelling approaches necessary integrate different aspects of the world food system[1]. These global models are simplified representations of the enormously complex nature of the food system (Figure 1), i.e. processes and infrastructure necessary to feed the world's population.

Previous global food studies widely differ on methods, models, datasets and the spatial-temporal resolution used. Large simplifications and assumptions are often necessary to deal with the multi-dimensional aspects of the food system: social, economic, political and bio-physical/environmental components. Climate change is only one of many factors to influence the regional and global supply and demand for food, and ultimately, food price.

A simplified representation of the global food system and some important factors driving food supply and commodity prices is shown in Figure 1. In an economic sense, food production encompasses the conversion of value from land, labour and physical resources (e.g. water and mineral nutrients) into consumables. Climate change can influence this efficiency of conversion by affecting crop growth; for example reducing photosynthetic rates, or increasing water stress and the ability of crops to intercept available sunlight and regulating yield damage factors such as pests, weeds and pathogens (Tubiello et al. 2007b).

World food prices are driven by the perceived balance between global supply and demand (Figure 1). However, there are other important market signals such as available food stocks, regional/national policy interventions, speculation in future markets, and trade policies that affect food price (Gilbert 2010). Food demand is mainly driven by population growth and food consumption *per capita*, in addition to demand from non-food uses such as for biofuel production. Higher food demand increases consumption, reduces stocks and causes prices to increase. Higher prices can stimulate additional production in regions where there are yield gaps to be filled (i.e. actual yield is below potential) and/or where land and production resources

[1] This report addresses the "conventional food system" which works within the paradigms of an economy of scale and aims for profit food systems" (e.g. local community producers, organic farming and cooperative farming) are not considered but may be of importance now and in the future to ensure regional food security.

are available for further expansion. The studies reviewed, and interpretations made in this report, consider how global climate and social change will influence the balance of production and consumption and how this will affect global food prices.

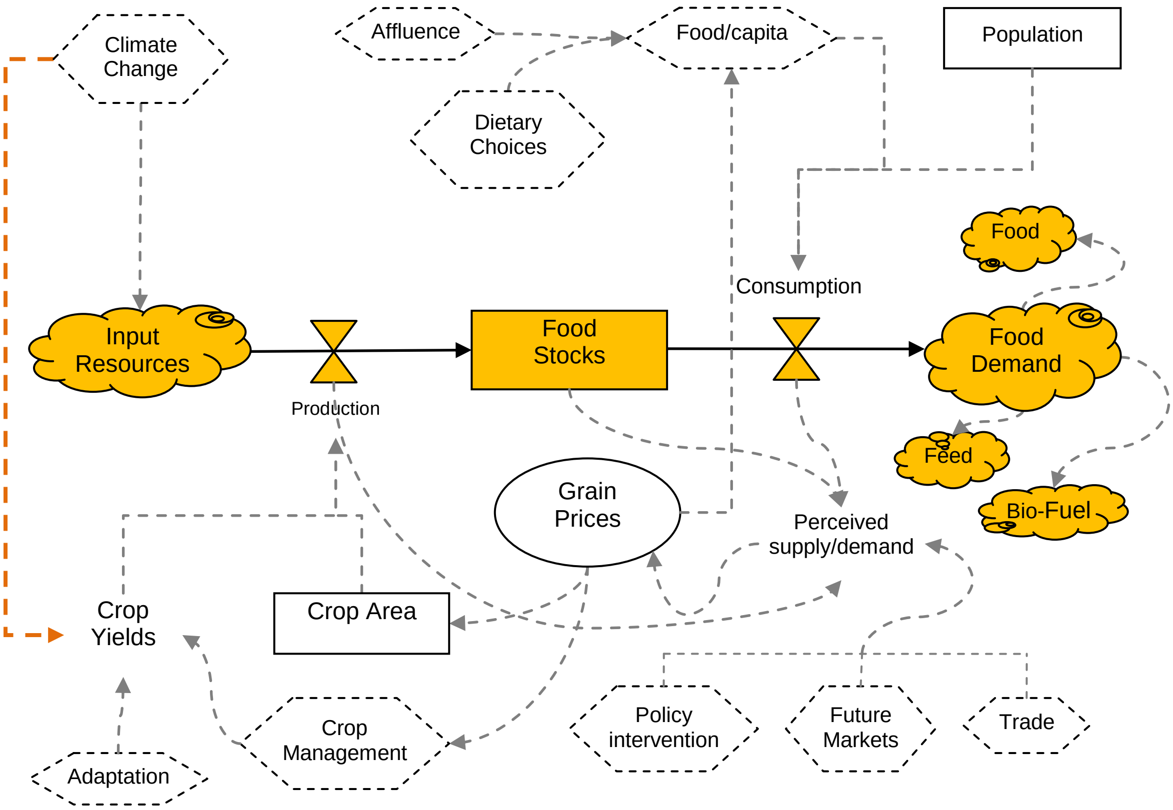

Figure 1. A schematic representation of food system components often addressed in global food assessment studies. Hexagons are factors driving food supply and price, rectangles are key stocks, and clouds are inputs and outputs as systems arbitrary boundaries. Full lines are a physical flow and dashed lines represent influencing factors. Triangles show flow rates.

Most of the reviewed studies consider only short-term bio-physical impacts on crop yields through changes in atmospheric CO_2 concentration, temperature and rainfall patterns. Less explored are other long-term effects of climate change that can reduce the efficiency of agricultural production (e.g. soil losses through erosion, less or contaminated groundwater and river recharge) and food industry infrastructure (e.g. damage to transportation and storage processes). In addition, climate change can affect the access to food through its impact on consumer's income or by creating demands for capital reallocation into alternative sectors of society (e.g. to pay for urban infrastructure damage caused by sea level rise).

The global food assessment studies reviewed in this report are described in Table 1.

Table 1. Some details on selected global food assessment studies assessed in this report.

Reference	Socio-economic Scenarios	Modelling Setup	Resolution
(Parry et al. 2004)	Baseline:1990s Future: A1FI, A2, B1 and B2; CO_2 stabilisation at 550 and 750 ppmv Farm- and regional-scale adaptation strategies	Bio-physical: Re-analysis of several previous simulations worldwide Climate: HadCM2 and HadCM3 Economy: BLS	11 global regions 2020s, 2050s, and 2080s
(Parry et al. 2005)	Baseline: 1951-80; 1990 Future: A1FI, A2, B1 and B2, CO_2 stabilisation at 550 and 750 ppmv	Climate: GISS, GFDL, UKMO, HadCM2, HadCM3 Bio-physical: IBSNAT databases, Economic: BLS	Global at various resolutions 2020s, 2050s, and 2080s
(Msangi & Rosegrant 2007)	Baseline (1961–90) Future: A1 and B2 Half/double ENSO event frequency	Climate: ECHAM4, HAdCM3 Bio-physical: GAEZ Economic: IMPACT-Water	2020, 2050, 2080 River basin scale to national level
(Fischer 2009)	Baseline: 1990s, 1960–90 or 2000 depending on scenario Future: A2 (with/without CO_2 fertilisation effect)	Climate: HadCM3, CSIRO Bio-physical: FAO/IIASA GAEZ Economic: BLS or Wold Food Model	2020, 2030, 2050, 2080 18 global regions (economic) and 0.5 grid-cell (bio-physical)
(Lee 2009)	Baseline: 1990 Future: A2	Climate: HadCM3 Economic: GTAP Bio-physical: Uses modelled datasets from previous studies.	2020 4 global regions
(Nelson et al. 2009)	Baseline:2000 Future: A2 with and without CO_2 fertilisation effect	Climate: NCAR, CSIRO Bio-physical: DSSAT	2000, 2050
(Schneider et al. 2011)	Baseline: 2000 Future: (no climate change)	Bio-physical: FAOSTAT datadet Economic: GLOBIOM	2000, 2010, 2020 and 2030 28 geopolitical global regions

Regardless of the different methodological aspects and datasets used, these studies have a number of common components:

- Several socio-economic development scenarios are compared.
- Climate data-sets are consistent with socio-economic scenarios for future time periods that consider climatic change.
- Crop yield datasets are either derived from historical data (for baseline) or simulated with bio-physical models in response to climates and soils.
- Simulation of food trade and prices are done with global econometric models.

Different spatial and temporal resolutions are considered depending on the study: from grid-cell to national to global regions; and from daily dynamics to static models. A schematic view of an integrated modelling assessment (IAM) shows how bio-physical and economic models can be linked in these studies (Figure 2).

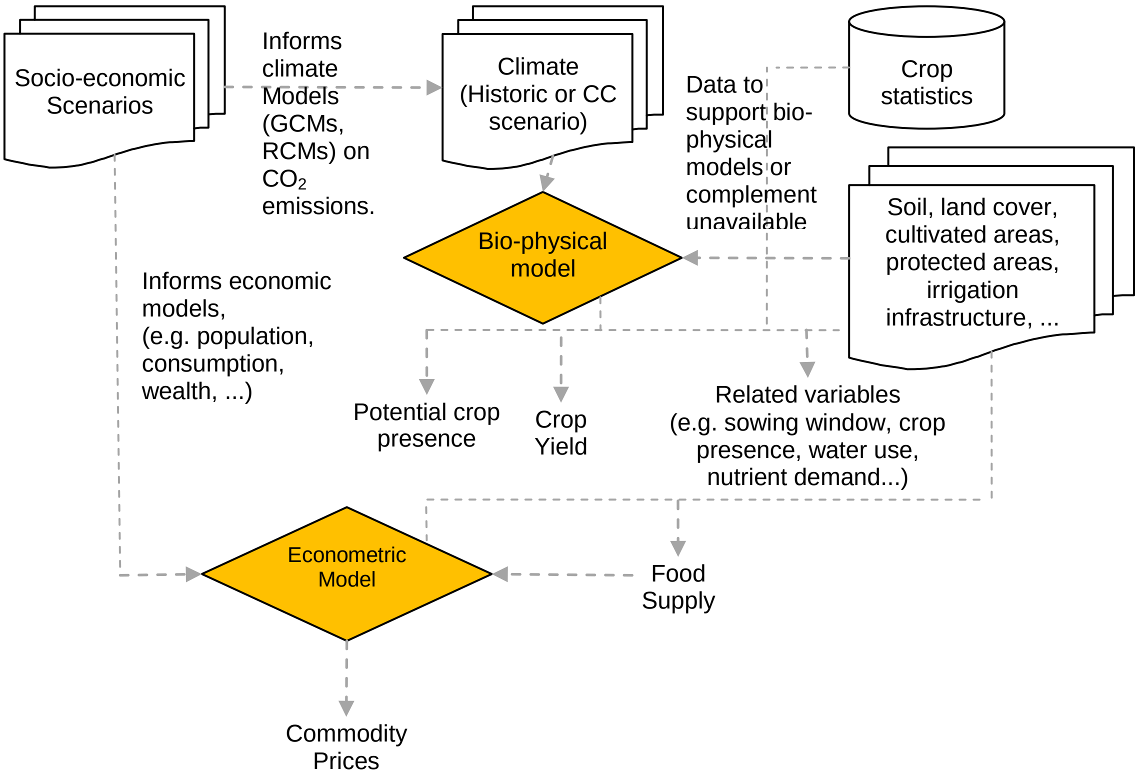

Figure 2. A schematic representation of an integrated modelling framework (IAM) of global food supply and prices. Individual global food assessments studies vary in terms of structure and datasets.

The main components of global food assessments using either uncoupled models or IAM are discussed in the following sections.

2.1.1 Socio-economic scenarios

Scenarios do not aim to predict the future but instead to deal with uncertainty by presenting a range of plausible futures, often without assigning probabilities to the outcomes (Reilly & Willenbockel 2010). Because the food system is difficult to predict, particularly in the long-term, the pre-definition of socio-economic scenarios is necessary to explore possible future development pathways. This method is particularly useful to deal with complex socio-ecological systems that cannot be dynamically simulated and explores uncertainties over long-term horizons that also cannot be represented by probability distribution functions of model parameters. Once designed, these scenarios educate the choice or development of exogenous variables (model inputs) both at bio-physical (e.g. atmospheric CO_2 concentrations and climate) and socio-economic (e.g. population and GDP) levels and how these change over time. Some important aspects assumed in these scenarios include, CO_2 emissions, population growth; accumulated wealth (e.g. GDP), trade policies and food crop demanded by other activities (e.g. biofuel).

Box 1. The IPCC socio-economic development pathway scenarios

In large, most global food assessments use climate and socio-economic datasets based on SRES-IPCC storylines (IPCC 2000) from the Intergovernmental Panel on Climate Change (IPCC). These are described as follows:

"...By 2100 the world will have changed in ways that are difficult to imagine – as difficult as it would have been at the end of the 19th century to imagine the changes of the 100 years since. Each storyline assumes a distinctly different direction for future developments, such that the four storylines differ in increasingly irreversible ways. Together they describe divergent futures that encompass a significant portion of the underlying uncertainties in the main driving forces. They cover a wide range of key "future" characteristics such as demographic change, economic development, and technological change. For this reason, their plausibility or feasibility should not be considered solely on the basis of an extrapolation of current economic, technological, and social trends.

• **The A1 storyline** and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

• **The A2 storyline** and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

• **The B1 storyline** and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

• **The B2 storyline** and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels...."

Adapted from: IPCC SPECIAL REPORT- EMISSIONS SCENARIOS (IPCC 2000)

2.1.2 Bio-physical modelling of food supply

In global food assessments, the response of crops to environmental factors is the main linkage between climate change and food supply. Crop growth and quality is affected by atmospheric CO_2 concentrations, air temperature, and water availability. Although the main climatic driver of "potential" crop yield is available incoming sunlight (Monteith 1977), "actual" yields are regulated by other climatic factors (e.g. temperature and water), soil characteristics (e.g. water storage capacity and nutrient content), and crop management decisions such as the use (or not) of irrigation, fertilizer amounts and the efficacy of pest control. These are all fed to model as input datasets or model parameters. Note that while some of the drivers of actual yield are under full influence of climate (temperature, sunlight and rainfall), others are influenced by management and the availability of inputs (sowing time, crop type, irrigation, fertiliser, pesticides, etc.). Variations in these management assumptions can be tested in modelling studies so to represent different adaptation options. The final combination of datasets and parameters varies considerably among studies, making direct comparison impractical.

The final output of bio-physical models is crop production. Production depends not only on crop yield (e.g. kg grain per hectare) but also on cultivated area (e.g. hectares per country) in time. Information on cultivated area comes from historical datasets (e.g. Monfreda et al. 2008) and the area of this land in different crop types is varied depending on relative crop prices and climate suitability (e.g. Lee 2009). It is also possible for the area of cultivated land to decline through time to represent different scenarios of land degradation, or consumption of cultivated land by urban, ecological or pastoral land uses. Historical crop yields can be obtained from national records to establish baseline yields (e.g. FAOSTAT 2009), or may be dynamically simulated with computer models using to climate and soil datasets, and assumptions regarding management. Climate records or simulated climate data files for baseline are retrieved from historical records (e.g. meteorological stations) or are re-analysed to cover the areas in between meteorological stations (e.g. interpolated, up-scaled or modelled data). Future climate is estimated using global climate models where atmospheric CO_2 concentrations are consistent with emissions from the Intergovernmental Panel for Climate Changes socio-economic scenarios (IPCC 2000).

Bio-physical models used to simulate crop growth; yield and water extraction can operate at single points (e.g. van Ittersum et al. 2003) or at a grid-cell basis for large areas using aggregated climate and soil characteristics (e.g. Bondeau et al. 2007).

2.1.3 Economic modelling of food prices

In global food assessments, econometric models are used to simulate trade flows among countries/regions and the final prices of food supplies at different periods. Models can either consider all sectors in the market at lower level of detail (general equilibrium models) or consider only specific segments of the market with greater detail (partial equilibrium models) (Palatnik & Roson 2009). The choice for partial or general equilibrium model in the analysis is often based on how important is to acknowledge implications to and feedbacks from sectors other than agriculture. There is a practical trade-off due to the more complex nature, computational requirements and larger parameterisation demanded by general equilibrium models. For both model types, commodity prices are dynamically adjusted until food supply equals food demand, when a final "equilibrium" price is then determined by the model.

2.1.4 Scope and limitations of global food assessments

Global food assessments deal with the complex nature of the global food system by simplifying its characterisation (Figure 1). Only selected components are considered, assumptions in model parameters are necessary, and available datasets have variable quality. This means that estimates of global food supply and price are uncertain. The main sources of uncertainty include the following:

Bio-physical and climate modelling.

- Variable quality, spatial/temporal resolution, and availability of datasets with global coverage (e.g. areas with access to irrigation, land cover, protected areas and soil characteristics).
- The representation of rainfall amounts and frequency are highly variable among global circulation models (GCMs)
- Extreme events (heat waves, floods and droughts), which are expected to be affected by climate change (Tebaldi et al. 2006), are not represented in climate dataset.
- The large variety of different (local) crop cultivars and their response to climate is not totally represented in the models.
- The rate by which technological change will improve crop yields is highly uncertain and has a significant leverage on results (Ewert et al. 2006).

Economic modelling of food prices.

- Land heterogeneity and conversion among land-uses not well represented (Palatnik & Roson 2009).
- Not all factors and feedbacks effecting food trade are represented.
- It is difficult to represent politically motivated changes to trade policy. There will be unforeseen factors affecting both the area of land in production and the demand for food crops that cannot be modelled.

In addition, model inter-linkage to enable IAM studies is still in its infancy (Ewert et al. 2011), including issues such as coupling data sets with multiple scales (e.g. from grid-cells, to local, to regional, to global).

These uncertainties are difficult to quantify based on current knowledge. Therefore, in this report, when results of specific studies are shown they merely aim to illustrate patterns of response and to point out the factors that influence world food supply and price. These results **should not** be interpreted as predictions.

3 Global food assessments – results

The results from selected global food assessments are analysed in this section. Given the diversity in methodologies and assumptions among these studies, results are not necessarily comparable. Results from more recent and detailed studies are preferentially shown to illustrate overall patterns of food system response. All references here cited are publically available, so detailed methodological details can be accessed if necessary.

3.1 Climate change impacts on food supply

Aggregated effects of climate change on "global" food supply depend on the magnitude of green house gas emissions and their "local" effect on climate over time. Results vary depending on the climate model and socio-economic scenarios evaluated. For example, for 2050 using the A2 scenario from IPCC (Box 1) with an average 3.4°C temperature rise (likely range 2.0 to 5.4°C), global wheat production was estimated to decline by 23% (CSIRO[2] model) to 27% (NCAR[3] model), while global maize production was only negligibly (<±0.5%) affected (Nelson et al. 2009; Prakash 2011). Using a similar climate model and climate scenario (CSIRO and IPCC-SRES A2) for rain-fed conditions (Fischer 2009), similar trends were shown for wheat but with smaller magnitudes of impact (Figure 3). A decline of 13 to 21% of global rain-fed wheat production is estimated by 2080. Rain-fed maize and sorghum are projected to increase slightly by 10% and 15%, respectively, depending on the assumed CO_2 fertilisation (Box 2) effect.

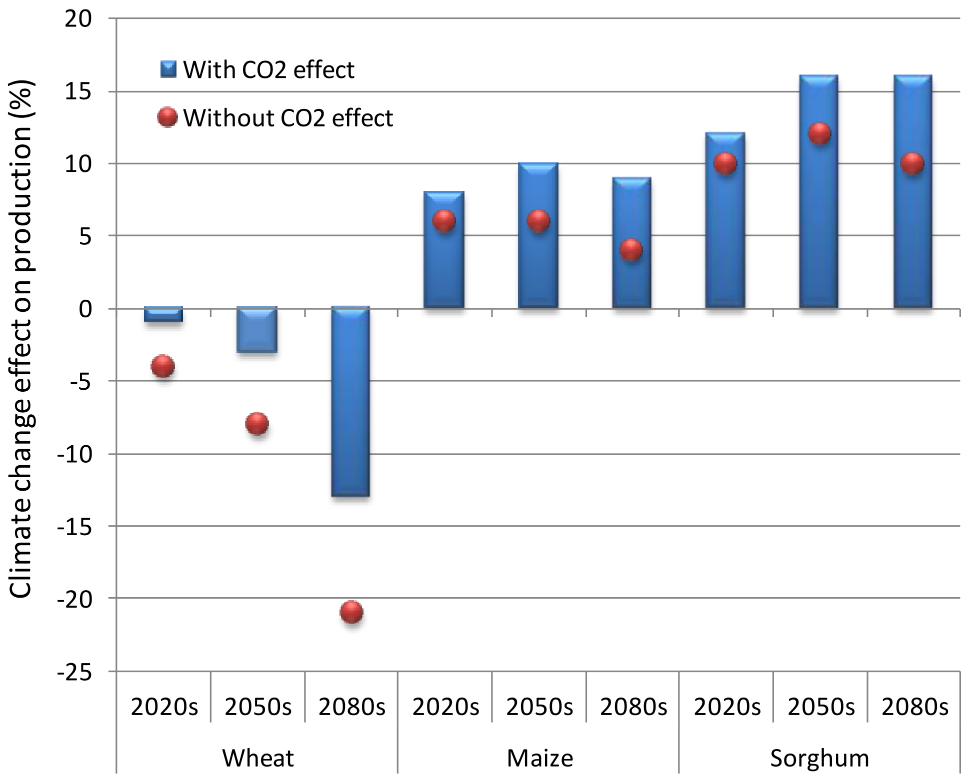

Figure 3. Impact of climate change on potential production of major cereals in current cultivated land (% change in respect to current climate) for the A2 scenario and CSIRO model with and without CO_2 fertilisation effect. Adapted from Fischer (2009).

[2] CSIRO model: Commonwealth Scientific and Industrial Research Organization, Australia
[3] NCAR model: National Centre for Atmospheric Research, US

A common insight from different studies (e.g. Fischer 2009; Lee 2009; Nelson et al. 2009; Parry et al. 2005) is that there are large geographic differences in the magnitude and direction of climate change impacts (e.g. Figure 4).

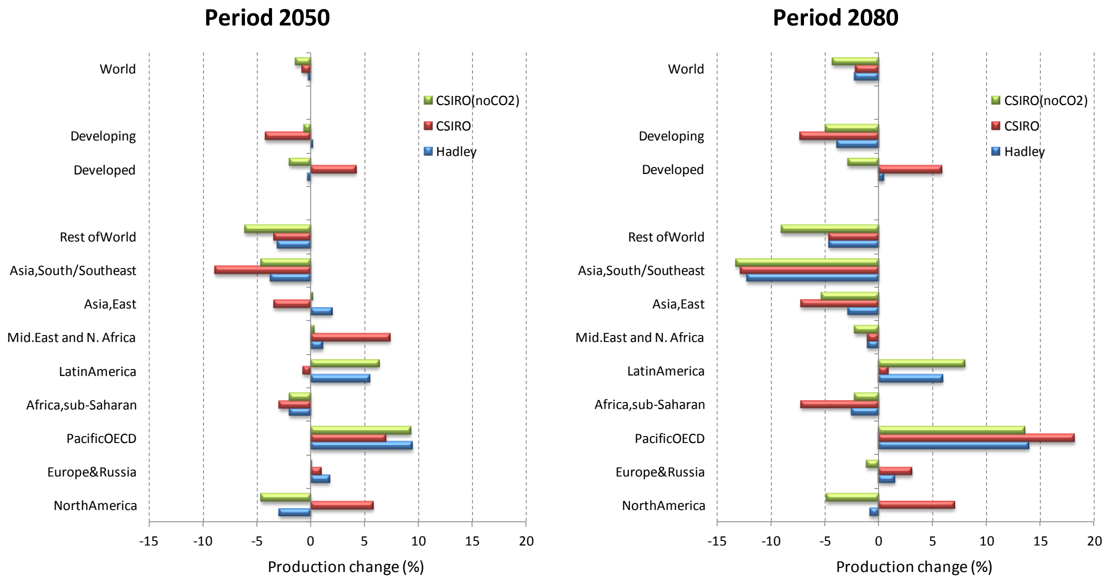

Figure 4. Impact of climate change on cereal production for two global circulation models (CSIRO and Hadley) with and without CO_2 fertilization effect for 2050 and 2080.

As an example, by 2080 production was projected to increase by ~8–12% in the Pacific OECD countries. This is in alignment with recent assessments for New Zealand crops that also show that warmer temperatures and CO_2 fertilisation effects can potentially increase yields of temperate cereals (Teixeira & Brown 2012). However, these estimates do not take into account yield damaging factors such as extreme events (e.g. heat waves, droughts and floods) and changes in pest pressure due to climate change.

In contrast to the Pacific region, countries in the South/Southeast Asian region suffer production losses of ~5% in 2050 and >10% in 2080. A common finding of these studies is that most negative effects occur in low latitude regions, particularly affecting developing countries (Figure 5).

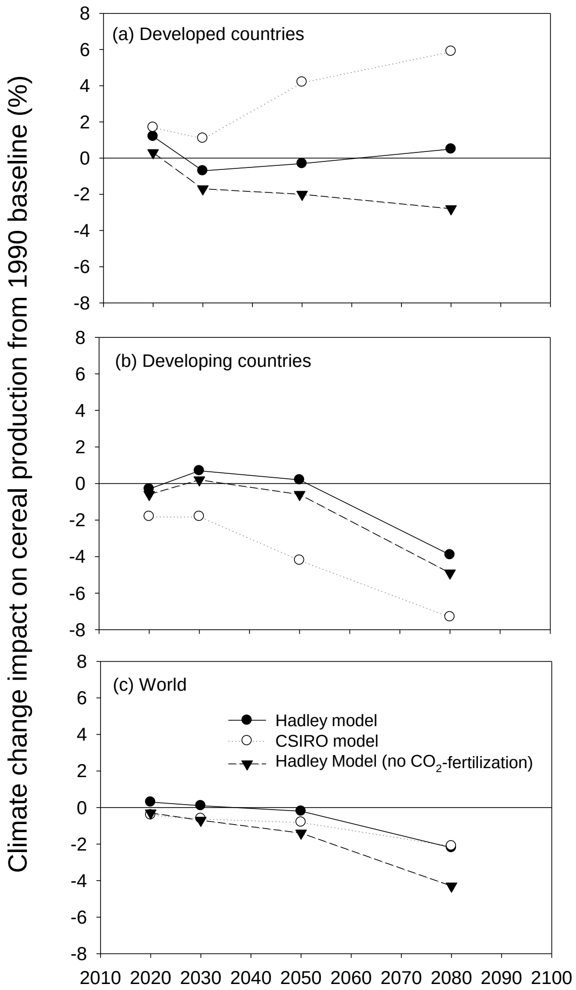

Figure 5. Climate change impact on cereal production for (a) developed nations, (b) developing nations and (c) world for two climate models using the A2 scenario. Cereals include: Adapted from Fischer (2009).

Regardless of uncertainties in climate scenarios and CO_2 fertilisation, the responses to climate change are more negative for countries in (sub-)tropical areas than for more temperate climates. As a consequence, developing countries are expected to increasingly become net importers of cereals due to climate change (Parry et al. 2005).

Another important factor influencing global food supply is the CO_2 fertilisation effect (Box 2). The magnitude by which elevated atmospheric CO_2 will effectively increase plant's photosynthetic rates, and consequently crop growth, has a large impact on projections of world food production (Figure 4 and Figure 5).

Box 2. The CO_2 stimulation of crop growth (CO_2-fertilisation effect)

Crops produce higher yields under elevated atmospheric CO_2 concentrations. The increase in atmospheric CO_2 from the ~390 ppm in 2012 is expected to enhance growth rates of several crops, particularly for C_3 type crops such as wheat, barley, soybean and rice. The 'CO_2-fertilization response' was observed in several experiments under controlled and open-air conditions (Ainsworth & Long 2005). Free-Air CO_2 Enrichment (FACE) experiments indicate an increase in light-saturated leaf photosynthesis by 10% to 20% when CO_2 concentrations increased from around 365 to 567 ppm, but this varies with crop species (Ainsworth & Rogers 2007). This reponse is because the carboxylation activity of the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) is limited under current CO_2 concentrations. Also, C_3 crops lose part of the carbon fixed by the 'photorespiration' process that is an inherent carbon cost of the C_3 photosynthetic pathway. Both these limitations are avoided in C_4 crops such as maize, sorghum crops and other tropical grasses because of anatomical and biochemical specialisations that enable CO_2 to be highly concentrated close to Rubisco active sites (which is then CO_2-saturated) and also avoid carbon losses due to photorespiration (Amthor 2001). This results in a more efficient photosynthesis in C_4 crops under current CO_2 atmospheric concentration and explains their lack of response to increasing CO_2.

Common to both C_3 and C_4 crops, is a consistent decrease in water use and an increase in water use efficiency (WUE) at high CO_2. This is because stomatal closure is triggered as a direct response of guard cells to elevated CO_2 concentration, limiting leaf transpiration (Ainsworth & Long 2005). Several crops showed an average decrease in stomatal conductance of between 20% and 40% at 567 ppm CO_2 when compared with a 365 ppm baseline (Ainsworth & Rogers 2007). The implication is that at higher CO_2 levels less water is transpired per biomass produced. This has been proposed as the main reason for positive but variable yield responses from 0% to 12% in C_4 crops at high CO_2 (Kimball 2011), particularly when growing under water limited conditions (Ainsworth & Long 2005).

Although the positive direction of yield response to increased CO_2 is well established for both C_3 and C_4 crops, there is still uncertainty and ongoing scientific discussion regarding the magnitude of yield increase that will materialise under farm conditions where other constraints to plant growth apply (Long et al. 2006; Tubiello et al. 2007a). The interactions among CO_2, limited water and soil nutrients and management are still not well understood (Kimball 2011). This has justified the use of simulations with and without CO_2 fertilization effect (e.g. Fischer 2009).

3.2 Climate change impacts on food prices

3.2.1 Price changes without climate change

Historically, world food prices consistently declined from 1970s to early 1990s, and then stagnated until 2002 (Fischer 2009). This pattern was mostly driven by increases in yield due to technological advances and agricultural inputs implemented after the green revolution after the 60s (Borlaug 2003).

Since 2002, world commodity prices have increased more than two fold with much greater volatility than during the past decade (Figure 6). Several factors were suggested as potential drivers of this trend, including the increasing demand of crops for food and biofuel uses, low food stocks, food market speculation and low productivity due to limiting climatic conditions (Gilbert & Morgan 2010).

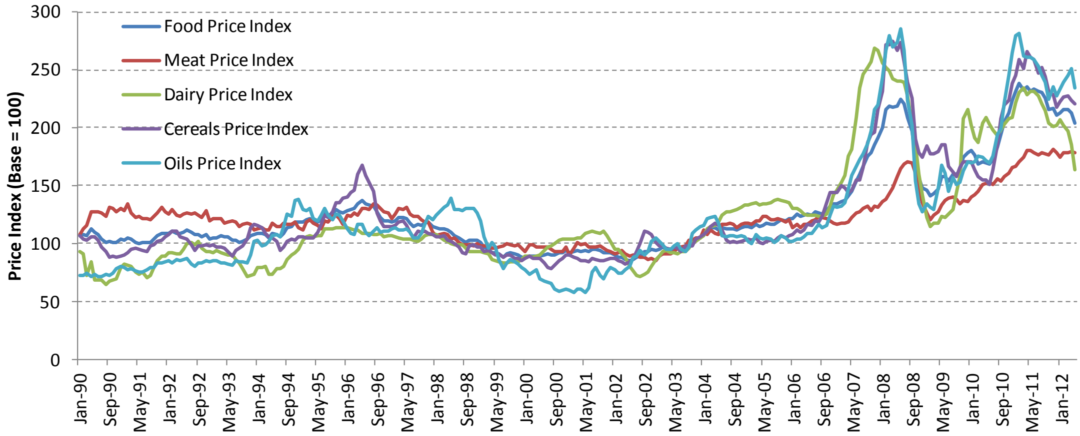

Figure 6. Price indexes for different food commodity types. Adapted from FAO Food Price Index at http://www.fao.org/worldfoodsituation/wfs-home/foodpricesindex/en/

Historical trends indicate that climate change is therefore only one of many drivers of food prices (Figure 1). Most global food studies "assume" that, without considering climate change impacts, agricultural commodity prices will continue to increase in response to higher demand for food (e.g. Figure 7). These assumptions are highly uncertain as previously discussed.

For example, analysis with the GLOBIOM model show that only small changes (-4 to +8%) were projected for food prices by 2030 without considering climate change (Schneider et al. 2011). In their study, the pressure of increasing demand on prices was mostly buffered by assumed increases in crop and livestock productivity – indicating the importance on assumptions regarding technological progress and agricultural intensification.

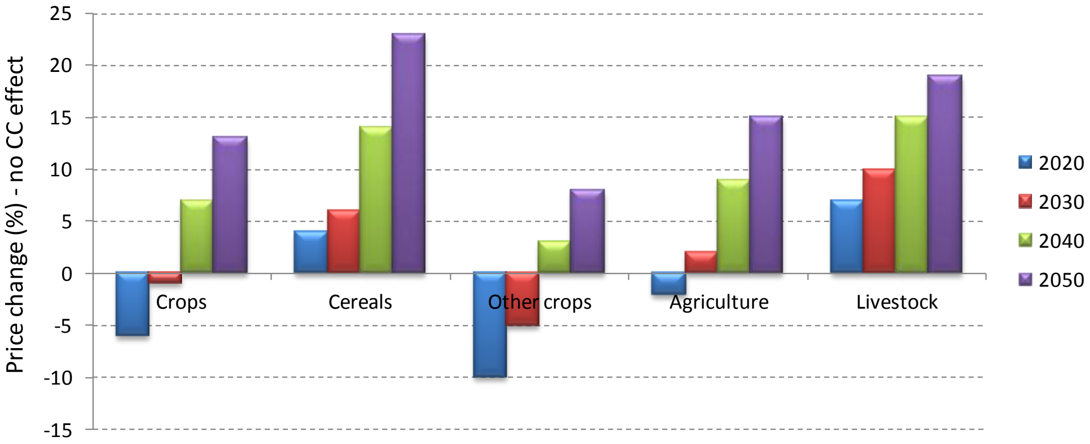

Figure 7. Example of assumed reference "scenario" of food price change in future periods without climate change impacts. Adapted from FAO-REF scenario (Fischer 2009).

Similarly, without climate change, Nelson et al. (2009) assumes prices will increase from 2000 to 2050 driven by population growth, income growth and biofuel demand. Price increases were assumed for rice (62%), maize (63%), soybeans (72%) and wheat (39%), these being considerably higher than the ones assumed by Fischer (2009) as shown in Figure 7. These differences highlight the uncertainties involved in this type of scenario development.

3.2.2 Price changes due to climate change

Over the baseline socio-economic scenarios, climate change effects on global food prices can be then isolated by testing how different climate scenarios affect crop yield.

In general, assessments show that commodity prices are affected by climate change mainly after 2050. Assuming CO_2 fertilisation effects (Box 2), prices change little in the first half of the 21^{st} century. By 2020, Lee (2009) has projected less than 3% increases in the price of rice, wheat and several other agricultural products, the exception being other cereals (6%) due to climate change. On the other hand, the absence of CO_2 fertilization effect (Box 2) triggers an earlier increase in prices of 5% in 2030, reaching ~10% in 2050 (Fischer 2009). After 2050, price increases due to climate change become more consistent, ranging from 10 to 40% depending on the crop and assumptions regarding CO_2 fertilisation effect (Figure 8).

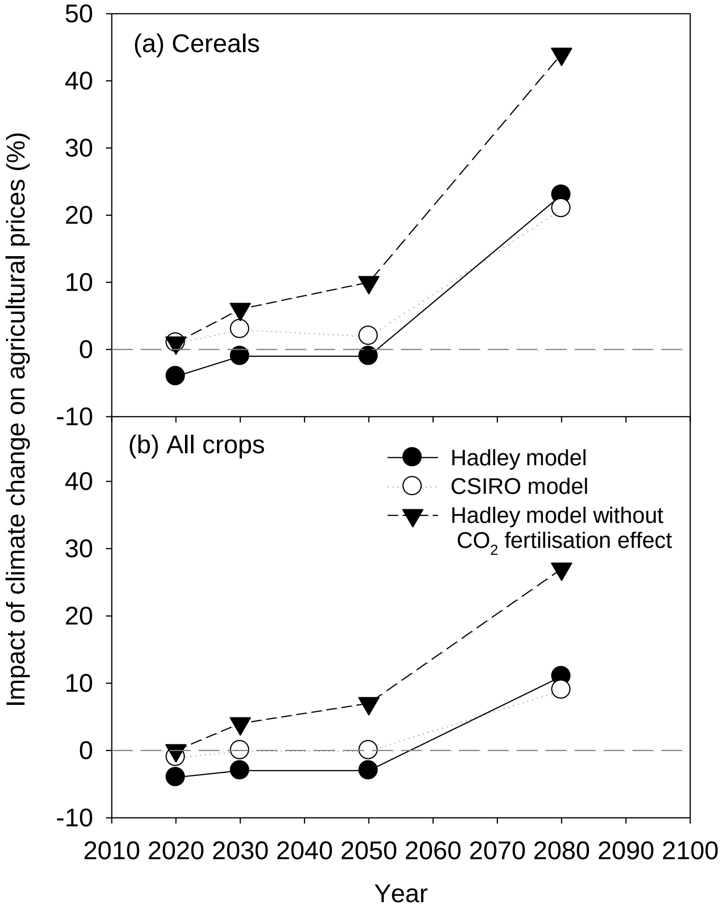

Figure 8. Impact of A2 climate change scenario on world cereals (a) and other crops (b) prices. Climate data from two global circulation models (Hadley or CSIRO) assuming presence or absence of CO_2 fertilisation. Adapted from Fischer (2009). Cereals include wheat, rice, maize, barley, sorghum, millet, rye, oats and buckwheat.

The actual impact of climate change on prices largely depends on the intensity of emissions and on the implementation and efficacy of adaptation measures. Parry et al. (2005) results showed a range in price increase from 32 to 83% in 2050 and 13 to 167% in 2080, depending on the emissions scenario considered (Figure 9).

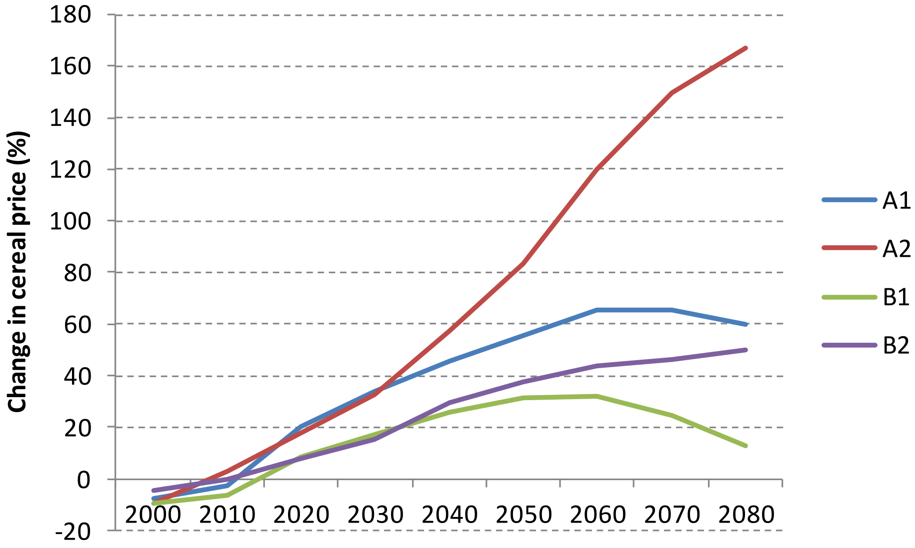

Figure 9. Impact of different scenarios on world cereal prices for four different climate scenarios (Parry et al. 2005). Scenarios assume atmospheric CO_2 concentration stabilising at 527 ppm (B1), 561 ppm (B2), 709 ppm (A2) and 810 ppm (A1), details in Box 1.

The effectiveness of adaptation measures, to reduce climate change impacts, also affects global food prices. Adaptation options for the agricultural sector include change in sowing dates, crop cultivars and species, use of irrigation, management of soil fertility and the use of pesticides or integrated pest management. The choice and combination of these options is localised and cannot be generalised to a country or global level. Recent studies have started to identify locally relevant adaptation options for crop production in New Zealand (Teixeira et al. 2012a), Australia (Howden et al. 2010; Luo et al. 2009) and other overseas cropping regions (Nelson et al. 2009; Olesen et al. 2011).

Although most impact assessments have some type of adaptation implicit (e.g. Fischer 2009), few have isolated its impact. An exception is Parry et al. (2005) who explored two levels of adaptation on global food supply and prices. They found that in-farm tactic adaptation options (i.e. small changes in crop calendar, use of available irrigation and change to available crop cultivars) increased yields by 4 to 14% in developed countries but not in developing nations. More expensive, regional and long-term strategic adaptation options (e.g. large shifts in crop calendars, increase in fertiliser application, the development of new cultivars and expansion of irrigation infrastructure) nearly cancelled out global decline in cereal yields, although developing countries still suffer ~5% production loss. The prices of cereals also increased -5–35% when adaptation options were applied instead of 23–145% in non-adapted systems. However, the costs to adapt were not internalised in these estimates. Adaptation depends on the access to technology and capital, implying that the overall economic performance of countries and regions will influence its effectiveness.

As a way to illustrate combined uncertainties in global food price estimates (from different models, datasets and methodology combinations) the 4th Assessment Report from IPCC (IPCC 2007a) compiled results of cereal price change in response to global temperature change for different studies (Figure 10).

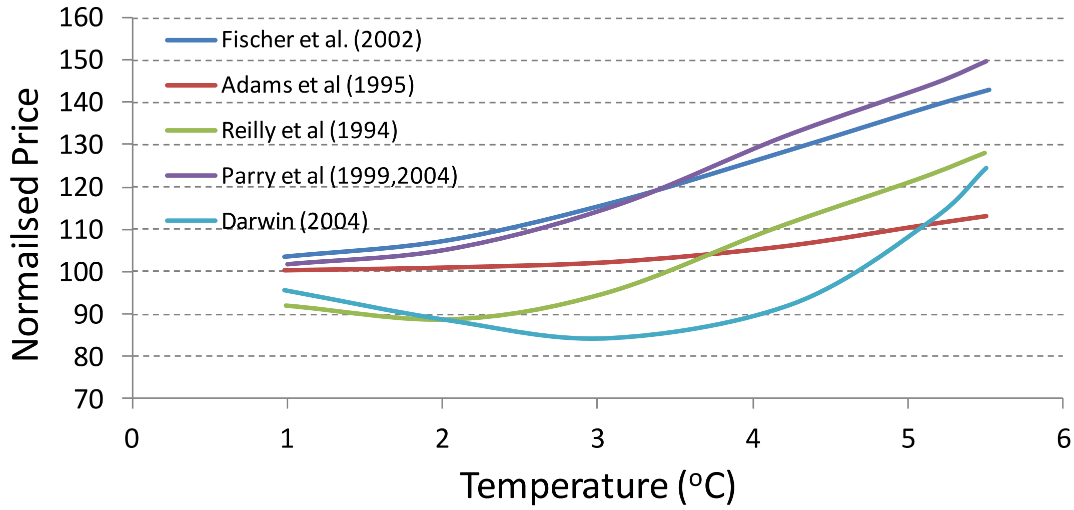

Figure 10. Cereal prices (percent of baseline) versus global mean temperature change for major modelling studies. Prices interpolated from point estimates of temperature effects. Adapted from IPCC (2007a).

The divergence among models is small at low temperature changes (<2°C), ranging from -12 to +7%. In contrast, at more severe climate change (>4°C), studies largely diverge in magnitude but agree on the direction of change with price increases from 11 to 50% at a 5.5°C higher temperatures (Figure 10).

4 Additional drivers of food supply and price

Of the various factors that affect food supply and prices, some have been more frequently discussed or included in studies that focus on climate change impacts. These include the effect of increasing climate variability, extreme events, rates of technological development, share of biofuel use and declining stocks of production resources. These are briefly discussed in the following sections.

4.1 Climate variability and extreme events

The frequency and intensity of extreme events (heat waves, strong winds, hail, storms and floods) is likely to increase with climate change (IPCC 2007a). Although these events are not yet well represented in climate models and datasets, they can cause significant crop losses.

For example, crop “heat stress” was shown to damage yield of key food and feed crops such as wheat (Ferris et al. 1998), maize (Wilhelm et al. 1999), rice (Singh et al. 2010) and soybean (Salem et al. 2007). Yield losses occur when extremely high temperature episodes coincide with the crop reproductive stage (Porter & Semenov 2005). ‘Heat stress’ disrupts reproductive processes and ultimately the sinks to store carbohydrates from photosynthesis (Prasad et al. 2006). Recent assessments have shown the risk of heat stress damage in specific crops and regions (e.g. Asseng et al. 2011; Challinor et al. 2005) and globally, particularly for continental climates at high latitude (Teixeira et al. 2012b).

Although climate variability and extreme events are not yet considered in most food assessments, Msangi & Rosegrant (2007) were able to isolate the global effects of climate variability by arbitrarily halving or doubling the number of El Niño/La Niña-Southern Oscillation events (ENSO). During ENSO climatic events, which are characterised by changed temperature patterns in the tropical Pacific Ocean, droughts are more severe and rainfall events more intense. These extremes in the hydrological cycle can cause damage to agricultural production through the occurrence water stress of plant, soil erosion and nutrient leaching but have localised effects depending on ENSO’s cool (La Niña) or warm (El Niño) phases. According to Msangi & Rosegrant (2007), ENSO events occurred 26 times (29% of the years) from 1901 to 1990. Assuming half of the frequency, these authors projected only minor changes (-2%) to the global food variables studied, including food supply and prices. On the other hand, if climate change caused a doubling of ENSO events, this was projected to cause a 15% increase in world food prices due to negative impacts on crop yields.

4.2 Biofuel expansion

Depending on its extent, the diversion of agricultural crops for the production of biofuel can increase demand for grains, compete for scarce resources (water and land) and drive increases to food prices. Biofuels derived from food crops, classified as 1st generation biofuels (Box 3), must be distinguished for 2nd generation biofuels which use products not sourced from cultivated land (e.g. wood and waste stream based products).

Box 3. Biofuels and food crops

Global biofuel production has grown steady from 16 billion litres in 2000 to more than 100 billion in 2011 (IEA 2012). Food crops are used for the production of the so called first-generation biofuels. These are produced from sugars, starch (ethanol) and vegetable oils (biodiesel) from arable crops such as maize, sugar cane, cassava, soybean and palm oil. Large economies like the United States, member states of the European Union, China, India, Indonesia, South Africa and Thailand have either committed to policy measures or set targets for the increase in the use of biofuels. The main national motivations are reducing the dependence on fossil fuels and mitigating climate change.

Although there is no evidence that biofuel contributed to the recent food price spikes (Gilbert & Morgan 2010), the potential increase in demand for large economies such as China and India is likely to influence food prices if first generation biofuels are used.

The technology for the production of second generation biofuels, which use cellulosic and lignin reach biomass materials (e.g. cereal straw, short cycle trees plantations, solid and green waste) instead of food crops, is under development but not yet commercially available (IEA 2011).

Different biofuel scenarios were explored by Fischer (2009) considering different shares of biofuel for transportation and different production technologies (1^{st} and 2^{nd} generation). The expansion of biofuel demand was projected to increase global cereal prices up to 40 percent units depending on the period (2050 or 2080) and CO_2 fertilisation effects (Box 2) considered (Figure 11).

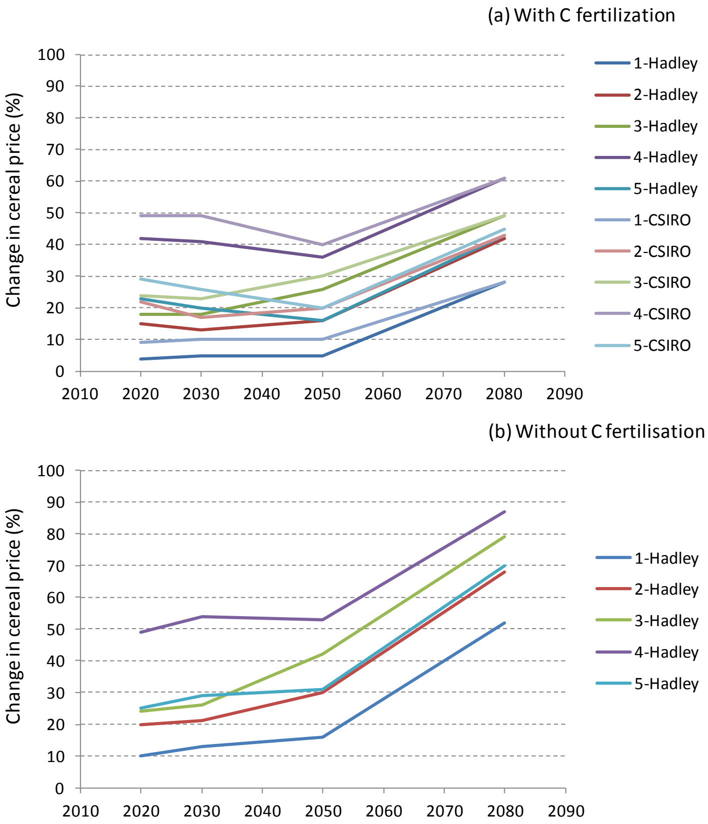

Figure 11 Change in prices of cereals (a) and all crops (b) considering the A2 climate change scenario, five bio-fuel scenarios and two climate models (Hadley and CSIRO) with and without CO_2 fertilization. Biofuel scenarios are described in

Table 3 in the Appendices. Adapted from Fischer (2009).

Both the demand for biofuel and the speed by which second generation biofuel technologies (Box 3) are deployed are important drivers of cereal prices (Fischer 2009). A consistent increase in cereal price, in response to increasing share of first generation biofuel used in transportation fuel, was projected by this author (Figure 12).

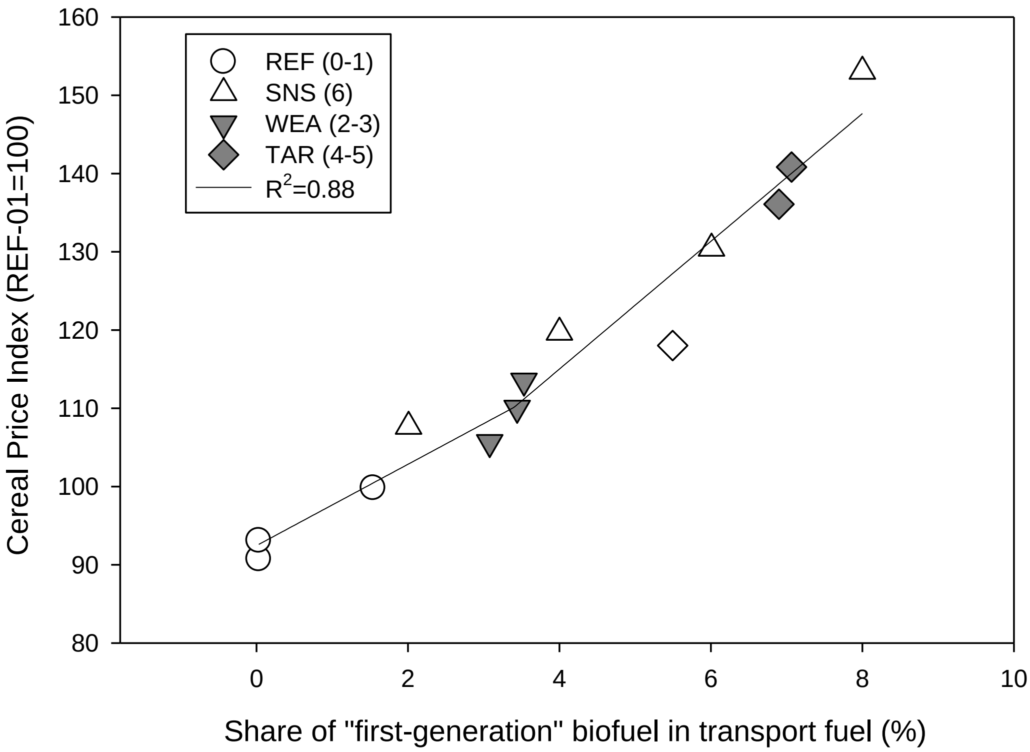

Figure 12. Impact of the share of first generation biofuels on normalised food prices. Adapted from Fischer (2009). Acronyms and numbers in parenthesis refer to scenarios and codes explained in

Table 3 in the Appendices.

4.3 Limited resources and technological development

The global food system is embedded within larger environmental and socio-economic systems (Figure 1). The food system output is therefore constrained by the limits imposed by environmental (e.g. climate and soils), physical (e.g. mineral nutrients and energy) and socio-economic (e.g. capital, labour and knowledge) factors.

Global food assessments, however, assume that most input resources are not limiting. Since the green revolution of agriculture in the 1960s, commercial cropping largely relies on external inputs such as fossil fuel, fertilisers, irrigation water and chemical pesticides to sustain high yields. These are directly or indirectly dependent on non-renewable resources like petrol, phosphate rocks (Cordell et al. 2009; Sverdrup & Ragnarsdottir 2011), and fossil water. One implicit assumption in these assessments is that technological development will buffer the scarcity of resources and enable continued yield increases closing productivity gaps. Assumptions regarding the impact of technological development on crop yield, which are inherently uncertain, have a great leverage on global food supply (Ewert et al. 2006).

The decline in the availability of input resources, without compensation by new technologies, would increase food costs and limit food supply. At the “aggregated” global system level these feedbacks were explored with scenarios that resemble current global development but future projections are uncertain (see Turner 2008). In extreme, but plausible scenarios, resource depletion and pollution lead to societal collapse (i.e. population and welfare decline) after a period when production resources (capital, land, labour) are diverted to agricultural sectors, so to keep up with increasing food demand (Meadows 2008; Meadows & Meadows 2007). The unknown remaining global stocks of key input resources, such as petrol and phosphate rocks, makes the quantification of real risks to world food supply and prices very difficult. Thus, when assessing the effects of climate change on future food prices, one should also consider scenarios in which input resources become limited (and more expensive) and substitute technologies incomplete, limiting the effectiveness of adaptation.

International food trade flow is another very important component to affect global food supply and prices (Reilly & Willenbockel 2010; Schmitz et al. 2012). National policies that influence the competition in the international market also affect world food price (e.g. farmer subsidies, taxes, import tariffs and export ban). The recent food price volatility during the 2008 price-spike (Gilbert & Morgan 2010) and the export embargo policy response from the Russian Federation (Welton 2011) illustrate the leverage of national policies. Trade policy changes are often politically motivated, so it is very difficult to predict when and how these changes will occur.

Finally, societal choices regarding food preferences also influence supply/demand and world food prices. For instance, a greater proportion of animal-derived foods have been historically consumed in countries as they develop and individuals have more disposable income (Gilbert 2010; Gilbert & Morgan 2010). Animal based foods have a much higher resource input such as land, nitrogen and particularly water (e.g. Doreau et al. 2012) than the dietary equivalents derived directly from plant products (Pimentel & Pimentel 2003). Therefore, demand for animal products tends to increase the need for cultivated land (for grazing) and feed grains (for housed animals), competing with production of grains for food. In contrast, grain demand for animal feed can decline in the future as consumers in developed countries become increasingly aware of the higher environmental footprint of these products. In a food-scarce world scenario, there will also be social implications of choosing animal products. Assuming that direct human consumption of grain is many times more efficient than using it for animal feed, dietary choices could impact the number of people under risk of hunger. As consumers become aware of such social consequences they may also favour direct consumption of grain over grain-fed animal products and this will also reduce global grain demand and prices.

5 Implications for the New Zealand arable sector

The price of agricultural commodities in the international market is of key importance to the New Zealand economy, through its impact via international trade and capital flows (Lattimore & Eaqub 2011). Currently, imports and exports account each for around one third of New Zealand's gross domestic product (GDP). Agricultural products, particularly dairy and meat, account for over 36% of New Zealand exports (Lattimore & Eaqub 2011).

Therefore, it is likely that climate change impacts on global food supply and prices (Section 3.1) will affect New Zealand's agricultural economy as a whole, including the arable sector. Although this section will mainly focus on indirect climate change effects on cropping farm returns via international trade, it is critical to also consider responses of other inter-linked New Zealand agricultural sectors to climate change.

5.1 Overview of current arable land use in New Zealand

The arable sector in New Zealand is characterised by around 2,000 farms growing a wide range of crop species (http://www.mpi.govt.nz/agriculture/horticulture/grains-seeds). The exact make-up of crop rotations depends on the value of crops, the environment in which the farm is located, access to irrigation, disease and weed management requirements, the need to ensure isolation of open-pollinated crops and proximity to processing infra-structure. Main crop options include grain cereals (wheat, barley, oats and maize), small seeds (ryegrass, brassicas, clover and carrots), forages (silage maize and forage brassicas) and vegetables (potato, sweet corn, onions, peas, carrots, squash and brassicas). Grain and seed, forage and vegetable crops account for 165,000 ha; 358,000 ha and 55,000 ha respectively. Grain, seed and vegetable crops are usually grown on specialist cropping farms. Forage crops may be grown as break crops on specialist cropping farms or as part of the pasture renovation cycle on pastoral farms.

Specific aspects of the New Zealand arable sector can influence its resilience to direct and indirect climate change impacts. These are:

Land use change flexibility. Traditionally there has been large flexibility in the land use option imposed on a farm in response to market signals, local resources and preferences. For instance, flat land farms in Canterbury can strategically shift land uses from a mix of crops and pasture options in response to returns from livestock (sheep) and crop (grain and large-scale vegetable) products. More recently, there has been substantial expansion of the dairy industry throughout New Zealand and this has consumed land that was historically in sheep and mixed cropping (Pangborn & Woodford 2011). The progression towards dairy farming reduces the flexibility to shift among land uses because of the high capital investment and specialised infrastructure required for milk production. In addition, there has been a change in the nature of cropping farms, with most crop farms now becoming specialist crop producers, without the use of pasture phases due to the recent low returns from sheep production.

The differences in economic return among cropping, sheep and dairy production were driven by export markets. This highlights the importance of world commodity prices to the land use portfolio in New Zealand.

Crop type flexibility. For most agricultural land uses in New Zealand, farmers have a large flexibility in the choice of crop types to be grown. Rarely two neighbouring cropping farms will grow the same mix of crops in the same order. This flexibility enables arable farmers to respond to market price signals within one growing season by tailoring their production system with crops and cultivars that are most likely to give the best economic returns. For example, when wheat prices were at historical highs in 2010, cultivated area increased in ~20% in relation to the previous three years (Statistics New Zealand 2011). A long-term response example is the expansion of forage crops driven by the increasing demand from the dairy industry and consequent higher market prices (MAF 2011).

Market diversity for arable products. The flow of key New Zealand arable products to the end-user is shown graphically in Figure 13. Although human consumption is the ultimate end use of nearly all arable farming operations, there are a number of paths by which arable products reach this end point (Figure 13). We have separated arable products into five categories depending on the path they take to their ultimate end use:

Food grain crops that are harvested and the grain consumed directly by humans with little or no further processing before it is sold to the final consumer.

Processing grain crops in which the harvested grain broken down into smaller components and sold to the consumer as processed ingredients (e.g. flour) or prepared foods (e.g. bread).

Feed grain crops in which the harvested grain is fed to livestock for the production of animal-based products for human consumption (e.g. meat and dairy).

Forage crops which are grown for their vegetative biomass (e.g. leaves and stems) to be fed to animals for the production of animal-based products for human consumption.

Crops which are grown specifically to produce commercial seeds. These are used by other national and overseas producers to sow vegetables, annual crops and forages that ultimately flow into products for animal and human consumption.

The main crop types and markets for each of these arable product end uses categories are briefly discussed.

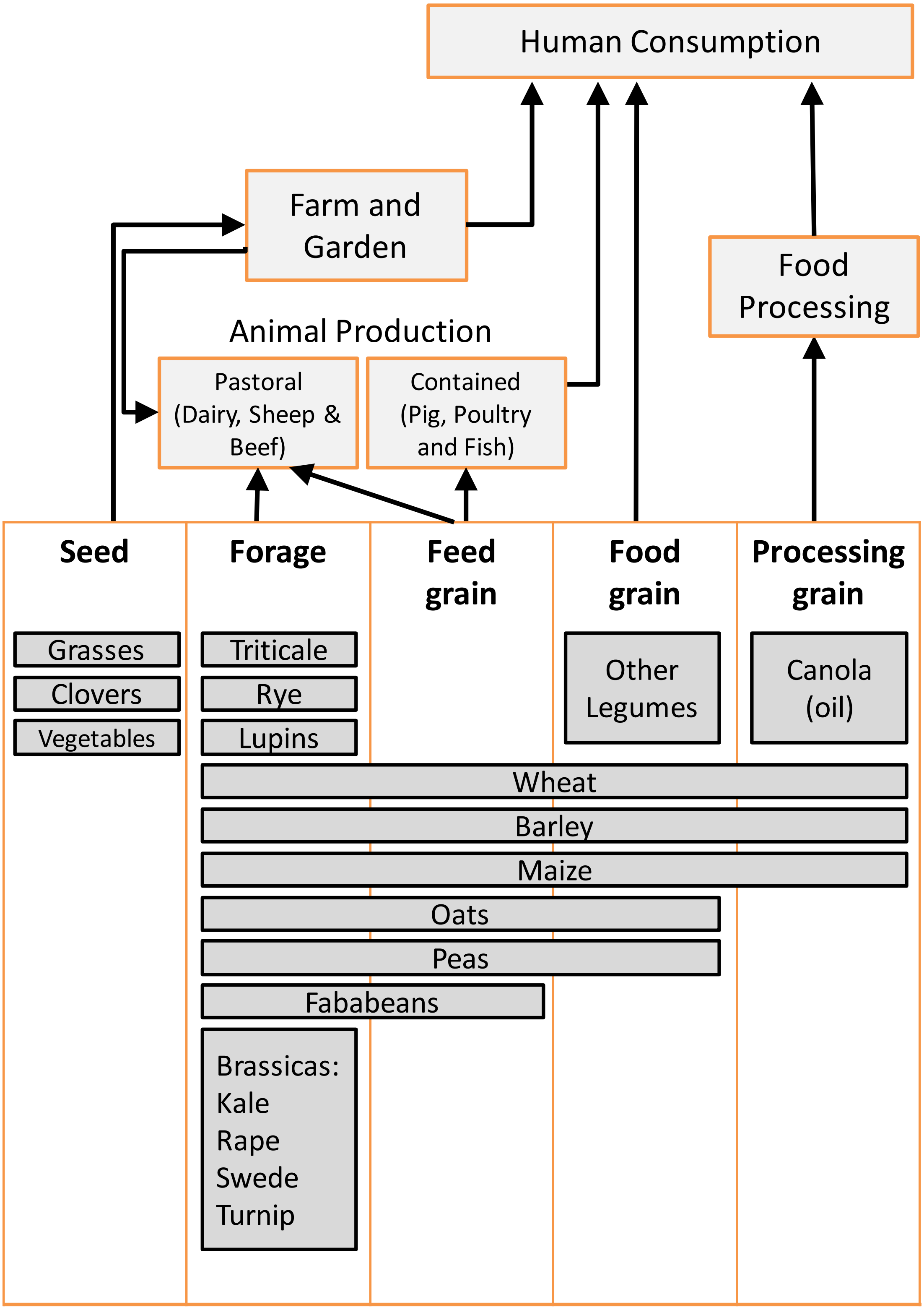

Figure 13. Crop categories and product end uses from arable farm systems in New Zealand.

5.1.1 Processing grains

The most commonly grown processing grain in New Zealand is wheat for flower production by the milling industry. New Zealand has a fairly static demand of 260,000 t of flour per year (http://nzier.live.egressive.com/sites/nzier.live.egressive.com/files/nztcwp4.pdf). Assuming a milling yield of 70%, this translates into an annual requirement for 371,000 t of milling wheat.

Although 383,300 t of wheat were produced in New Zealand in 2011, a substantial proportion of this was for feed wheat (http://www.nzgsta.co.nz/wp-content/uploads/industry-info/AMI-quarterly-report-September-2010.pdf) explaining the short fall of bread wheat supply to New Zealand. This deficit is mostly met by imports from Australia to supply wheat mills in the North Island, rather than transporting it from the South Island (http://nzier.live.egressive.com/sites/nzier.live.egressive.com/files/nztcwp4.pdf). This partial dependence on imported wheat and the easiness of storing and transporting wheat explains the close linkage between global wheat prices and the price that New Zealand farmers receive for their product. Therefore any changes to wheat supply and demand caused by climate change and global demography will impact the value that New Zealand growers achieve. The demand for flour in New Zealand is inelastic (http://researcharchive.lincoln.ac.nz/dspace/bitstream/10182/4107/1/aeru_rr_124.pdf) as there are few substitutes for flour-based products in our diet. Thus, we are unlikely to see a move away from flour and bread wheat demand, these may remain high into the foreseeable future following New Zealand population growth.

Barley is processed to extract malt for fermentation and use as a food ingredient. New Zealand's malt production is sufficient to satisfy domestic consumption and malt products are exported. This ties the value of malting barley closely to the global market price.

Oats are processed to rolled oats and are a key component in cereal meals. New Zealand also provides sufficient oats to satisfy its own domestic demands and some exports. The farm prices for oats and barley are closely related to global wheat prices because these crops are easily substituted by wheat in arable crop sequences.

Oil crops such as canola and sunflower are minor groups in New Zealand, with nearly all oil-based foods (e.g. cooking oil and margarine) being imported. There has been some expansion in the production of canola for biofuels recently but the ongoing importance of this crop option is unclear, so we will not consider New Zealand biofuels crops in this review.

The consumption of food products derived directly from pulses is minor in New Zealand and exports of pulse grains for processing or direct consumption vary depending on export demand and prices.

5.1.2 Food grain

The consumption of whole or unprocessed grains is minor in New Zealand. There is little production of such grains on New Zealand cropping farms and participation on export markets is consequently negligible. We have considered rolled oats as a processing grain, rather than a food grain, but it could equally well be considered a food grain due to the minor extent of processing. If this is the case, it would be one of the more important food grains produced in New Zealand.

5.1.3 Feed grain

Wheat, barley, oats, maize, peas, faba beans and lupins are all grown as stock feed for livestock consumption domestically. Traditionally, these have been used for the feeding of housed animals in the poultry and pig industries. However, recent high milk prices have stimulated an expansion of grain feeding crops for the dairy industry to balance cow diets and improve production (http://www.regional.org.au/au/asa/2010/plenary/climate-change/7402_robertsonmj.htm). A further emerging market for feed grain is the aquaculture industry which has ambitious expansion plans in New Zealand (http://www.aquaculture.govt.nz/files/nz_aquaculture_strategy/AQUAStrat5yrplan2012.pdf).

Locally the price that growers receive for feed grain varies substantially, as demand is driven by the seasonality of pasture production (in response to climate variability) and the cost of imported substitutes. Imported substitutes include the feed grains that could be grown domestically (300,000 –450,000 t of grain is imported annually including milling wheat) and palm kernel expeller (1,000,000 t imported annually). Because, feed grains are easily substituted with other feeds in the animal diet and demands fluctuate substantially, the price farmers obtain for feed grains also changes substantially from year to year. This is driven by both the global cost of imported grain substitutes and the local production of pasture substitutes. The value of animal products also has a large influence on the demand for feed grains. Livestock producers can chose to feed less grain to their animals when marginal returns on their product declines, particularly in the dairy industry.

Globally the demand for feed grains from arable farms is driven by human consumption of animal-derived food products. This demand has tended to increase over time as populations become more affluent and choose to eat more animal protein (Gilbert 2010). However, the production of food via animals is less efficient than direct grain consumption in the conversion of input resources (e.g. water, energy and minerals) (Pimentel & Pimentel 2003). If climate change has major effects on global food production, it could cause a shift from animal-based food products to plant-based food products in order to satisfy the human population's dietary demands. This trend would see products moved from the feed grain consumption path to the food or processing grain end-use path. The same crop types are used for grain or livestock feeding and they are easily substituted for one another in the arable farm system.

5.1.4 Forages

There is a wide range of forage crop species grown on New Zealand cropping and pastoral farms. Forage production is central to the New Zealand economy due to the large share of animal-based products export (Lattimore & Eaqub 2011). All forage crops are grown with the intention of supplementing the seasonal pasture availability, during periods when animal demand exceeds pasture growth. Brassicas (kale, swedes and turnips) and cereals (oats, wheat, barley, triticale and rye) are grown to produce a bulk of maintenance feed during the summer/autumn that can be carried forward and fed *in situ* during winter to dairy, beef and sheep at periods of pasture deficit. Other brassicas (rape and turnips) and cereals (oats, barley and triticale) are grown in the spring to provide supplementary feed for high producing stock (e.g. milking cows) during summer pasture deficits in areas prone to summer droughts. Cereals (wheat, oats, barley and triticale), pulses (peas and faba beans) and maize are also grown to produce silage. Silage is stored and used as a tactical feed supplement to boost production of high value animals during periods of pasture feed deficit or in high stocking rate systems. Crop residues are also an important form of forage used by animal farmers to balance animal diets or as maintenance feed during winter.

Forage crops can be complemented with feed grains or palm kernel expeller and demand is closely linked to seasonal pasture growth on animal farms. Historically, this has caused substantial variation in the value of forage crops. In recent years, forages crops have seen a higher and more stable value driven by demand from the dairy industry. This has been caused by the recent high value of dairy products and the high capital costs of dairy farm infrastructure. Because of this, dairy farmers have been motivated to allocate all the pasture and forage crops grown on-farm to high producing milking animals. As a result, there has been increased demand for off-farm feeding of non-milking animals (dry cows in winter and year-round feeding of replacement stock). This has driven an increase in the import of supplementary feed onto the milking farm. This impact has been amplified considerably by the increase in the national dairy herd from 2.4 million cows in 1990/91 to 4.5 million cows in 2010/11 (http://www.dairynz.co.nz/file/fileid/39959). The significant increase in the amount of forage grown in New Zealand in recent years has been driven by the high marginal returns in dairy farming, which also enabled importing of supplementary feed. Therefore, higher dairy prices increase the demand for land for forage production while a reduction in milk prices leads to a more pastoral-based system with reduced inputs and lower demand for forage and feed grains as supplements.

5.1.5 Seed crops

The production of seed crops is important for both the domestic and export markets of New Zealand. Domestically, this market supplies high quality seed for improving pasture production for the dairy, sheep, and beef sectors. Internationally, New Zealand is an important exporter of grass and clover seeds. The pastoral sector, which should remain important to the New Zealand economy in the future, is likely to ensure future demand for ryegrass, white clover and other pastoral crop seeds.

More recently, there has been a substantial expansion in the areas grown with crops for seed multiplication. These include off-season multiplication of breeding lines and advanced lineage selections for Northern Hemisphere seed companies, and the multiplication of high value vegetable seed crops (e.g. carrots). The high level of skill and technological proficiency of New Zealand farmers has ensured reliable yields of high quality seed for international clients, which is likely to drive continued growth in this market.

5.2 Impacts of climate change via global supply and prices

Based on the results of global food assessments (Section 0), three food price change scenarios (in response to climate change) were designed (Table 2) to explore impacts on the New Zealand agricultural sector.

5.2.1 Price response to climate change (scenarios)

The “low” price increase due to climate change scenario assumes that the world is effective in mitigating climate change effects over a short period but there will be a small price increase due to changes in the Earth’s climate system in response to greenhouse gasses’ emissions that have already been realised. This scenario is in line with the IPCC B1 story line that assumes only slight climate change effects by 2050; so a 5% price increase due to climate change is assumed by 2080 for aggregate food commodities (Table 2). The social and technological changes that would accompany this change are outline in Table 2. This include effective adoption of low carbon technologies to drive economy, stabilisation of world population by 2050, the liberalisation of global trade and more even distribution of wealth.

Table 2. Global food price scenarios assumed for this section.

Price increase due to climate change	Low $ increase	Medium $ increase	High $ increase
Climate change impact on food price[1]	0% by 2050 5% by 2080	5% by 2050 15% by 2080	15% by 2050 30% by 2080
Atmospheric CO_2 range (ppmv)[2]	450 ppm by 2050 520 ppm by 2080	520 ppm by 2050 630 ppm by 2080	520 ppm by 2050 700 ppm by 2080
Mitigation/Adaptation effectively	Successful. Technologies and efforts in different societal sectors (food, energy, and economy) enable reduction in emissions.	Partially effective. Increase in efficiencies do not offset absolute emissions due to population growth and consumption per person.	Failed. Business as usual economic growth model prevails and increases emissions at highest spectrum of IPCC estimates.
Potential CO_2 fertilisation effect on crop yields[1]	5% by 2050 10% by 2080	10% by 2050 15% by 2080	10% by 2050 8% by 2080[3]
Global population	Stabilises at <9 billion by 2050 and reduces after that.	Stabilises at >9 billion between 2050 and 2080.	Increases to >9 billion in 2050 and continue increasing by 2080.
Trade	Mostly liberalised and unbiased by national policies. Food production gap between developed and developing countries is small.	Partially liberalised and unbiased by national policies. Food production gap between countries is partially buffered by international trade.	Food security concerns foster protective policies that bias prices and volumes in international markets. Developing countries as net importers from developed countries.
Biofuel	Mostly 2nd generation in conjunction with other sustainable energy sources (e.g. solar and wind).	Mostly 1st generation but being a small share of the global mix of traditional and new energy sources.	Biofuels used marginally. Energy sector develops independently of food sector.
Affluence	Increased and well distributed wealth among individuals and nations. Small income gap between social classes. Food security improved.	Increased wealth but unevenly distributed. Food security risks oscillate in hot spots of hunger such as South Asia and sub-Saharan Africa.	Reduced wealth per individual (globally). Large gap between rich and poor. Pockets of food insecurity increase.
Dietary preferences	Vegetarian and low environmental footprint diets are globally preferred.	Vegetarian and low environmental footprint diets.	Increasing demand for animal protein diets in wealthy regions and nations of a socio-economically diverse society.
Correspondence to scenarios from other studies IPCC-SRES (Box 1) Millennium Assessment (Table 4)	B1 Techno Garden	A1B Global Orchestration and Adapting Mosaic	A2 Order from Strength

[1]Indicative values only to reflect trade-off between positive CO_2 fertilisation (Box 2) and negative warming effects on crop yields. Based on Section 0 results and scenario studies in New Zealand (Stroombergen 2010). [2]Indicative values only. Ranges vary with climate model used. Adapted from IPCC webpage at: http://www.ipcc-data.org/ddc_co2.html.
[3]Assumes that negative climate change impacts (e.g. shortening of crop cycles and damage due to extreme events) offsets CO_2 fertilisation effect (Box 2).

The high price increase due to climate change scenario assumes that global efforts to mitigate greenhouse gas emissions fail and climate change effects continue to increase, which is in line with the IPCC A2 storyline. This depicts a world in which the high end of climate change impacts occurs. In this possible future, social and economic drivers will continue on their current track with ineffective low carbon options for driving economies, continued population growth, trade policies focused on national interests and uneven distribution of wealth. This leads to much higher food prices and also to a less stable world economically, environmentally and politically.

A medium price increase scenario could be reached by different combinations of the different dimensions of the global food, social and political system. For example, with a high population increase but lower consumption *per capita*, or through partial shift to more vegetarian diets would produce intermediary demand on food commodities and CO_2 emissions. Some level of medium price increase could be considered most likely because the low and high price increase scenarios are towards the lower and upper extremes of potential outcomes (although still plausible). In the following sections we concentrate our discussion on these two boundaries of possibilities, the low and the high price increase due to climate change scenarios.

5.3 Future implications to the New Zealand arable sector

In this section, possible consequences of climate change impacts on global food supply (Section 0) in relation to specific sectors of the arable industry are discussed for the "low and the high" price increase due to climate change scenarios (Section 5.2.1). The following sections simply explore and discuss possible outcomes, depending on each scenario, and "should not" be taken as a prediction of the future.

5.3.1 Processing grains

For the low price change due to climate change scenario (Table 2), in which global supply and demand are less affected by climate change, it is expected that bread wheat imports from Australia will remain important to New Zealand and domestic prices will continue to be firmly linked to global markets with similar fluctuations as currently. Similarly, barley, oat and maize values would remain closely linked to the global prices because arable growers around the world can easily adjust production systems to match global demands. Under this scenario, continued improvement in farming efficiency will be required to remain economically viable, as input prices continue to increase faster that product prices and production around the world benefit from CO_2 fertilisation effects.

The low price change scenario (Table 2) infers that wealth is better distributed and consumers become increasingly aware of the social and environmental impacts of the foods they choose to eat (see discussion in Section 0). This could see animal-based foods being substituted by plant-based foods also in wealth countries. Rather than reverting back to diets based on whole pulse grains, which are common in developing countries, higher value meat and milk substitutes processed directly from plants could be demanded by wealthy consumers. This could increase the demand for pulse crops to be processed into high-value protein foods and foster R&D for processing such dietary options.

In the scenario assuming high price increase due to climate change (Table 2), food demand increases faster than supply due to the decline in overall production caused by climate change and the continuous increase in population. Under this scenario, New Zealand wheat imports from Australia would be less reliable and more costly. This is because of the negative climate change impacts on Australian production (lower yields and higher variability) and the increased demand by international markets. This could further increase the price that wheat importers would need to pay for grain and increase the value of domestically grown wheat accordingly. A possible consequence would be that local flour producers could wish to insulate their supplies from the price and availability fluctuations in the wheat market and encourage the expansion of domestic milling wheat production, increasing the resilience of the milling sector. As such, we could see mills prepared to pay a premium for contracting domestic wheat production, particularly wheat produced near processing facilities in the North Island where the greatest reliance on imported wheat exists. Furthermore, under this scenario, demand for animal-based products is likely to increase to meet the demands of wealthy nations. This would drive further the expansion in the dairy industry and create greater demand for feed grains and forage crops, which would intensify competition among agricultural activities for land and increase food prices. Cultivated area for processing grains, feed grains and forage crops can be easily substituted for one another within an arable system, so the value of bread wheat would have to adjust to ensure sufficient domestic supply. Similarly, under the high scenario, global demands for barley-, maize- and oat- based-products tend to increase. In the face of reduced global production of all cereals, the industry will need to pay higher prices for processing grains to ensure supply and growers could expect local prices to increase at least in line with global price increases.

5.3.2 Feed grains

For the low price increase due to climate change scenario (Table 2), less consumption of animal-based products could cause a substantial reduction in the demand for feed grains. A limited increase in demand and price for both meat and milk products in the international market would limit both the demand for supplemental feeds in pastoral systems (dairy, beef and sheep) and for housed (poultry and pork) animal systems. Furthermore, under this scenario, availability of imported feed grains will remain high and global prices will remain low, causing a limited incentive for feed grain production. High protein processing grains might provide an alternative to feed grains in this scenario as consumer demands shift toward direct consumption of plant-based foods.

The situation would be very different under a high scenario (Table 2). First, there will be an increase in demand for animal products as some societies become more affluent but remain indifferent to the wider impacts of their consumption choices. This increase in demand will also be amplified by an increase in total population, putting additional pressure on global demand for feed grains. This, together with an increase in the value of dairy and meat products, would drive an increase in domestic demand for feed grains. Under this scenario global feed grain values will increase, as will the value of other substituting arable products, driving an increase in the value of domestically produced feed grains.

5.3.3 Food grains

The low price increase due to climate change scenario (Table 2) could imply in a greater relevance of food grain crops for New Zealand cropping farmers. A preference to consume grains directly, rather than consume animal food products, would presumably create markets for food grain pulses such as chick pea, lentil, and beans which are high protein substitutes for animal-derived food products. It is unlikely that there will be an increased demand for direct consumption of cereal grains as consumers may continue to favour these in a processed form, although markets for less processed food (whole grain) could increase due to the health benefits associated. For food grain production to increase in New Zealand there would need to be some relative price premium over existing crop options. There is an emerging trend of consumers being prepared to pay a premium for environmentally and socially responsible food which could help provide this premium (Saunders et al. 2010). However, the most likely price premium will come from the discounting of feed grain prices relative to the price and food grains because of reduced demand for animal based foods.

Under the high price increase due to climate change scenario (Table 2), food grains will most likely continue to be a small proportion of the crops grown in New Zealand. This is because price incentives for processed grain, feed grain and forages are high and New Zealand growers are currently specialised in these products. However, pulses form an important part of the diet in many developing countries and the impacts of climate change on the production of pulses in these regions is likely to be negative in this case. This means export markets for unprocessed food crops could open up to New Zealand crop producers. The value of these exports could also be high due to the general increase in food grain prices under this scenario. This would mean pulses could become a viable crop option for New Zealand crop farmers, providing alternative break crops that have the benefit of biological nitrogen fixation for the crop system.

5.3.4 Forages

The outlook for forages will be very similar to that for feed grains as they are equally well substituted within the arable crop system and demand for their consumption will be driven by global demands for animal-derived food products. Thus, under the low scenario (Table 2) there will be a reduction in demand for forage crops while under the high scenario an increased demand and value of forage crops is expected.

5.3.5 Seed crops

The demand and value for seed crops is expected to be the least affected by changes in global consumer behaviour and crop production. Regardless of the scenario considered (Table 2), demand for high-quality seed for multiplication of a wide range of crop types is necessary to maintain production levels in crop and pasture systems. This suggests that seed industries will continue to value the high skill base of the New Zealand arable sector in providing seed multiplication services. Also, the demand for herbage seeds (e.g. ryegrass and white clover) would be less affected by climate change impacts on the international market. There are large areas of land in the world that are unsuitable for arable cropping but can still grow pastures for grazing animals. This potential market for herbage seeds is unaffected by increasing trends to move towards direct consumption of plant products, from the point of view of land use, because grazing livestock farming will not be competing with food production for direct human consumption.

For a “high” price increase due to climate change scenario (Table 2), the value of seed crops could increase to balance the higher demand for grain production. These crop activities can be easily substituted in the arable rotation. If demand for seed multiplication and herbage seed remains high, as previously discussed, then higher markets for seeds would be expected to ensure supply.

6 Overall remarks and conclusions

Global food supply responds to climate change. For most studies, negative impacts of climate change on global food supply are minor until the middle of the 21st century but become important later in the century (Fischer 2009). The magnitude and timing of impacts differ among scenarios and studies highlighting the significant uncertainties inherent to this type of study. Crop yield reduction occurs earlier and is larger for high CO_2 emission scenarios, particularly when the CO_2 stimulation of photosynthesis (Box 2) is assumed ineffective.

Climate change impacts are geographically heterogeneous. Larger negative impacts of climate change on crop yields occur in tropical and sub-tropical countries. Countries in temperate areas (high latitudes) suffer lower yield reductions or show potential for higher yields. Adaptation of crop management is often necessary to minimise damage or harness opportunities driven by climate change.

Global food prices respond to climate change and many other drivers. Climate change is just one of many drivers of global food prices. Socio-economic and political drivers have strong leverage on world food prices. Without considering climate change, most baseline scenarios assume increasing food prices throughout the 21st century in response to greater demand from a larger and wealthier global population. Dietary choices, driven by the awareness of social and environmental impacts of food production (particularly in wealthy countries) may have important impacts on *per capita* grain demands. Similarly, the extent of the demand for food crops to produce biofuels (1st generation technology) has the potential to foster competition for land, water and other production resources contributing to increase world food prices.

The New Zealand agricultural sector is highly susceptible to changes in global food commodity market. This is due to the openness of New Zealand's economy, the country's reliance on agricultural exports, lower government influence on prices, and a relatively small share of international markets (Lattimore & Eaqub 2011). These conditions strongly link local prices to world commodity prices. Higher export earnings have the potential to drive economic growth and improve the standard of living of New Zealanders. Recent modelling studies in New Zealand suggest a 2% increase in real gross national disposable income (RGNDI) from the expected increase in agriculture commodity prices caused by global warming (Stroombergen 2010), particularly if other crop-producing nations do not benefit from CO_2 fertilisation (Box 2).

Naturally, harnessing benefits of higher global food prices due to climate change is only justifiable as long as additional negative effects of climate change (in New Zealand and overseas) remain within limits, for example avoiding decline in domestic crop yields or destabilisation of socio-economic aspects of society (e.g. the number of people under risk of hunger). Global food security can be compromised by climate change impacts, particularly in regions like sub-Saharan Africa and South Asia (Fischer 2009; Fischer et al. 2009; Parry et al. 2005). For New Zealand, without considering risks of increased extreme events and pest damage to crops, recent impact assessments suggest that climate change impacts on broad acre cropping projected for the 2040s are relatively small (Jamieson & Cloughley 1998; Teixeira & Brown 2012) and adaptation measures are available to maintain current productivity levels (Teixeira et al. 2012a). The change in return to New Zealand wheat farmers was shown to range from 6.3-14.0% depending on carbon policies and mitigation costs (within and outside New Zealand) assuming the A2 scenario (Saunders et al. 2010; additional data as pers. comm.). Put together, these productivity and price changes in New Zealand largely contrast with the consistent negative climate change impacts on crops at warmer climates, particularly in developing countries in tropical and sub-tropical regions (Section 3.1).

Global changes in consumer preferences are important to the New Zealand agricultural sector. The demand for and value of New Zealand agricultural products in overseas markets depends on a wide range of socio-economic factors (e.g. Saunders & Barber 2008). These include, for example, dietary preferences for plant-based instead of animal-based foods and for certified products with low CO_2 and water environmental footprints. These are particularly important in the low price increase due to climate change scenario considered (Table 2).

Under the low price increase due to climate change scenario, global food production keeps pace with demand and prices respond mostly to socio-economic drivers. Changes in consumer preference may see a reduced demand for animal-based food products causing a shift from feed grain and forage production to more grain for food and processing. Economic incentive for alternative crops, e.g. grain legumes for human consumption of plant protein, may be created under this scenario. The value of seed production (herbage and horticulture) is likely to remain similar under this scenario given the specialised nature of the market.

Under the high price increase due to climate scenario, New Zealand exports benefit from greater demand for animal protein (dairy and meat). Domestically, continued expansion of livestock production drives an increase in the demand for forage and feed grain. Higher grain prices in the global market intensify competition between grain and forage/feed production for land and water resources. This, together with higher prices of imported alternatives, increases prices for all crop types.

There are still important unknowns and uncertainties in global food assessment studies. For example, the likely impacts of climate change on the frequency and magnitude of extreme events (e.g. foods, heat waves and severe droughts), changes to seasonal rainfall patterns and on crop damage caused by pests and diseases are not yet addressed in these studies. The science for linking models and scaling datasets in IAM assessments is still in the early stages of development (Ewert et al. 2011). Finally, the impact of climate change in other economy sectors (energy, tourism and fishing) are not considered within an integrated modelling approach and do not include economic loss from short-term extreme events such as floods and landslides (Stroombergen 2010).

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Appendices

Table 3. Scenarios of biofuel development (Fischer 2009)

Scn	Original Acronym	Scenario description
0	FAO-REF-00	Starting in 1990, assumes a world without any agricultural crops used for biofuel production.
1	FAO-REF-01	Assumes historical biofuel development until 2008; biofuels feedstock demand is kept constant after 2008; used as a reference simulation to which alternative bio-fuel scenarios are compared for their impact.
2	WEO-V1	Assumes transport energy demand and regional biofuel use as projected by International Energy Agency (IEA) in its WEO 2008 Reference Scenario. Second-generation conversion technologies become commercially available after 2015; deployment is gradual
3	WEO-V2	Assumes transport energy demand and regional biofuel use as projected by IEA in its WEO 2008 Reference Scenario. Assumes that due to delayed arrival of second-generation conversion technologies all biofuel production until 2030 is based on first-generation feedstocks.
4	TAR-V1	Assumes transport energy demand as projected by IEA in its WEO 2008 Reference Scenario. Assumes that mandatory, voluntary or indicative targets for biofuel use announced by major developed and developing countries will be implemented by 2020, resulting in about twice the biofuel consumption compared to WEO 2008. Second-generation conversion technologies become commercially available after 2015; deployment is gradual (percentage as in WEO-V1)
5	TAR-V3	Assumes transport energy demand as projected by IEA in its WEO 2008 Reference Scenario. Assumes that mandatory, voluntary or indicative targets for biofuel use announced by major developed and developing countries will be implemented by 2020. Accelerated development of second-generation conversion technologies permits rapid deployment; 33% and 50% of biofuel use in developed countries from second-generation in 2020 and 2030 respectively.
6	SNS	Sensitivity scenarios assuming low (V1), intermediate (V2), high (V3), and very high (V4) share of first-generation biofuels in total transport fuels

IEA: International Energy Agency. WEO: World Energy Outlook

Table 4. Global future scenarios described in the Millennium Ecosystem Assessment*.

Global Orchestration
The Global Orchestration scenario depicts a worldwide connected society in which global markets are well-developed. Supra-national institutions are well placed to deal with global environmental problems, such as climate change and fishery. However, their reactive approach to ecosystem management makes them vulnerable to surprises arising from delayed action or unexpected regional changes.
Order from Strength
The Order from Strength scenario represents a regionalized and fragmented world concerned with security and protection, emphasizing primarily regional markets, and paying little attention to the common goods, and with an individualistic attitude toward ecosystem management.
Adapting Mosaic
The Adapting Mosaic scenario depicts a fragmented world resulting from discredited global institutions. It sees the rise of local ecosystem management strategies and the strengthening of local institutions. Investments in human and social capital are geared toward improving knowledge about ecosystem functioning and management, resulting in a better understanding of the importance of resilience, fragility, and local flexibility of ecosystems.
TechnoGarden
The TechnoGarden scenario depicts a globally connected world relying strongly on technology and on highly managed and often-engineered ecosystems to deliver needed goods and services. Overall, eco-efficiency improves, but it is shadowed by the risks inherent in large-scale human-made solutions.

*Adapted from Chapter 8. Four Scenarios. Available at: http://www.maweb.org/documents/document.332.aspx.pdf