Chapter 5. Broad acre Cropping

Adapting broad acre farming to climate change

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Abstract

Broad acre farming in New Zealand is characterised by a variety of land uses such as: growing annual crops (e.g., wheat, barley and oats) and forages (e.g., brassicas and green-feed cereals); and large-scale vegetable production for fresh consumption or seed production (e.g., potatoes and carrots). Intensive crop rotations are generally used, and have historically achieved high yields and good quality due to the favourable New Zealand climate and rapid adoption of improved farming practices. Climate change is expected to create both challenges and opportunities for the New Zealand broad acre cropping sector. Crop model simulations suggest that potential yields of wheat and barley could increase on average by nine per cent under future temperature and elevated CO_2 conditions, when water and soil nutrients are not limiting. However, to translate this potential into actualised profitable crop yields, careful technological and management change is required. For example: on-going improvement in irrigation availability and its efficiency; development and/or use of new species/varieties to match the changed environment; and adjusting sowing dates, timing of fertiliser applications and pest control management. For cases where model simulations indicate yield declines, such as for maize, peas and potatoes, these same adaptation options can help minimise losses. Negative climate change effects will be mostly due to high temperatures shortening the crop cycle and reducing the time available for sunlight interception and photosynthesis, offsetting the potential benefits from CO_2 fertilisation and reduced cold stress. However, this increases the opportunity for growing 'break' crops such as forages between main crops. For situations where rainfall may decline, improving irrigation practices, water use efficiency and building drought-resilient systems are key strategic adaptations. Impacts of climate change on global markets and key cropping regions worldwide will also affect broad acre farming in New Zealand via international trade.

Initially this chapter characterises broad acre farming with particular attention to the variety of land uses (e.g., annual crops, forages and large-scale vegetables) and crop rotations present in New Zealand. It then describes the mechanisms by which climate change can impact on the yield and quality of different crops. Supported by a series of simulation studies with the APSIM model, the chapter critically evaluates possible adaptation options for New Zealand's crop rotations. A number of contextual factors are also formally considered, along with a case study of improving irrigation efficiency through technological change. A broad-based review helps to build some clear recommendations for managers seeking to expand adaptive capacity.

Contents

1 Introduction

Arable crops directly provide around 50% of the calories consumed by humans, particularly from cereals such as wheat, maize and rice (WHO/FAO 2003). Broad acre cropping also provides feed for livestock which supply further nutrition (e.g., meat, milk and eggs) and fibre for human consumption and use. Whilst vegetable crops make a smaller contribution to dietary energy supply, they also have an important role to balance human nutrition. The global demand for grains will certainly increase in the future as the world population is expected to increase from 7 billion in early 2012 to around 9 billion by 2050 (Lutz & Samir 2010). Prospects of reducing the proportion of malnourished people in the world, today at ~15% of global population, will further increase grain consumption. As economies develop, a wealthier population may prefer to eat a more protein-rich and varied diet that would further increase the demand for feed grain for livestock production. In contrast, the choice for a healthier and more varied diet would drive an increased demand for vegetable crops. Future challenges for food production include the declining stocks and increasing costs of input resources (e.g., fuel, synthetic fertilisers and pesticides), damage to production resources (e.g., soil erosion, desertification and decline in aquifer levels) and the competition among land uses, including the recent use of food crops for bio-fuel production (Fischer et al. 2009). The increase and changes in global food demand will have an impact on the broad acre cropping sector both internationally and in New Zealand. To satisfy these demands there will need to be an increase in crop yield (kg produce/ha), the area under production (ha), and more efficient use of current production factors (kg input/kg produce).

The pace of climate change projected for the coming decades (see Chapter 2) imposes additional pressure on food supply from broad acre crops. Yield and quality will be affected differently throughout the world's cropping regions. The increases in CO_2 concentration, seasonal temperature, frequency of extreme climatic events and shifts in rainfall patterns all point to an unprecedented need for rapid changes to broad acre cropping systems. The adaptation of crop management, the genotypes used and a re-thinking of agricultural systems (e.g., creating new industries and changing land uses) may ensure that local and global demands for food are safely met with minimum environmental impact.

In this chapter we discuss the mechanisms by which increasing atmospheric CO_2 concentrations and climate change are influencing cropping in New Zealand, and then critically evaluate on-farm adaptation options.

2 Overview of broad acre cropping in New Zealand

2.1 National importance

In New Zealand, a wide range of broad acre crops are produced. These crops fit into three general categories. The first is arable crops, which include cereal grains and legumes grains, herbage, forage and vegetable seeds, and which accounts for 165,000 ha (Agricultural Census 2007). The second category is large-scale vegetable production with a wide range of vegetables grown, the most common of these being potato, onion, squash, carrot, sweet corn, peas, brassicas and lettuce. Vegetable production accounts for a further 55,000 ha (Plant & Food Research 2011). These two categories are represented by separate industry bodies: the Foundation for Arable Research (FAR) and Horticulture New Zealand, respectively, but arable and vegetable crops are frequently grown on the same properties in rotation with one another. The third category is forage crops grown for supplementary feeding and wintering of livestock. These include forage brassicas and cereal crops grown for grazing in situ, and cereal and maize crops grown for silage production. Forage crops may be grown in rotations with other arable and vegetable crops on intensive cropping farms or used as a break crop between successive pastures on sheep, beef, deer and dairy farms. Maize and cereal silage production is represented by the Foundation for Arable Research and each type accounts for around 50,000 ha and 8,000 ha respectively (FAR, pers. comm., 2012). Forage brassica is not represented by a single industry body and statistics on the areas grown are more difficult to obtain. Unofficial estimates suggest the area may exceed 300,000 ha (de Ruiter et al. 2009b).

Cropping directly produces ~3.1 per cent of New Zealand's agricultural export earnings (InternationalTradeMAF 2012) and accounts for less than 3.5% of total agricultural land use in New Zealand. While relatively small, broad acre cropping is strategically important to the New Zealand economy because it ensures a reliable supply of grain, seeds and fresh vegetables for domestic consumption; and broad acre forage production also ensures the feasibility of many pastoral systems (Ministry for Primary Industries 2012). For instance, 500,000 t of potatoes, 85,000 t of carrots and 82,000 t of brassica are produced annually, and of this 85%, 79% and 98% are consumed domestically (Plant & Food Research 2011). Similarly, the farm gate value of arable crops is ~$650M, of which ~$255M is exported (FAR, pers. comm., 2012). Around 60% of arable production is consumed domestically as feed for the pig, poultry and dairy industries, grain for processing (e.g., wheat for flour) and herbage seed, for pasture renewal (FAR 2011b).

Arable farming in New Zealand is characterised by very high productivity when compared with the global average (Figure 5.1). Record wheat yields in excess of 15 t grain per ha are achieved in New Zealand due to favourable climate and optimal management conditions (Armour et al. 2004). These outstanding yield performances are largely a consequence of farmers' high technological literacy and a culture of embracing innovation that has ensured an increase of 3 to 4% per year for wheat and ryegrass seed production from 1998 to 2010 (FAR 2011b).

These specific characteristics of the New Zealand's arable sector largely influence the resilience and the effectiveness of adaptation options to climatic impacts. These are discussed in the following sections.

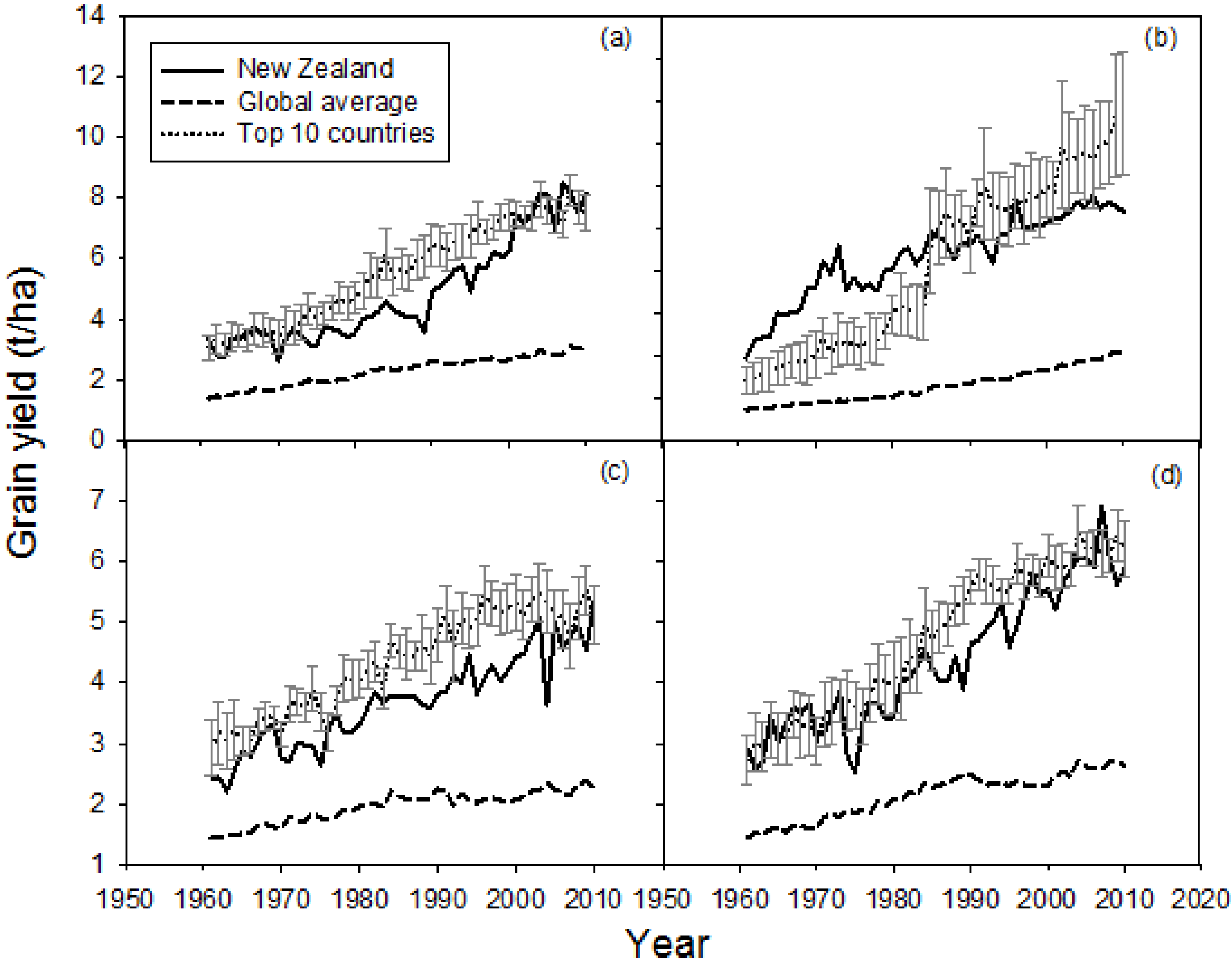

Figure 5.1. Historical evolution of grain yields for selected cereal crops in New Zealand compared with global average and the average yield of the 10 countries with highest last 10-year yield. Crops are (a) Wheat, (b) Maize, (c) Oats and (d) Barley. Source: www.faostat.fao.org (accessed in January 2012). Error bars show one standard deviation.

2.2 Broad acre cropping systems and distribution

In New Zealand, broad acre cropping is an intensive land use characterised by high inputs and yields. Cropping is almost always conducted as part of a rotation that can be characterised in two general rotation types. The first is 'continuous cultivation rotations', where grain, seed, forage and vegetable crops are grown in sequence. These are cropping or vegetable production farms where farm operators are experts in the production of broad acre crops. The second type refers to 'pastoral rotations' where broad acre crops are grown in rotation with pasture, usually as part of pasture renovation. In this case, crops are grown by the pastoral farmer to provide supplemental forage to livestock. Alternatively, land may be leased to vegetable growers who benefit from the low disease levels that occur in paddocks with a pastoral history. Where forage is grown in pastoral rotations, one or two crops may be grown to reduce weed levels in the paddock before re-sowing perennial pasture species. The most common forage crops grown in pastoral rotations are kale, swedes, turnips, annual ryegrass, cereal for winter grazing or silage (wheat, barley, triticale or oats) and maize silage.

Under continuously cultivated systems the range of crop types and rotations varies enormously. 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). Regional preferences for these crop species can be explained by market drivers and regional soil and climate suitability. For example, nearly 90% of all wheat and 67% of barley are produced in the Canterbury plains where mild temperatures, dry summers and the availability of irrigation favours cereal production. In contrast, most maize for grain is harvested in the warmer climate of the North Island where this C_4-type crop (see Section 3.3) can be grown until maturity due to a lower risk of autumn frost than in the South Island (Statistics New Zealand 2010). Most maize is harvested earlier as silage to provide high-quality forage for the dairy industry. Silage maize is mostly grown in the North Island (~32,000 ha) but can be also be grown as far south as Canterbury (~2000 ha) beyond which cold temperatures and frost risk limits its suitability and economic viability (MAF 2011).

Production of fresh vegetables is concentrated around urban centres to ensure easy and fast transport to supermarkets or ports. For example, the three largest green vegetable producing regions are Auckland (24%), Canterbury (20%) and Manawatu-Whanganui (17%) that serve Auckland, Christchurch and Wellington Cities, respectively. The largest potato-producing area is Canterbury with 43% of total production, the majority of this for French-fry production followed by Waikato, Manawatu-Wanganui and Auckland where the majority of fresh sold potatoes are grown. Forage brassica production is spread throughout New Zealand for the purpose of providing feed for livestock during periods of pasture deficit (de Ruiter et al. 2009b).

2.3 Exposure to climate variability

The economic viability of crops is not only influenced by the average climate of a location but also by climate variability (Porter & Semenov 2005). Temperature and rainfall are the main weather variables to drive inter-annual yield variability (Section 3). Overall, the higher the inter-annual yield variation, the higher the risks of production. More intensive production systems, which rely on higher inputs (e.g., fertilisers, pesticides, irrigation) and best management practices, are partially able to buffer climatic drivers – and show both higher absolute yields and lower yield variation. This relationship is illustrated in simulations (Figure 5.2) for a wide range of wheat production scenarios and climates (Box 5.2) in New Zealand using the Agricultural Production Systems sIMulator (APSIM) model (Box 5.1).

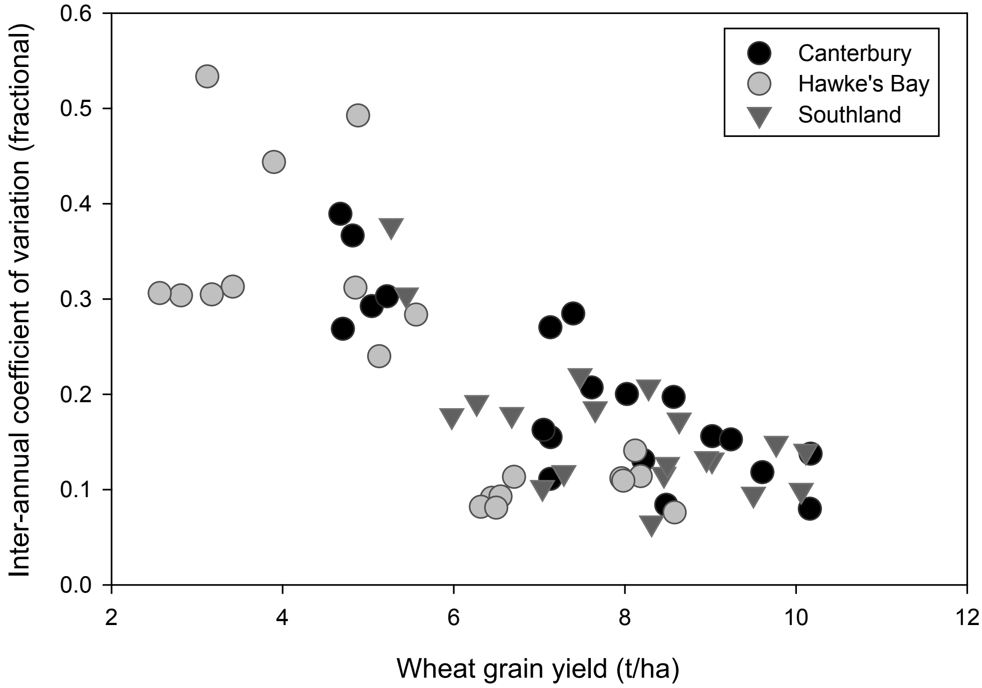

Figure 5.2. Inter-annual yield variability represented by the coefficient of variation (CV) for wheat crops simulated with the APSIM model at three locations in New Zealand considering contrasting climate and management conditions (see Box 5.2 for details).

Box 5.1. The APSIM model.

The Agricultural Production Systems sIMulator (APSIM) is a modular modelling framework that has been developed by the APSIM Initiative in Australia to simulate biophysical process in response to management practices and climate (McCown et al. 1996). The model has been extensively described in the peer-reviewed scientific literature and tested for different crops and a range of environments (Keating et al. 2003)

Most crop simulation studies in this chapter used the generic APSIM–Plant module. This standalone module represents key crop physiological processes in response to input weather fields, soil properties and crop management on a daily time step. The physiological responses are coded as sub-routines which individual crops can access. Being common to all crops, routines in the APSIM-Plant module are structured in separate blocks representing crop phenology, biomass growth, canopy expansion, root system development, organ senescence, and uptake and partitioning of water and nitrogen. These sub-modules contain the science and understanding required to simulate major functional components of crop growth and development.

Box 5.2. Modelling methodology for adaptation studies.

The APSIM model (Box 5.1) was used to assess the impact of climate change and to test the effect of different adaptation options for four key arable producing regions in New Zealand (Waikato, Hawke's Bay, Canterbury and Southland). Simulations considered typical varieties of wheat, barley, green feed crops (i.e. wheat-type crops grazed in a vegetative stage), silage maize, peas, kale and potato that were specifically parameterised for New Zealand conditions. Typical crops sequences for each location were simulated for two soils types with contrasting water holding capacity (WHC) of 80 mm/m (light soil) and 160 mm/m (heavy soil) under dry-land and fully irrigated conditions. Weather data were from the National Institute of Water and Atmospheric Research (NIWA) Regional Climate Model downscaled for a baseline historical climate (1980–1999) and two future (2030–2049) climate change scenarios B1 and A2 from IPCC (IPCC 2000). All adaptation exercises were performed using subsets of these climate/crop/soil/management combinations.

The combination between biophysical and management components of the production system, such as soil types and irrigation, also influence yield and its variability. In Figure 5.3, another APSIM simulation shows yield variability of dry-land winter wheat followed by a greenfeed crop (i.e., winter cereal for livestock feeding) for a 20 year period using historical weather in Canterbury and Southland.

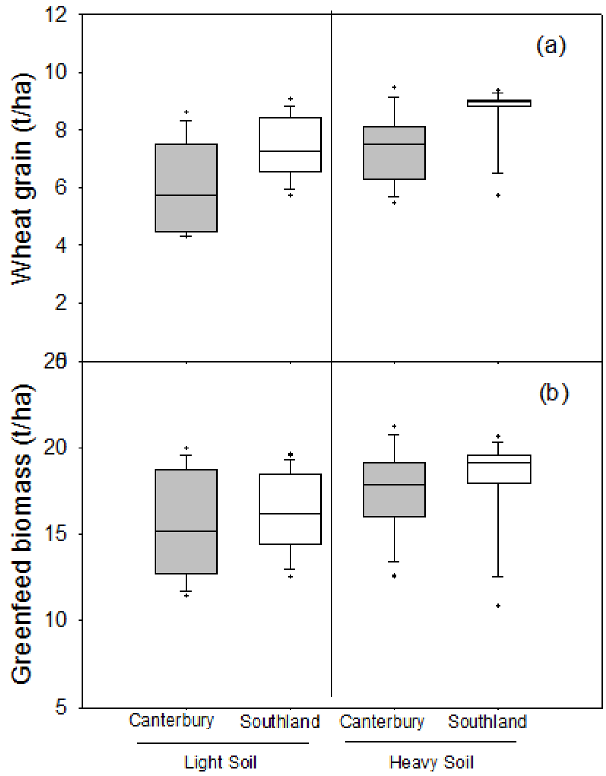

Figure 5.3. Yield variability of a dry-land crop rotation for a baseline climate (1980–1999), 20–year simulation in two locations (Canterbury and Southland) for light and heavy soil types using the APSIM model (Box 5.1). (a) Winter wheat. (b) Greenfeed cereal crop. See Box 5.2 for methodological details. The box line represents the 50th percentile, box boundaries indicate 25th and 75th percentiles, whiskers show the 5th and 95th percentiles and points show the maximum and minimum values.

The wetter climate in Southland not only enabled higher dry-land yields (more than 25% for wheat and 10% for greenfeed) than Canterbury but also consistently reduced inter-annual yield variability (Figure 5.3). Similarly, soil type had a large buffering effect on yield variability. In years of lower rainfall, crops grown in heavy soils had access to a larger amount of stored water that enabled growth and minimised yield variability.

Changes in rainfall patterns are a particularly important determinant of future yield variability (Sinclair 2011) because crops respond to both amounts and timing of water supply in relation to plant demand (Section 3.2). Climate change is expected to increase this variability further due to more frequent extreme rainfall or drought events (Section 3.4).

3 Climate change impacts on arable crops

Changes in climate can have an impact on the yield and quality of arable crops through different mechanisms. Increased temperature and its variability, increased atmospheric CO_2 and change in precipitation amounts and distribution are elements of climate change that will probably affect the performance of crops. A plethora of field, growth chamber, laboratory and modelling research has been performed in New Zealand and elsewhere to assess the response of broad acre crops to climate (e.g., Jamieson et al. 2000; Kimball 2011; Rosenzweig & Wilbanks 2010). The main climate change impacts on crops are summarised in Table 5.1 and discussed in the following sections.

Table 5.1. Impact knowledge summary highlighting those currently experienced in New Zealand and those anticipated given international evaluations.

Driver	Impact	New Zealand	International
High seasonal temperature	Impacts the rates of: • Crop development • Canopy expansion • Photosynthesis • Respiration • Transpiration	Well-established responses. Mostly positive or neutral yield responses were projected for middle year 2040 climate	Well-established responses. Positive or negative yield impacts depending on location and climate scenario considered
Drought stress	Reduces canopy expansion rates Reduces photosynthesis rates	Well-established decline in crop yield	Well- established decline in crop yield
Increase in CO_2 concentration	Increase in photosynthesis rates and crop yield Decrease in transpiration rates with increase in water use efficiency	Strong experimental evidence Magnitude still uncertain under farm conditions	Strong experimental evidence Magnitude still uncertain under farm conditions
Heat stress (short peaks of extremely high temperatures)	Disruption of reproductive processes causing reduction in harvest index	No reports found	Strong experimental and empirical evidence including from recent heat waves in Europe in 2003, Russian Federation in 2010
Other extreme events (frosts, storms, hail and high wind)	Crop damage reduces yield and quality in the short- (e.g., crop lodging) and long-term (e.g., soil erosion)	Impacts of extreme events on crop damage are well known but difficult to project and quantify	Impacts of extreme events on crop damage are well known but difficult to project and quantify
Pests pressure	Influence on damage to yield caused by insects, pathogens and weeds	Good theoretical basis. Limited modelling capability to assess it	Good theoretical basis. Scattered evidence and limited modelling capability to assess it

3.1 Temperature

Yield of broad acre crops is strongly influenced by temperature. The observed global average surface temperatures increased by 0.6°C ± 0.2°C, over the 20th century. This was due in part to increases in CO_2 and other greenhouse gases in the atmosphere most likely caused by anthropogenic activities (IPCC 2007b). For New Zealand, temperatures are projected to increase from 1°C to 4°C by the middle year 2090 from baseline (1980–1999) values depending on the region and emission scenario considered (Chapter 2).

The rates of important crop physiological processes are regulated by the temperature experienced by crops (Hay & Walker 1989). Changes in mean temperature and its variability influence both crop growth (e.g., photosynthesis) and development (e.g., time to flowering) in different ways, depending on the cardinal temperatures specific to each process (Section 3.1.1).

3.1.1 *Cardinal temperatures*

Cardinal temperatures are conceptual temperature thresholds that relate the rate of a specific crop physiological process to the temperature experienced by a plant organ. The rates of phenological development, leaf appearance, photosynthesis and respiration respond in a curvilinear manner to temperature, as a reflection of underlying plant enzymatic activity (Bonhomme 2000). In general, the rates of these processes increase from negligible values at low temperatures until a maximum is reached within an optimum temperature range, after which rates flatten and subsequently decrease (Reddy et al. 2000; Kimball 2011).

Crop physiologists and modellers simplify these curvilinear responses by using a 3-segment piecewise linear function to identify hypothetical temperature thresholds (Figure 5.4). The four endpoints of each segment of this function represent the cardinal temperatures: the base temperature (T_b), the lower optimum temperature (T_l), the upper optimum temperature (T_u), and the ceiling temperature (T_c) (e.g., Soltani et al. 2006). For example, in wheat, maximum development rates are observed at around 22°C but approach negligible values below 0°C and above 33°C (Porter & Semenov 2005).

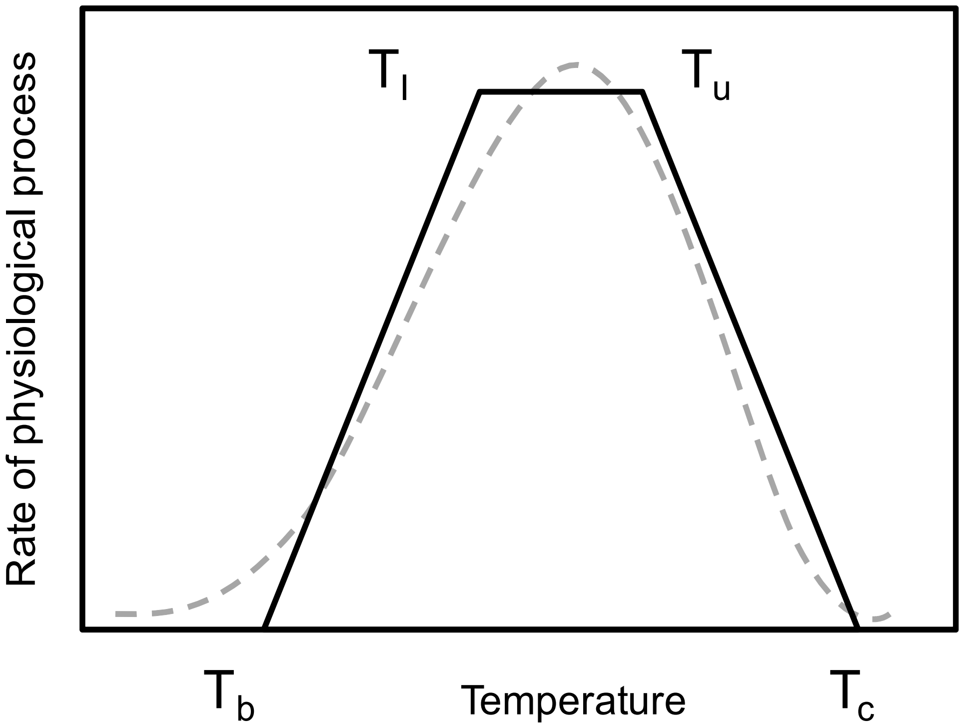

Figure 5.4. Schematic representation of the rate of crop physiological processes to cardinal temperatures showing base (T_b), the lower optimum (T_l), upper optimum (T_u), and ceiling temperatures (T_c).

The impact of temperature on crop yield depends not only on the ‘mean’ but also on the diurnal temperature ‘variability’ (Figure 5.5).

To illustrate the relevance of temperature variability, during the quasi-linear phase of positive response to temperature (Figure 5.5a), it can be seen that two different daily temperature amplitudes ($v1<v2$) with a similar mean value (x1) lead to the same mean process rate ($y1=y2$). In contrast (Figure 5.5b), the exact same amplitudes ($v1$ and $v2$) when occurring at a higher mean temperature (x 2) during the ‘curvilinear’ phase (beyond optimum temperatures), lead to different rates of physiological response ($y1>y2$).

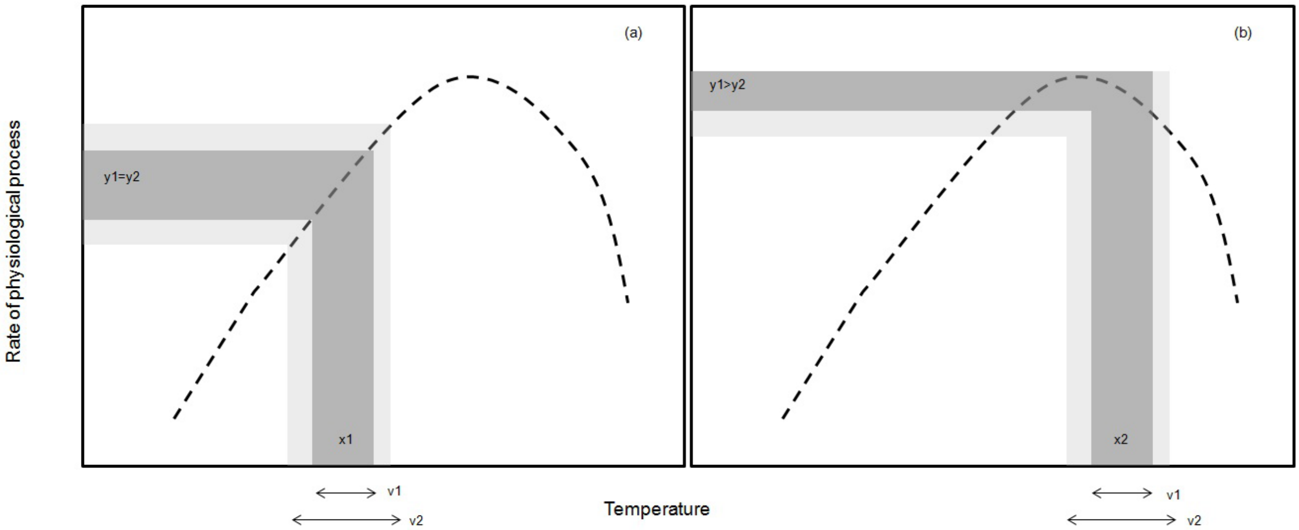

Figure 5.5. Schematic representation of the mean rate and variability of crop physiological processes (y1 or y2) in response to two mean temperatures (x1 and x2) and two different amplitudes (v1 and v2). Adapted from Porter & Semenov (2005).

3.1.2 Developmental responses to temperature

Temperature is the main driver of plant vegetative and reproductive development rates (Hodges 1991). These processes are better quantified in thermal-time units (Tt in degree-days [°Cd]) than in chronological time. Warmer temperatures will therefore affect the duration of crop phenological phases (Section 3.1.1). In the cool, temperate climate of New Zealand, where crops often grow at sub-optimal temperatures during spring and autumn, warming will most likely shorten crop cycle lengths. The transition through crop phenological stages (e.g., germination, emergence, seedling, vegetative, flowering and maturity) will be accelerated (Hodges 1991; Craufurd & Wheeler 2009). In isolation, the shortening of the crop cycle limits yields by reducing the time available to intercept sunlight and access soil moisture and nutrients. However, this effect can be counterbalanced by faster rates of canopy expansion and photosynthesis in response to higher temperature and CO_2 concentrations when water and nutrients are not limiting (Section 3.3). Vegetative development, characterised by leaf appearance and branching, is strongly driven by thermal-time accumulation. For example, the leaves of a short-maturity maize hybrid grown in Canterbury were shown to appear each around 46°Cd (Teixeira et al. 2011b). Considering historical climate and a T_b of 8°C (see Section 3.1.1), this implies that each leaf takes around 12 days to appear in spring (average seasonal temperature of ~12°C) but only 6 days in summer (average of ~16°C). In a warmer climate this maize hybrid will produce leaves faster and consequently reach maximum canopy cover earlier in the growth season. Similarly, the time to reach critical reproductive stages, such as anthesis and the grain-filling period can be anticipated under warmer temperatures. This influences the temporal matching between critical yield formation phases such as grain-filling and prevailing environmental conditions (Section 3.4.1). Finally, extreme high temperatures can terminate crop development if lethal temperatures are reached. Most crops are reported to be killed by temperatures of around 45°C to 55°C (Porter & Gawith 1999). Such temperatures occur at unshaded soil surfaces, and can reduce crop establishment particularly under conventional tillage systems (Korner 2006).

Other environmental drivers, notably day length (photoperiod) and the exposure to cold temperatures (i.e., vernalisation), further influence crop development by sequentially controlling the thermal-time requirement for transition from vegetative to the reproductive period (Dennis & Peacock 2009). Natural and induced selection of varieties has led flowering to occur during more favourable climatic conditions for a location, improving species survival or agronomic performance, respectively. Important cereal crops in New Zealand such as wheat, barley and oats have varieties with different levels of sensitivity to day length and vernalisation. For example, photoperiod-sensitive wheat varieties require more thermal-time accumulation to reach flowering (i.e., they mature later) when exposed to short day lengths during their vegetative period than insensitive varieties (see e.g., Section 4.1.2).

While day length responses are not directly affected by climate change, the fulfilling of vernalisation requirements will be influenced by fewer cold days in the future. Yield decline due to non-fulfilment of vernalisation requirements was identified as an important climate change impact for cereals grown in high latitudes (Parry et al. 2005), in Mediterranean climates (Guerena et al. 2001) and in cropping areas in China (Xiong et al. 2007). Unfulfilled vernalisation requirements retard crop development and can cause low flower bud initiation, ultimately reducing yields (Harrison et al. 2000). The actual impact of climate change on yield through vernalisation will depend on local background temperatures and vernalisation requirement of the specific varieties.

3.1.3 Growth responses to temperature

Crop growth, or the daily rate of crop biomass production, is strongly driven by light interception but further regulated by temperature, water and nutrients (Monteith 1972). Temperature regulates the rates of canopy photosynthesis and plant respiration that ultimately control the net conversion of intercepted light into biomass (i.e., the crop's radiation use efficiency, RUE). For instance, wheat photosynthesis rates at 5°C are only 25% of the maximum rates that occur at an optimum temperature of ~25°C (Lawlor & Mitchell 2000). Growth can also be indirectly influenced by temperature through its effects on the rate of canopy expansion and consequent interception of solar radiation (Section 3.1.2). Crop respiration, which consumes nearly 50% of total assimilates acquired by photosynthesis, also responds to temperature (Amthor 1997). Warmer temperatures increase maintenance respiration rates, which approximately double at each 10°C increase (McCree 1974).

Small changes in temperature can reduce production of crops that are already grown close to their temperature optima. This is the case for soybean and cotton in mid- and low-latitude production regions (Lawlor & Mitchell 2000). In contrast, in high-latitude regions such as in New Zealand, canopy development and net photosynthesis rates are often limited by low temperatures during autumn and spring. In these conditions, increases in temperature can lead to higher growth rates because of an increase in light interception and RUE during these periods (Ludwig & Asseng 2006).

The overall effect of temperature on crop growth and yield is, therefore, the result of a complex and often competing interaction between the effects on photosynthesis, respiration and light interception on carbon assimilation and allocation. Indirect effects of temperature on yield via soil processes (e.g., nutrient mineralisation), frost damage (Section 3.4.3) and pest pressure (Section 3.5) will be also influenced by climate change.

3.2 Precipitation

The amount and timing of rainfall are important determinants of inter-annual variability of dry-land crops (Lobell & Burke 2008). Climate change effects on rainfall patterns can have both negative and positive impacts on agricultural production (Sinclair 2011). High rainfall often increase crop yields in (semi-)arid environments by reducing the risk of water stress, while excess rainfall can reduce yield through waterlogging, diseases and nutrient leaching in already wet regions.

Although rainfall patterns have a major impact on inter-annual yield seasonality (Sinclair 2011), future projections of rainfall are more uncertain than for other climatic variables, and estimates largely differ among models (see Chapter 2; Smith et al. 2005).

3.2.1 Low rainfall

In New Zealand, climate change is expected to increase drought risk for important cropping regions, particularly in the country's east coast (Chapter 2). A multi-model analysis projected a 10% to 20% reduction in rainfall amounts and increasing variability in the seasonality of rainfall in these regions by the middle year 2040 (Reisinger et al. 2010).

Low rainfall can limit crop growth in different ways. When water supply is less than crop demand, yield is mainly reduced by limited canopy expansion and increased leaf senescence, thereby decreasing sunlight interception (Stone et al. 2001a), and reduced photosynthesis rates due to stomatal closure (Stone et al. 2001b).

In addition to annual rainfall amounts, inter-seasonal rainfall variability is an important determinant of crop yield

(Sinclair & Muchow 2001). Crop demand for water and its sensitivity to water stress varies throughout the crop cycle (Asseng et al. 2008). For example, in cereal crops yield can be characterised by the product of its yield components: (i) the number of ears per unit area; (ii) the number of grains per ear; and (iii) the individual grain weight. Because these components are developed sequentially, the timing of moisture stress dictates which components are most affected. Early stress mainly affects the number of tillers, and hence ears, per unit area; while late stress affects the number of grains per ear and grain weight.

The interplay between rainfall amounts and variability explains the often positive, but not necessarily strong, relationship between total growing season rainfall and crop yield (Rosenzweig & Tubiello 1997). For example, in the North Island of New Zealand, simulated maize yields increased by 23-25 kg dry matter per mm seasonal rainfall, but total amounts explained only 60 to 70% of the inter-annual yield variation (Teixeira et al. 2011a). The remainder of yield variation was influenced by other climatic variables (e.g., temperature and solar radiation), soil type and management. On the other hand, in the South Island of New Zealand, the timing of drought stress was found to play a less important role than its intensity for wheat, barley and maize grain production (Jamieson et al. 1995). Lengthening the intervals between rainfall events may limit yields through water deficits (Section 3.2.1) even if total seasonal rainfall amounts are unchanged (Sinclair 2011), particularly for soil with low water-holding capacity.

3.2.2 High rainfall

Climate change in some New Zealand locations may result in more intense precipitation events spaced at longer time intervals (see Chapter 2; Reisinger et al. 2010). Excess precipitation and flooding can cause considerable yield and quality losses through: (i) oxygen deprivation in the root system; (ii) soil and nutrient erosion through run-off; (iii) deep percolation and leaching of nutrients (particularly nitrogen); and (iv) increased risk of crop diseases due to a more humid micro-environment.

Effects on yield due to damage to roots caused by lack of oxygen or diseases due to excessive humidity can reduce the soil depth explored. This limits the access to mineral nutrients and water later in the crop cycle exacerbating subsequent water limitation. In addition, risk of crop lodging is increased at excessively wet soils, particularly when coinciding with conditions of strong winds during advanced stages of crop phenology.

Excess rainfall may also carry environmental consequences as increased percolation of water through the soil moves nutrients below the root zone, increasing the risk of nutrient load to aquifers and surface waterways (Sinclair 2011).

3.3 Carbon dioxide

The CO_2 concentration in the atmosphere increased from 280 ppm in the pre-industrial period to more than 390 ppm in early 2012. Scenario analyses from the IPCC consider global increase to around ~475–565 ppm in 2050s and ~540–955 ppm in 2100s depending on possible pathways of global development (see Chapter 2; IPCC 2000).

Atmospheric CO_2 diffuses into plants' leaves through stomata and is fixed via photosynthesis to build plant biomass (Qaderi & Reid 2009). Through the same pathway that CO_2 diffuses into the leaves, water is lost through transpiration. The leaf level water use efficiency (WUE; g CO_2/g water) is a result of the different rates of these two diffusion processes. Therefore, projected increases in CO_2 are expected to affect both growth and transpiration rates in broad acre crops.

3.3.1 Crop growth

The future increase in atmospheric CO_2 is expected to enhance growth rates of several crops used in New Zealand, particularly for C_3 type crops such as wheat, ryegrass, potato, oats and barley. This 'CO_2 fertilization response' was observed in several experiments under controlled and open-air conditions (Ainsworth & Long 2005). A meta-analysis for several Free-Air CO_2 Enrichment (FACE) experiments has shown that there was an increase in light-saturated leaf photosynthesis by 10% to 20% when CO_2 concentrations increased from around 365 to 567 ppm, but the range of response varied with crop type (Ainsworth & Rogers 2007). Similarly, Kimbal (2011) reports an average increase of 13% in net photosynthetic rates for several C_3 crops under 550 ppm CO_2

concentration, compared to a 353 ppm baseline. There are two reasons for these consistent responses of C_3 crops to increasing CO_2. First, carboxylation activity of the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) is limited under current CO_2 concentrations. Second, C_3 crops lose part of the carbon fixed by the 'photorespiration' process that is an inherent carbon cost of this photosynthetic pathway. Both these limitations are avoided in C_4 crops 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, and consequently higher RUE, 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 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). There is no conclusive evidence of differential biomass partitioning to plant organs in response to CO_2 and this remains an area for further research (Allen & Boote 2000).

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 (Long et al. 2006; Tubiello et al. 2007a). The interactions among CO_2, water, nutrients and management are still not well quantified (Kimball 2011).

3.3.2 Crop development

The effects of CO_2 on crop development are less certain than for growth processes. In some studies the appearance rates of crop organs (leaves, ears, spikes and tillers) were shown to increase at higher CO_2 concentration (Lawlor & Mitchell 2000), while other studies found negligible (or no) changes to phenological development in key arable crops such as rice (Horie et al. 2000), soybean (Allen & Boote 2000), cotton (Reddy et al. 2000) and potato (Miglietta et al. 2000). Faster crop development under high CO_2 concentration may be an indirect response to increases in canopy temperature (Section 3.1) due to reduced transpirational cooling caused by stomatal closure.

3.3.3 Interactive effect of CO_2 with other growth factors

The CO_2 fertilization effect is influenced by other growth factors, particularly temperature, nitrogen and water supply. While isolated effects were relatively well quantified, very few studies have looked at the interactions between these factors (Ludwig & Asseng 2006).

Under sub- or supra-optimal temperatures, the reduction in the rate of development (Section 3.1.2) and growth (Section 3.1.3) processes can negate or overpower the CO_2 fertilization effect (Ainsworth & Rogers 2007). A large meta-analysis (Ainsworth & Long 2005) indicated that the CO_2 stimulation of photosynthesis was greater at temperatures >25°C, which is close to the optimum for several C_3 crops.

Nitrogen stress reduces the CO_2 fertilization response. In C_3 crops, nearly 25% of total leaf nitrogen is invested in the enzyme Rubisco, compared with between 10% and 15% for C_4 crops. When nitrogen supply is limited, photosynthesis stimulation by increased CO_2 was shown to decline by up to 20% (Ainsworth & Long 2005). The mechanisms involved relate to down-regulation of the photosynthetic machinery due to excess carbohydrate, and limited formation of photosynthate sinks such as new leaves, tillers and grains (Ainsworth & Rogers 2007). In addition, indirect effects of low nitrogen nutrition such as the reduction in root growth further reduce yields by limiting the volume of soil explored and access to additional nutrients and water (Lawlor & Mitchell 2000).

Under limited water supply conditions the effect of CO_2 fertilization is more evident. Higher CO_2 concentrations reduce the loss of water vapour through leaf transpiration and, therefore, improve the water use of crops (Leakey et al. 2009). In some situations, accelerated crop development due to increased temperature, caused by reduced transpirational cooling under high CO_2 concentrations, may be indirectly beneficial for crops grown under water-limited conditions. For example, faster phenological development enables earlier crop maturity that can, in some cases, strategically avoid exposure to late droughts by anticipating the onset of the grain-filling period (Soltani & Sinclair 2012).

In summary, CO_2 fertilization responses depend on the interaction with other growth factors, generally being higher under optimum mineral nutrition and sub-optimal water supply conditions (Ludwig & Asseng 2006). The quantification of these interactions is still uncertain but crop models are suitable tools to further integrate and analyse the complex interaction of these climatic factors together with changes in crop genotypes and management (White et al. 2011). Other practical implications of CO_2 fertilization responses relate to crop quality. For example, under higher CO_2 concentration there may be a need for higher nitrogen fertiliser applications to maintain grain protein concentration in wheat due to the reduction in the carbon:nitrogen ratio in the crop biomass (see Section 3.7).

3.4 Extreme events

The Fourth Assessment Report (AR4) of the IPCC suggests that the frequency and intensity of extreme events is likely to increase with climate change (see Chapter 2; IPCC 2007a). Heat waves, strong winds, hail, storms and floods are examples of climatic events that can cause significant crop losses.

3.4.1 Heat stress on crops

The frequency and intensity of heat waves is projected to increase with climate change (IPCC 2007a; Tebaldi et al. 2006). When extremely high temperature episodes occur during the crop reproductive stage, and even if these episodes last only a few hours, crop yields are reduced (Porter & Semenov 2005). 'Heat stress' damage to yield was observed in several broad acre crops such as wheat (Ferris et al. 1998), maize (Wilhelm et al. 1999), rice (Singh et al. 2010), cotton (Liu et al. 2006), groundnut (Challinor et al. 2005), soybean (Salem et al. 2007), tomato (Pressman et al. 2002) and oil-seed brassicas (Morrison & Stewart 2002). Yield loss is caused by disruption of reproductive processes, for example, through the reduction in the number of flowers per plant, impairment of pollen tube development, reduced and more variable pollen release and viability, and decreased ovule fertilization rates (Prasad et al. 2006a). As a consequence, crop yields are reduced by limited sink capacity (e.g., fewer grains) to store photosynthates, and there is a decline in plant harvest index (HI).

There is wide variation in sensitivity to heat stress among crop species and varieties (e.g., Prasad et al. 2006b). Currently, critical temperature thresholds and the thermal-sensitive period are not yet well defined for different crop varieties. In general, crops are at their most sensitive for one or two weeks around flowering. Critical temperature thresholds range from less than 30°C for wheat crops (Barnabas et al. 2008) to up to 35°C for soybean (Salem et al. 2007).

It has been suggested that the risk of heat stress is greater at high latitudes (~40°–60°) and in continental cropping regions (Teixeira et al. 2012). In New Zealand, the oceanic climate may provide partial buffering against the frequency and intensity of extreme temperature episodes (Chapter 2). The nature of heat stress damage mechanisms suggest that adaptation is possible by changing the time when flowering occurs (e.g., changing sowing dates and variety maturity) and using more resistant varieties.

3.4.2 Storm damage, strong winds, hail and flooding

The risk of storms is expected to increase due to increased evaporation rates from oceans (IPCC 2007b). However, there is still significant uncertainty on the projected changes for storminess magnitude and high winds with climate change (Chapter 2). Cropping in coastal regions and island nations such as New Zealand are at particular risk from storm damage. Strong winds increase risks of crop lodging, seed shedding and harvest losses of rowed crops. This compromises yield, harvest operations and crop quality, particularly from cereals and small seeds such as ryegrass. Excess or unseasonal rainfall can cause yield and quality loss through seed shedding, longer time and costs for seed drying, floods and also increase the risk of environmental damage. Hail events can be particularly damaging to a diversity of crops. A change in storm patterns may result in more intense precipitation events spaced at larger time intervals (Sinclair 2011). If annual rainfall is concentrated into fewer, larger storms, there is a greater risk of water run-off, deep percolation, soil erosion and the transport of soil nutrients into streams and rivers. Even though an intense storm might recharge the soil with water, a lengthened dry period increases the vulnerability to water deficit even if the total rainfall remains unchanged. Long-term crop productivity can be compromised by frequent extreme events causing erosion and nutrient depletion of soils.

3.4.3 Frost events

Below-freezing temperatures can cause yield damage and culminate in 'killing-frosts' (Inouye 2000). Subfreezing temperatures induce the formation of ice crystals within or between plant cells which induce tissue damage and loss of solute from cells. The impact of frosts depends on the intensity and timing of cold temperature events in relation to crop phenological stage. Frost can also affect the viability and vigour of seed (DeVries et al. 2007). Often, soft and differentiating tissues such as new leaves, flowers and buds are more susceptible to damage than structural organs such as stems. Sub-lethal frosts can indirectly cause yield losses by creating conditions for pathogenic infections (Elmore & Doupnik 1995) to establish themselves in roots, buds and flowers (Inouye 2000). For example, soft rot caused by *Pseudomonas fluorescens*, usually not a common maize pathogen, can became an opportunistic facultative parasitic after frost damage (Elmore & Doupnik 1995).

Intuitively, the mean number of frost events and their intensity is expected to decrease with future increases in temperature. This is illustrated by the relative intensity of frost events simulated for four locations in New Zealand (Figure 5.6).

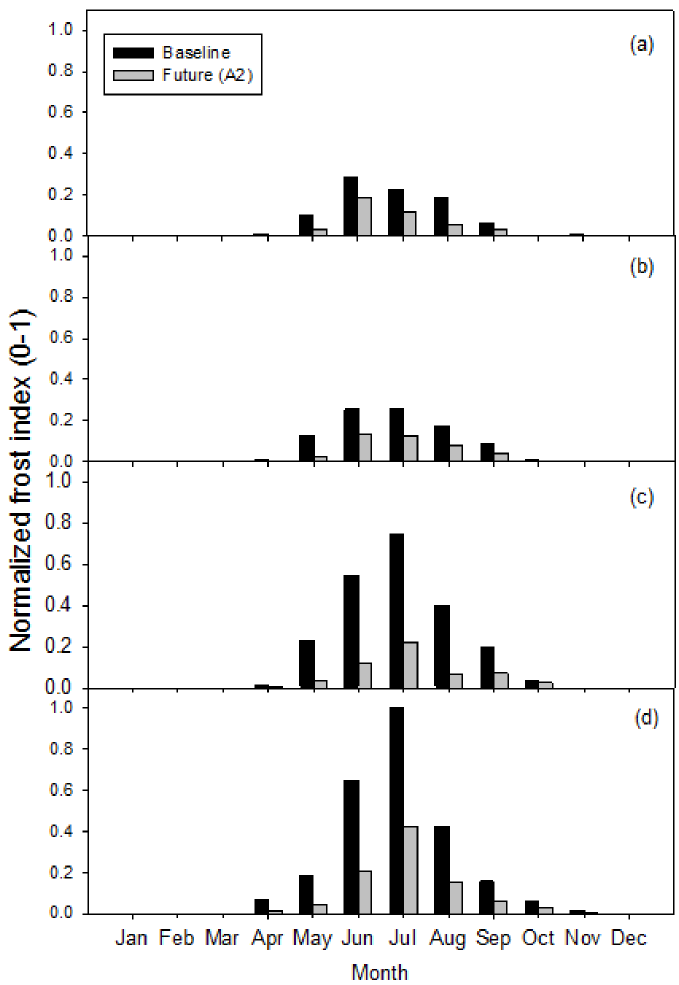

Figure 5.6. Normalised frost-risk index assuming crop damage starting at minimum temperatures of 0°C and reaching total damage at -4°C.Calculations for a 20-year simulation assuming a baseline climate (1980–1999) and a future (2030–2049) A2 emission scenario for four New Zealand cropping regions using downscaled NIWA datasets (Box 5.2). Locations are (a) Hawke's Bay, (b) Waikato, (c) Canterbury and (d) Southland.

Paradoxically, climate change might increase the risk of frost damage through different mechanisms related to the timing of events (Ball et al. 2011). While the increase in temperature 'mean' value reduces the risk of frost, an increase in temperature 'variance' was shown to increase the risk of frost (Rigby & Porporato 2008). Prospects of faster crop development and earlier sowing in spring can expose plants to freezing temperatures in this period of greater temperature variability. Indirectly, failure to fulfil vernalisation requirements due to warmer temperatures in autumn (Section 3.1.2) can delay flowering time and expose plants to late frosts.

Although climate change is likely to influence the risk of frost, it is difficult to project future changes due to the complex interaction between increased temperature, CO_2 and micro-climate aspects (e.g., altitudinal and management differences) that also influence frost damage (Inouye 2000). For example, both increased (Lutze et al. 1998) or decreased (Boese et al. 1997) frost sensitivity in response to higher CO_2 concentrations were reported in the literature, suggesting the need for further study of this topic.

3.5 Pest damage

The yield damage caused by biotic factors such as insects, pathogens (fungal, bacterial or viral) and weeds on agricultural production is one of the largest sources of crop losses (Oerke 2006). Globally, it is estimated that more than one-third of attainable yield of major food crops is lost due to pest damage (Oerke et al. 1994).

Climate change is likely to influence the frequency and intensity of pest damage on arable crops because host and pest development are strongly driven by environmental factors (Coakley et al. 1999; Sutherst et al. 2000; Juroszek & von Tiedemann 2011). This relationship is evidenced by documented changes in pest ecology (Harrington et al. 2001) and the influence of major climatic patterns on the severity of pest damage in different crops and locations (Chakraborty 2005). For example, El Niño/La Niña-Southern Oscillation (ENSO) patterns were shown to be associated with the incidence of wheat scab in China (Zhao & Yao, 1989 cited by Chakraborty, 2005) and soybean rust in the south of Brazil (Del Ponte et al. 2011).

Similarly, the increase in CO_2 concentration was also shown to influence crop resistance to pests, pest life cycle and host-pest interaction (Chakraborty & Datta 2003). The CO_2-fertilization effect favours early and intense canopy cover which may create a more favourable micro-environment for pest development (e.g., Chakraborty et al. 2000). Faster pathogen development and fecundity under higher CO_2 levels and temperatures could accelerate evolution towards more aggressive and pesticide resistant instances through faster mutation and selection (Scherm & Coakley 2003).

There are few documented studies of the impact of climatic changes on pests in New Zealand. The global area from which invading pests originate is projected to increase because current low temperatures limit their entrance into New Zealand (Kriticos 2011). Therefore, as a general pattern, it is possible that pest pressure will increase in New Zealand with climate change. First, because low temperature thresholds for pest development will be less frequently surpassed as climate warms. Mild winters enable pest overwintering and large early-spring initial populations. Second, warmer spring-summer temperatures will accelerate pest development and the number of generations per season (Ziska et al. 2011). Faster phenological development for insects (Cannon 1998), pathogens (Juroszek & von Tiedemann 2011) and weeds (Hayman & Sadras 2006) can increase pest damage in cropping systems. Finally, the southern migration of host crops, such as maize, is expected to be followed by corresponding pests (e.g., cutworm, aphids, and tropical grass weeds). Case studies with climate change effects on wind-born insect migration, lucerne weevil, Argentine stem weevil and corn earworm have been recently discussed for New Zealand conditions (Cock et al. 2011). However, there is little quantitative understanding about how much climate change might affect pest impact in New Zealand and abroad. To provide a realistic assessment of whether a particular pest will (or will not) become more widespread and abundant requires consideration of the overall pest/host-plant/natural-enemy relationship and how this is likely to alter under different climatic conditions and over varying time scales (Gerard et al. 2010). Consequences will be greater if pest distributions shift into regions outside the distribution of their natural enemies, although a new community of enemies might then provide some level of control (Thomson et al. 2010).

3.6 Impacts on global markets and other cropping regions

The most important element of any farm business is the value of the product that is produced. Farmers rapidly adapt year-to-year as prices of particular products change. Because grains are easily stored and transported, the prices that arable farmers receive for their products are closely linked to their value on the global market. Consideration of the effects of climate change on global grain production in the context of global supply (as influenced by climate and technology adoption) and demand (as influenced by population change and individual consumption) must be taken when formulating strategies to respond to climate change.

Previous food assessments have suggested that future global changes, in conjunction with climate change, are likely to increase the demand for grains and their prices relative to historical records (Rosenzweig & Parry 1994;

Fischer 2009). Importantly, these studies show that climate change impacts are spatially uneven and vary largely from country to country. Overall, more negative impacts are expected for agriculture in developing countries, even when adaptation options and technological improvements are considered (Rosenzweig & Parry 1994; Parry et al. 2004).

Lobell et al. (2011) have shown that over the past 30 years, upward trends in temperature in most grain growing regions have caused a significant reduction in global maize and wheat yields. At a regional scale they have shown that tropical and subtropical countries suffered the largest impacts of increases in temperature. These countries also showed slower increases in crop yield during the same period (Lobell et al. 2011). This was attributed to a slow adoption of improved practices and technology, illustrating a limited ability to adapt to climate change in comparison to developed countries.

Depending on the pace of global warming (Chapter 2), the impacts summarised above are expected to amplify in intensity. Ultimately, this will mean a reduction in the global supply of grains and, in the face of increased demand, the world will likely see an increase in global grain prices (Rosenzweig & Parry 1994).

This situation may benefit countries that are net exporters of calories, as long as fair international trade practices are developed and maintained. In addition to New Zealand, fewer than around 30 such countries including, for example, Australia, the USA, Canada, Brazil and Argentina that are net exporters of calories (FAO 2002). This potential increase in food demand and in international prices represents an important opportunity for the New Zealand arable sector. Moderate climate change is expected to be positive for several crops in New Zealand and the high skill level of growers mean they can rapidly adapt if needed to respond to market opportunities (Section 2).

3.7 Impacts on crop quality

Climate change can influence the economic viability of arable cropping sector not only through its impacts on yield but also by affecting the quality of the marketed produce (i.e., nutritional and industrial value). For example, the milling industry often offers price incentives for better quality hard wheat grain with higher protein contents and favourable ratios of amino acids for the making of high-quality breads (Stone & Savin 1999).

Climatic factors that promote additional carbon uptake through photosynthesis (e.g., CO_2 fertilization, Section 3.3) can 'dilute' the nitrogen (N) content in plant biomass and reduce grain protein content (Pleijel & Uddling 2011). Elevated CO_2 was shown to decrease grain protein concentration in spring wheat by 7.9% and also alter its protein composition (Högy et al. 2011). However, this effect is minimised when additional nitrogen supply decreases plant C:N ratios (Kimball et al. 2001). A recent meta-analysis suggests that mechanisms additional to the dilution effect, such as the direct impairment of plant nitrate uptake and assimilation processes, can further explain the consistent decline of wheat grain protein at high CO_2 concentrations (Pleijel & Uddling 2011).

High temperature, nutrient and water stress can affect grain protein and its composition depending on when the stress occurs (Martre et al. 2006; Balla et al. 2011). For example, exposure to temperatures >35°C during grain filling was shown to reduce dough strength by affecting protein content of the grain (Wrigley et al. 1994).

Indirectly, grains and forage quality can be compromised by the impact of pests and diseases due to excess rainfall or changes in other climate factors that favour increase in pest pressure (Section 3.5).

3.8 Assessing combined impacts

The assessment of combined climate change impacts can be done through the use of process-based crop simulation models. Modelling studies, even with known limitations (Section 6), are to a large extent able to integrate plant responses to increased temperature, CO_2 fertilization, and changes in rainfall (amounts and patterns) for different management and soil types (White et al. 2011). These integrated responses are more difficult and expensive to assess through traditional field- or glasshouse-experimentation alone.

A recent yield impact assessment was performed using the APSIM model (Box 5.1) in New Zealand with NIWA's downscaled B1 (low) and A2 (high) climate scenarios (Chapter 2 and Box 5.2) for mid-point year 2040 (Teixeira & Brown 2012). Without considering any adaptation of management, the analysis suggests that yields of some crops such as forage kale, winter forages, temperate cereals including wheat (Figure 5.7b) and barley, would increase due to faster canopy expansion and photosynthesis rates stimulated by higher CO_2 and temperatures. In contrast, yields were maintained or slightly reduced for other crops such as field peas, potatoes (Figure 5.7d) and silage maize due to the shortening of the crop cycle overshadowing increases in canopy expansion and photosynthesis, particularly under the A2 climate scenario.

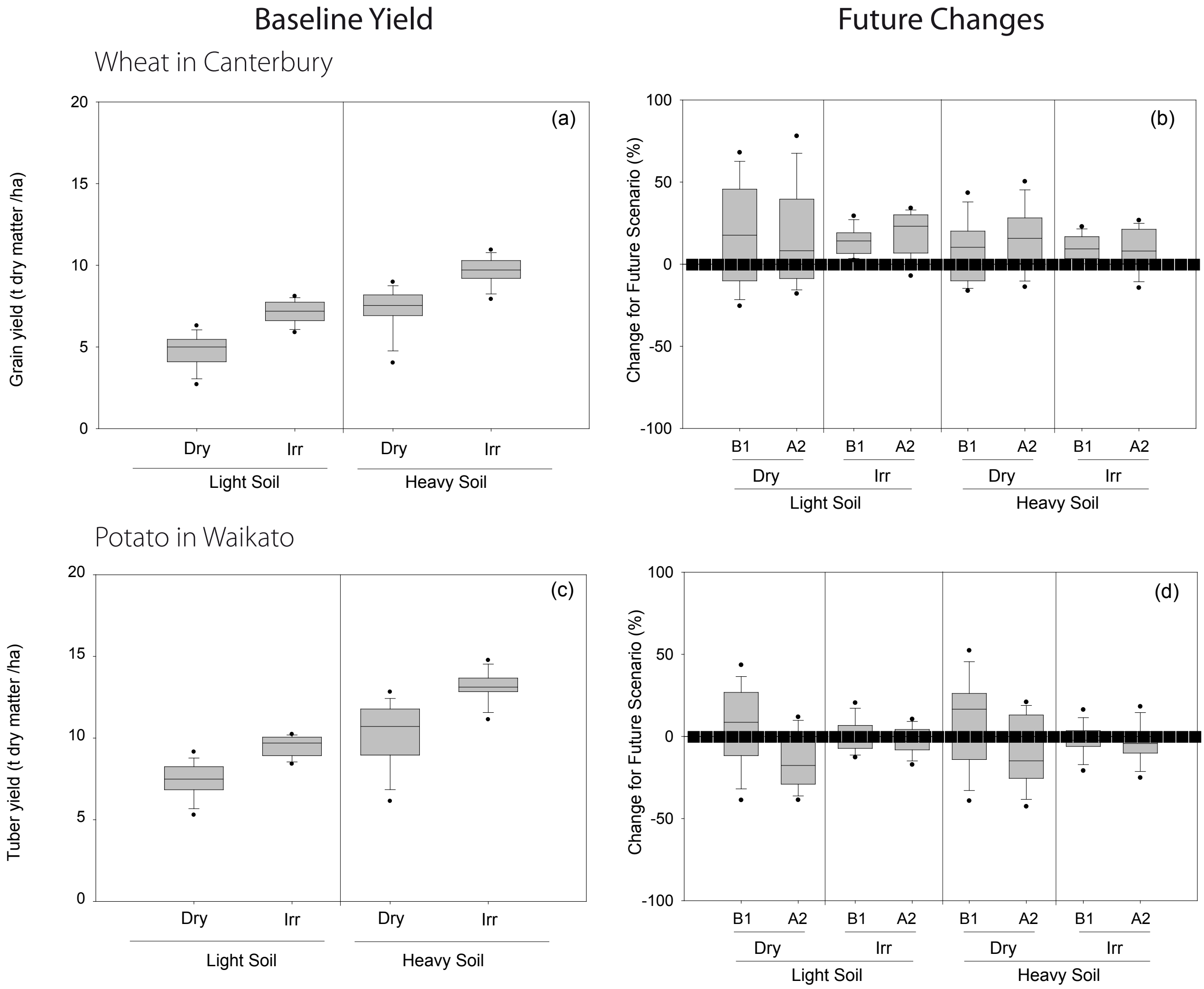

Figure 5.7. Baseline yields and projected future changes for the B1 and A2 climate change scenarios (2030–2049) considering dry-land (Dry) and Irrigated (Irr) conditions in two soil types (Box 5.2). (a, b) Maize in Canterbury. (c, d) Potato in Waikato. Adapted from (Teixeira & Brown 2012). The box line represents the 50th percentile, box boundaries indicate 25th and 75th percentiles, whiskers show the 5th and 95th percentiles and points show the maximum and minimum values.

The baseline results in these simulations highlight the importance of water supply as a major driver of yield responses both for wheat and potato (Figure 5.7a–c). Use of irrigation and heavier soils consistently increased yields and reduced yield variability by ensuring a more consistent supply of water during crop growth.

These results are in alignment with previous CLIMPACTS reports in New Zealand (Jamieson & Cloughley 1998) and projections for mid- to high-latitudes in the 4th Assessment Report (AR4) of the IPCC (IPCC 2007a). Specifically, in the IPCC AR4 report, crop yields in mid- to high-latitudes were projected to be maintained or to increase by 10% to 15% for a 1°C to 2°C increase due to CO_2 fertilization and less cold limitation. However, yield declines are expected above the 2°C to 3°C mean temperature increase that offsets CO_2 fertilization, particularly if no adaptation measures are implemented (IPCC 2007a).

4 Climate adaptation options for the cropping sector

Adaptation to climate change can generate benefits to the broad acre cropping sector either by reducing potential damage or harnessing opportunities. In general terms, the benefits of any adaptation technology can materialize through: increased resource capture (e.g., sunlight, water and nutrients); increased resource utilisation efficiency (i.e., more biomass produced per unit of water transpired or sunlight intercepted); an improved partitioning of photo-assimilates into the harvestable part of the crop; a reduction in yield losses due to stress factors (e.g., pest damage or extreme weather events).

Most of the literature reporting results which explore the effectiveness of individual adaptation options are specific to the location and crop studied. In this section, we identify potential adaptive options and the mechanisms underpinning their benefits for broad acre cropping systems. The objective is to apply these general principles to other sites and crops in New Zealand. We have split the adaptation options into tactical, strategic and transformational.

Table 5.2. Adaptation strategies identified for the broad acre cropping sector.

Tactical	*Strategic*	*Transformational*
• Change in crop calendars • Change in crop varieties • Use of conservation agriculture • Improvement in soil water and irrigation management • Improvement in soil nutrient management • Improvement in pest management	• Change in crop species • Develop new 'climate-resilient' genotypes • Use of precision agriculture • Monitoring and forecasting programmes • Irrigation development and expansion	• Develop new cropping systems • Development and adoption of innovative technologies • Change to alternative land uses

4.1 Tactical adaptation options

Tactical adaptations are mostly characterised by the use of already available best management practices that can be applied at low cost and in a short time frame. These are mostly management options that farmers already use to adapt to existing climate variability. Because farmers are adapting to year-to-year climate variability, these management strategies are expected to naturally occur in the short term with little policy or science intervention. This type of 'autonomous' adaptation is most effective at mild climatic changes when environmental variables are close to the range already experienced by broad acre farmers (Alexandrov et al. 2002).

4.1.1 Adapting cropping calendars

The decision 'when to sow' and the planning of 'when to harvest' a crop is one of the most flexible and inexpensive tactical adaptive measures frequently used by farmers. In New Zealand, warming due to climate change is likely to create a wider sowing window by removing cold temperature limitations to crop growth and development (Section 3.1). This creates an opportunity to further manipulate crop calendars to the extent allowed by other management and climatic constrains.

Several modelling studies, in diverse environments, have shown that the negative impacts of climate change on crop yield could be partially mitigated by simply changing sowing dates (Cuculeanu et al. 1999; Tubiello et al.

2000; Ghaffari et al. 2002; Meza & Silva 2009). For example, multi-model simulations in the southeastern part of the USA by Alexandrov & Hoogenboom (2000), showed that by sowing maize 10 to 50 days earlier than current calendars it was possible to increase yields by around 38% for dry-land conditions. Similarly in this study, by sowing winter wheat earlier in autumn it was possible to avoid warm temperatures during the critical period of grain formation and reduce yield losses due to heat stress (see Section 3.4.1).

In New Zealand, benefits of shifting sowing dates may vary largely with crop species. For example, yields of C_4 crops such as maize (grain and silage) and sweet corn were shown to increase at earlier sowing dates both in field experiments and simulation exercises (Wilson et al. 1994; Sorensen et al. 2000; Fletcher et al. 2011). At the moment, low soil temperatures (<12°C) during early spring delimit the start of maize sowing – from early September for Hawke's Bay to early November in Canterbury. In the future, this threshold is likely to be crossed earlier, enabling earlier sowing dates. Actual benefits depend on optimising the synchrony between canopy expansion and seasonal incident solar radiation, which may require the use of longer maturity hybrids (Fletcher et al. 2008).

The preceding discussion in this section is mostly relevant to the growth of individual crops. However, in New Zealand, the potential benefits of adapting crop calendars are better assessed for crop rotations instead of single crops only. The relocation of one crop in time influences the sowing period and performance of the following one. This is particularly important in intensive crop rotations with only short fallows, which is common practice in New Zealand (Section 2.2). For example, although the yield of silage maize crops is individually maximised with 'early spring' sowing dates (Teixeira et al. 2011a), the maximum productivity of a maize plus winter–cereal rotation is obtained at later sowing dates in 'early summer' (Fletcher et al. 2011). One of the main mechanisms driving this trade-off is the accumulated light interception by the whole cropping system. By matching peaks of canopy cover with periods of high incident solar radiation, farmers can optimise canopy photosynthesis either for single crops (Sorensen et al. 2000) or crop rotations (Densley et al. 2006).

Sowing dates also influence the availability of other resources such as water (from rainfall or soil storage) and minerals. For example, earlier wheat sowing dates in South Australia were shown to reduce climate change negative impacts only when crops had at least 25mm of stored soil water available at sowing (Luo et al. 2009). Soil moisture at sowing can be an important determinant of sowing dates that are delayed by either 'too dry' conditions that do not enable seed germination or 'too wet' conditions that compromise soil workability for machinery operation.

Using NIWA's RCM-based climate data projections (see Chapter 2 and Box 5.2), the effect of changing sowing dates is illustrated in a modelling study for summer kale crops grown in a light soil (Figure 5.8). The analysis show that a wide range of yields (between 2 and 13 t/ha) is observed when sowing kale crops in December, as historically done, for the A2 emission scenario in Canterbury. However, by delaying sowing until February, there was a large reduction in the inter-annual yield variability without reducing median values. This was explained by the shorter growing season for the February sowing (as kale was always harvested in July) that allowed avoidance of the driest period of the year. A February sowing could therefore be a suitable strategy for risk-averse pastoral farmers who are growing broad acre forage crops. Later discussed in Section 4.4 are the lack of response to a further delay in sowing dates until April and the use of different fallow periods shown in Figure 5.8.

Finally, the benefits of changing sowing dates should not be analysed in isolation but as part of a technological bundle to adapt to climate change (Fleischer et al. 2011). In fact, benefits are maximised when combining sowing dates with crop varieties (Section 4.1.2) and considering other factors such as the seasonality of pest pressure, machine availability for farm operations and differential market prices. There are climate/management trade-offs that limit the extent by which sowing dates can be changed. For example, the ability to harvest previous crops and to prepare fields on time; the need to sequence the management; the machinery availability to harvest a range of crops within a short time window; and the occurrence of water logging or water deficit can also restrict sowing and cultivation operations.

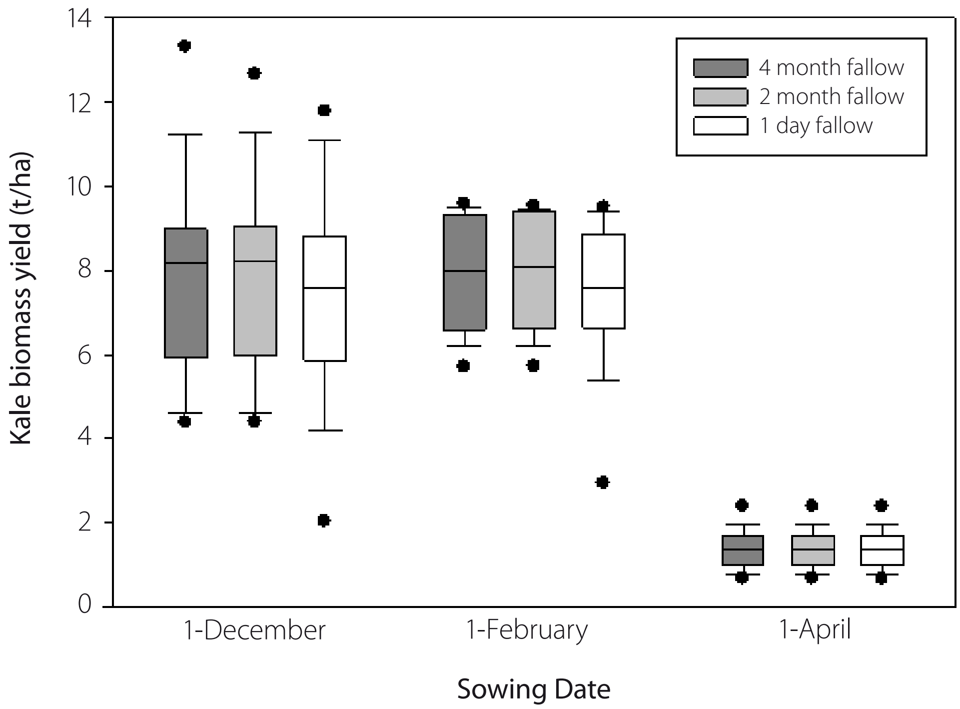

Figure 5.8. Simulated yields of dry-land kale grown on a silt loam soil in Canterbury using weather data from the A2 emissions scenario from 2030–2049. Yields were simulated for three sowing dates and three fallow treatments (4 months, 2 months and 1 day prior to planting) in each sowing date, respectively. The box line represents the 50th percentile, box boundaries indicate 25th and 75th percentiles, whiskers show the 5th and 95th percentiles and points show the maximum and minimum values.

4.1.2 Changing crop varieties

The possibility of choosing varieties with different responses to climate and sensitivities to biotic and abiotic stresses gives farmers flexibility to adapt to climate change tactically. For example, by using varieties with different maturity duration (i.e. thermal-time requirement to reach flowering, Section 3.1), farmers can manipulate the matching between phenological events and weather conditions. Such an approach is already used to adapt to current climate conditions. For example, maize growers in Canterbury use shorter maturity hybrids than in Waikato because growing seasons are shorter and cooler. Most of the differences between broad acre crop varieties in New Zealand are related to either change in phenology or pest/disease resistance.

Several modelling studies have shown that climate change impacts could be minimised by using alternative (currently available or hypothetically designed) crop varieties (Cuculeanu et al. 1999; Tubiello et al. 2000; Wang et al. 2011). For example, yield losses were reduced by using 'late-maturity' varieties of spring cereals such as barley in the Czech Republic (Trnka et al. 2004) and wheat in Italy (Tubiello et al. 2000) sown early in the season. In practice, producers often combine different varieties and sowing dates as a technological package for optimal matching between climate and phenological stages (see Section 4.1.1).By using late-maturity (long-cycle) varieties and sowing early in spring, farmers can extend the period by which the crop intercepts light and increase total net canopy photosynthesis. Alternatively, to avoid possible early autumn droughts, farmers can use early maturity (short-cycle) varieties that will be harvested before the period of water scarcity. Similar benefits can be envisioned for dry-land conditions in New Zealand if drought events become more frequent and intense.

The faster the pace of climate change, the more often growers will need to shift to 'better adapted' varieties. The consequence is, that to fully benefit from varietal choice farmers must have a wide range of crop genotypes available. To illustrate this, the APSIM model was used to classify a subset of 45 commercially available wheat varieties tested at The New Zealand Institute for Plant & Food Research (PFR) in relation to their sensitivity to photoperiod and vernalisation (Figure 5.9).

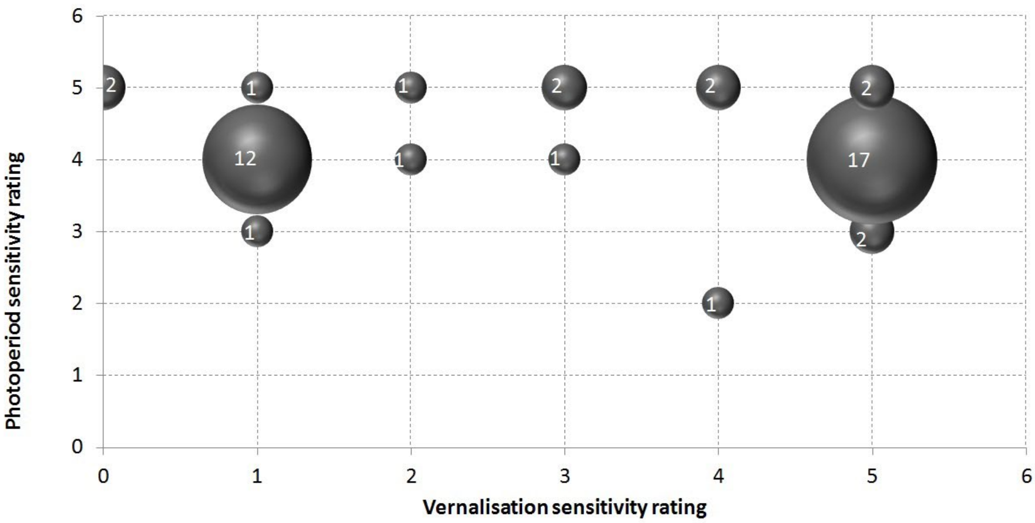

Figure 5.9. Distribution of 45 New Zealand wheat varieties in relation of their sensitivity to photoperiod and vernalisation ranging from 0 to 5 in the APSIM model parameterisation. Bubble size indicates the number of varieties within each vernalisation/photoperiod-sensitivity position (Brown 2011, pers. comm.).

The analysis highlights that although most genotypes have a similar high sensitivity to photoperiod (scoring ~4.0), there is a much wider range in sensitivity to low temperatures for vernalisation requirements (see Section 3.1.2). The potential impact of hypothetical varieties with nine contrasting photoperiod and vernalisation sensitivity combinations was evaluated in a simulation exercise (Figure 5.10) using the APSIM model (Box 5.1). The study considered autumn-sown wheat varieties grown in Canterbury from 2030–2049 with the high (A2) emissions scenario.

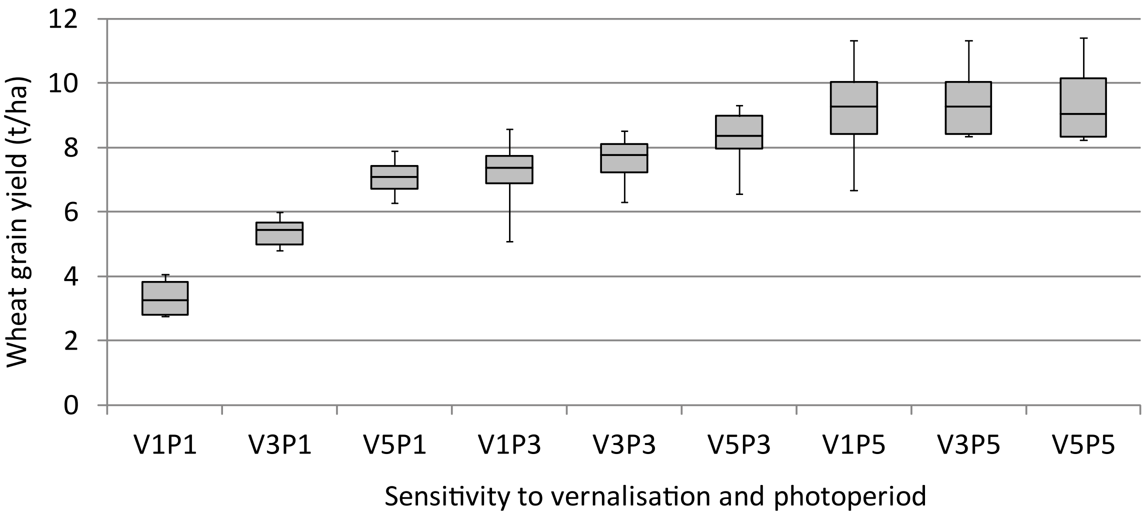

Figure 5.10. Grain yields for autumn sown wheat varieties with three vernalisation (V) and three photoperiod (P) sensitivity ratings (1, 3 or 5) used in the APSIM model parameterisation (Box 5.1). Simulations were done for Canterbury using the future scenario A2 (2030–2049). The box line represents the 50th percentile, box boundaries indicate 25th and 75th percentiles, whiskers show the 5th and 95th percentiles.

The analysis shows that genotypes with the highest photoperiod sensitivity gave higher yields regardless of vernalisation sensitivity. This was mainly due to longer growth cycles and radiation interception in highly sensitive varieties. It is important to consider what background genetic material might be useful for future breeding programmes. The above analysis showed higher photoperiod sensitivity and longer durations are needed for giving optimal yields under climate change. However, this analysis only considered material that is currently commercially available. Alternative materials, with even longer durations, might be suitable for improving yields further in the future.

A potential bottleneck for adaptation with new varieties is the long time required to breed these new genotypes. For example, a new wheat variety takes at least 8 to 10 years to be released after the first crosses (PFR breeders 2012, pers. comm.). This means that crosses made now may not be optimum for the climate in which the variety is to be used unless these can be anticipated.

4.1.3 Conservation agriculture

Conservation agriculture (CA) refers to agronomic practices that increase soil cover by leaving previous season's crop residue (e.g., reduced tillage operations). Conservation agriculture techniques are often identified as adaptive options able to increase the resilience of arable systems to climate change (Farkas et al. 2009; Hobbs & Govaerts 2010; Verhulst et al. 2011). By minimising or eliminating the use of conventional tillage (e.g., ploughing and harrowing) it is possible to increase soil water retention, and the carbon (C) and nitrogen (N) content of soils (Delgado et al. 2011; Lal et al. 2011). This increase in soil quality reduces the risk and intensity of water stress in a warmer and drier climate. In a wetter climate, CA practices can minimise water logging, nutrient leaching and erosion through better soil cover and structure. Specifically, increased soil cover and reduced soil disturbance are able to: reduce soil evaporation and water run-off; increase soil water retention due to higher organic matter contents; reduce wind-induced soil erosion and soil structural breakdown caused by raindrop impact; increase water infiltration rates due to improved soil structure; suppress weed competition by blocking radiation incidence on bare soil that otherwise would enable germination of competing species (Farkas et al. 2009; Hobbs & Govaerts 2010; Lal et al. 2011; Verhulst et al. 2011). Additional indirect benefits of CA are a reduction in energy use due to fewer machinery operations, and prospects of earlier planting due to faster operations. In New Zealand, machinery and techniques for reduced tillage and no-till agriculture have long been available (Choudhary & Baker 1993).

The benefits, risks and costs of conversion from conventional practices to CA ones have to be analysed within a cropping systems context. For example, in some specific conditions conversion to no-till can reduce achieved yields (Toliver et al. 2012). To maximise the benefits of CA as an adaptation measure to climate change, aspects such as initial investments, terrain slopes for machinery operation, machinery availability and pest pressure must be taken into account. Conventional tillage may be a necessary measure to strategically break the cycle of pests or high infestation of specific weeds. Risks of CA include increasing dependency on herbicide applications for weed control and associated costs at farm level (Morris et al. 2010). In addition, soils under CA typically warm up and dry out slower than tilled soils, and hence, crop germination and seedling establishment can be delayed. Populations of grazing pests can also build up under CA increasing the risk of poor and failed crop establishment. The occurrence of compacted soil layers and drainage problems should be evaluated and corrected before the implementation of CA programmes.

4.1.4 Improving management of soil nutrients

Climate change is likely to affect plant demand and soil supply of mineral nutrients by influencing soil processes that respond to temperature and soil water (e.g., N mineralisation and fixation). The 'CO_2-fertilization' effect and higher temperatures in New Zealand will potentially increase nutrient demand and the need for fertiliser input, particularly of N, to sustain higher potential yields (Section 3.3) and crop quality (Section 3.7). This additional demand for N has both economic implications (increased production costs and risks due to volatile fertiliser prices) and additional environmental footprint. Soil nutrient supply may be either increased by faster carbon and nitrogen cycles under higher temperature or reduced by drier conditions with over-depleted soils.

Changes in the amounts, type and timing of nutrient application can help adaptation to climatic changes by increasing nutrient use efficiency through 'tighter' nutrient cycles (Delgado et al. 2011). For example, the combined use of seasonal forecasting (Section 4.2.4) and variable rate technology (VRT; Section 4.2.3) could enable more efficient application of lime, phosphorous, potash and nitrogen according to plant demand and soil supply– when assessed on a temporal and spatial scale.

The use of cover crops and the cycling of crop residues (see Section 4.1.3) helps to minimise the demand for synthetic fertiliser. Nitrogen fixing species could be more frequently included in arable crop rotations as alternative break crops. Possible options include forage crops (e.g., lucerne) or protein rich grain crops (e.g., faba beans and lupins) that are already acclimatised to New Zealand conditions. The economic viability of new leguminous species to be included in New Zealand crop rotations will depend on market demand (e.g., faba beans' use in the poultry industry), competitiveness with imported options (e.g., soybeans), pest management strategies and impact on the flexibility of crop rotations (e.g., long-term lucerne stands).

4.1.5 Improving soil water and irrigation management

With climate change, more frequent drought events are projected for important arable cropping regions (see Chapter 2), particularly New Zealand's East Coast (Reisinger et al. 2010). An increase in rainfall variability implies that water shortages in the driest seasons will be greater and yields poorer than at present, increasing the risk of crop failure. Adaptation measures should be tailored to minimise drought impacts and also exploit the potential of wet seasons for dry-land and irrigated systems.

4.1.5.1 Dry-land arable systems

Water demand changes seasonally with canopy development (Section 2.2.2) and with atmospheric conditions such as temperature and vapour pressure deficit (Section 2.2). This implies that farmers can manipulate water demand by changing sowing dates and crop varieties (Sections 3.1.1 and 3.1.2). For example, more efficient use of water and lower risk of drought stress can be achieved by allocating the growth period during cooler and wetter periods of the year, when water use efficiency is inherently higher due to low atmospheric demand. However, potential crop growth is limited during this period because incident radiation is lower. These trade-offs are illustrated in a simulation (Figure 5.11) with barley crops for the 'high' A2 climate scenario (see Chapter 2 for details) using the APSIM (Box 5.1) model. In New Zealand, barley crops are typically sown in October (late spring). The analysis shows that by the middle year 2040, the use of earlier sowing dates in August increased the mean yield by around 35% and largely reduced the inter-annual variability. This provides a more productive and less risky cropping option. By moving to an autumn sowing in May, there was an additional (~20%) increase in mean yields – but this was at a cost of increased inter-annual variability. While the lowest annual yields for the May sowing were similar to the August sowing ones, the highest yields were substantially better, surpassing 7 t/ha. These benefits occurred because by moving to an autumn sowing, the potential duration of crop cycle was extended due to the lower temperatures (Section 3.1) making the cycle more capable of exploiting higher rainfall supplies in the wet years. These benefits have to be considered in the context of crop rotations because an early-autumn barley sowing would compromise the available time window to grow winter forages. The net economic return of this system depends on the additional income from extra barley production in relation to costs with machinery operation and crop husbandry for an early sowing.

Another prospect for adapting dry-land systems to climate change is to make more efficient use of rainfall. Yield gains can be achieved either by improving rainfall capture and storage, and/or by better converting rainfall into biomass. Higher CO_2 levels improve transpiration efficiency (Section 3.3) and crops with deeper root systems are better able to extract rainfall stored deep in the soil for producing yield. Changing crop variety or type offers possibilities of improving the utilisation of rainfall (and this is covered in Sections 4.1.2 and 4.2.1). Improved residue and tillage management can improve soil structure for better moisture infiltration and water holding capacity of soils (Section 4.1.3). Care must be taken not to consider these options in isolation but instead to consider the trade-offs among climatic and management factors – as illustrated in a simulation exercise in Section 4.4.

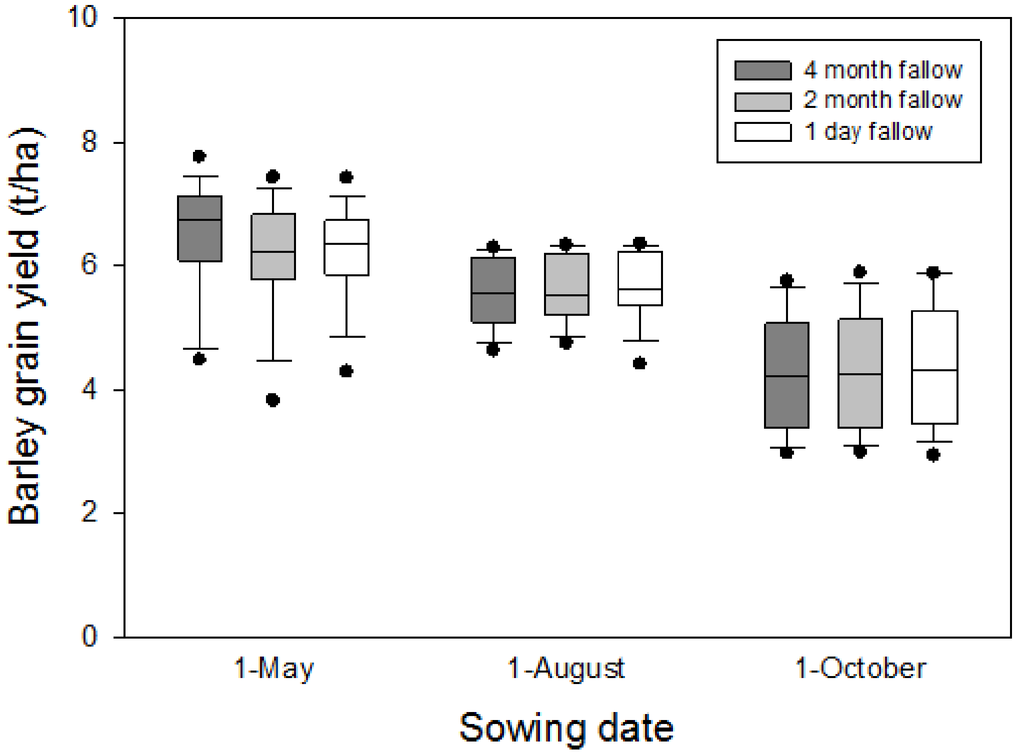

Figure 5.11. Simulated grain yields of dry land barley grown on a silt loam soil near Canterbury using weather data from the A2 emissions scenario from 2030–2049 considering three sowing dates and three fallow treatments (4 months, 2 months and 1 day prior to planting). The box line represents the 50th percentile, box boundaries indicate 25th and 75th percentiles, whiskers show the 5th and 95th percentiles and points show the maximum and minimum values.

4.1.5.2 Irrigated arable systems

The uncertainty and limits imposed by seasonal rainfall can be largely buffered with irrigation. In this sense, the provision of additional irrigation water would be a useful strategy to adapt to climate change by increasing yield and reducing its variability. However, the effectiveness of irrigation at offsetting water stress limitations depends on the size of the rainfall deficit (which varies from year to year), the water holding capacity of the soil, the timing of crop water demands, the amount and cost of available irrigation water and the efficiency with which it can be applied. Irrigation resources may be already reaching overallocation in some New Zealand regions (Chapter 8). Pressure to share this water fairly and reduce the environmental impacts of irrigation means water allocations may decrease in the future. Higher evaporative demand due to warmer temperatures (Section 3.2) and competing urban water use is expected to further increase pressure on water resources (Chapter 8). Improving the efficiency of irrigation utilisation will be an important means of adapting to climate change.

A simulation with the APSIM model (Box 5.1) was set to assess the benefits of irrigation for different crop species, irrigation systems, soil types and hypothetical limits of water allocation (Figure 5.12). A crop rotation was simulated for Canterbury in the 2030–2049 period using the A2 climate scenario and assuming increasing future irrigation allowances (see Box 5.3, and Chapter 2 for details). The analysis shows that different crop species responded differently to irrigation allowances. Summer-sown kale was the most responsive crop because water demand is highest at this time, in comparison with wheat and barley which have most of their growth occurring in cooler periods of autumn and spring. Barley was less responsive than wheat due to its shorter growth duration and consequent lower water demand. The least responsive crop was autumn-sown forage that grew most of the time during the cooler and wetter period of the year.

The provision of irrigation allowances increased the long-term yield and reduced variability for most crop types (Figure 5.12). However, the response to water allowance depended on the efficiency of the irrigator type (centre-pivot or roto-rainer). For example, for the less efficient roto-rainer irrigator, wheat yields started to decline fast at a 400mm irrigation allowance while this was only evident at less than 300mm for the more efficient centre-pivot. Centre-pivot consistently gave higher yields than the roto-rainer because it allows more frequent irrigation at lower rates and minimises the intensity and frequency of plant water stress and water losses by drainage.

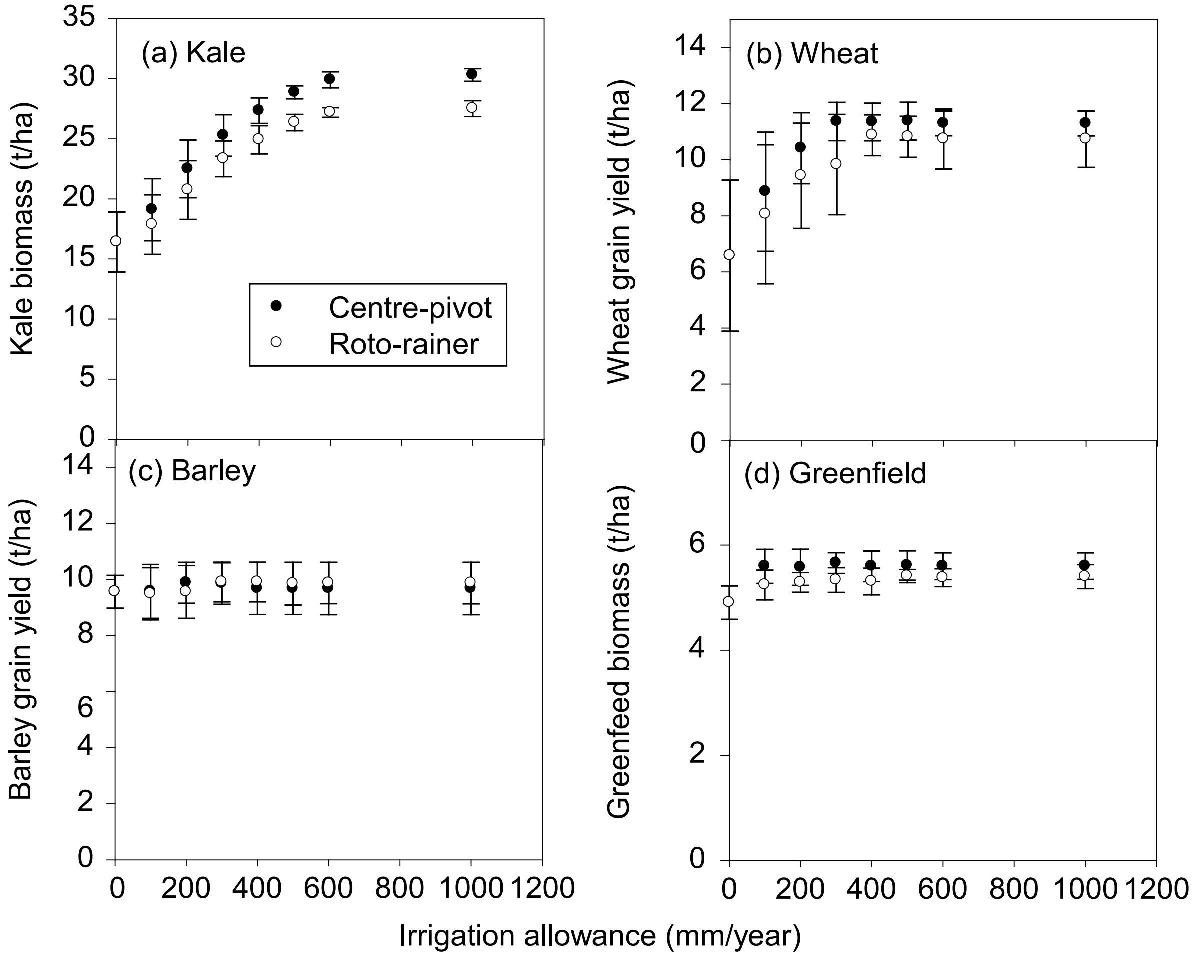

Figure 5.12. Simulated yields of four crops grown in a rotation in Canterbury assuming contrasting maximum annual irrigation allowances from 0 to 1000 mm, two irrigation systems (centre-pivot and roto-rainer) for the A2 emissions scenario from 2030–2049. Errors bars delimit the 25th and 75th percentiles of 20-year simulations. Crops are (a) Kale, (b) Wheat, (c) Barley, and (d) Greenfield.

Soil type also had a large impact on the response to irrigation allowances and systems (Figure 5.13). The kale yield on a heavy soil was nearly double that of a light soil under low irrigation allowances (<200 mm) using a roto-rainer. The yield advantage achieved from having heavy soils was greater for roto-rainer systems than centre pivot ones because application amount and timing of centre pivot systems could be better tuned to light soils. This difference between center-pivot and roto-rainer systems was more evident at low irrigation allowances (Figure 5.13).

The additional water storage capacity of heavy soils was increasingly important at lower irrigation allowances and with irrigation systems of limited efficiency.

Total amounts of applied irrigation water were similar between central pivot and roto-rainer systems on the heavy soil type, but consistently less water was applied by the central pivot in the light soil (Figure 5.14). These results reinforce the benefits of more efficient irrigation systems particularly for light soils.

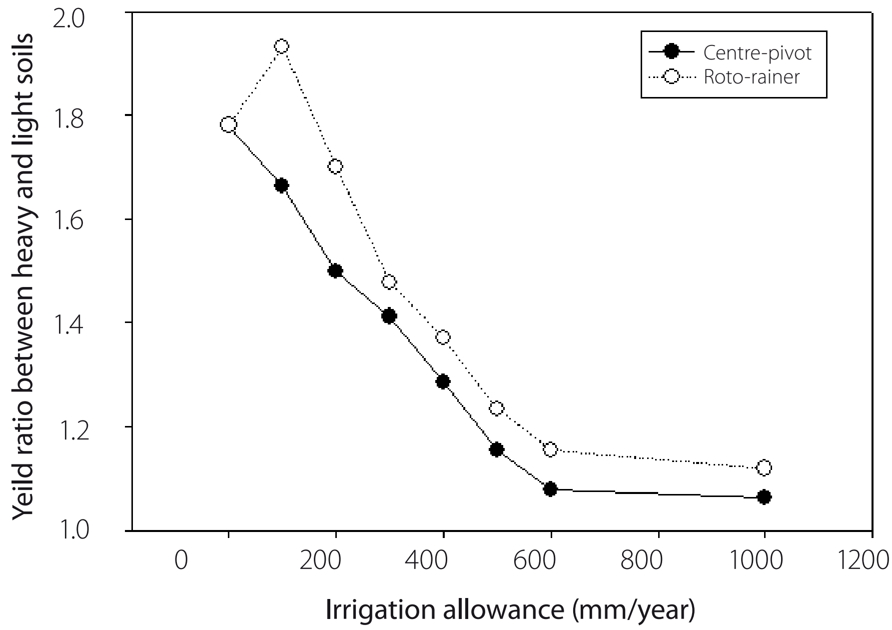

Figure 5.13. Relative increase in yield for kale crops when grown in a heavy soil type (288mm of available soil water) in relation to a light soil (93mm of available soil water) for irrigation allowances from 0 to 1000 mm/year.

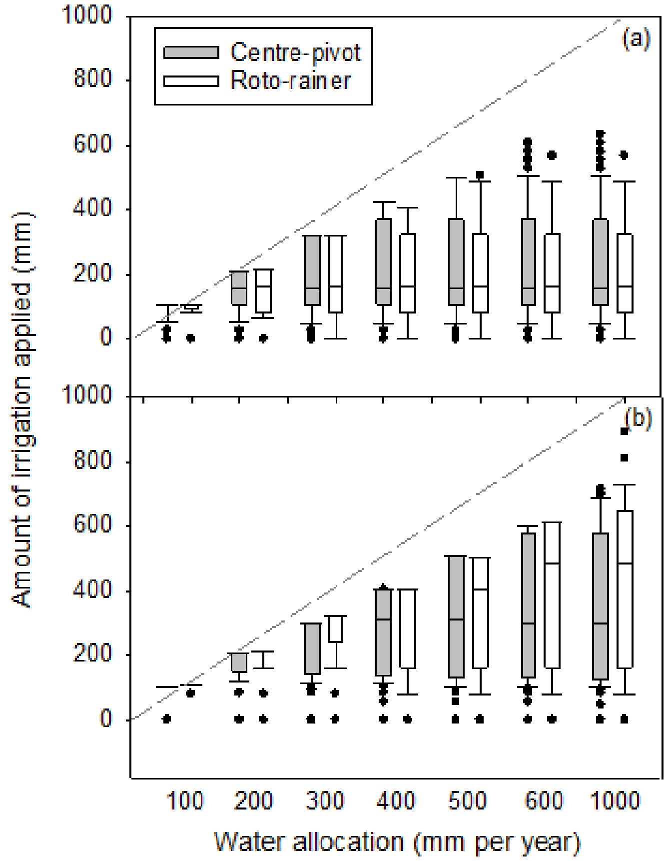

Figure 5.14. Simulated annual irrigation amounts applied to crop rotations in Canterbury for irrigation allowances from 100–1000 mm per year for two irrigation systems (centre-pivot and roto-rainer) using weather data from the A2 emissions scenario from 2030–2049. The dashed line indicates a 1:1 relationship. (a) Heavy soil and (b) Light soil. The box line represents the 50th percentile, box boundaries indicate 25th and 75th percentiles, whiskers show the 5th and 95th percentiles and points show outliers.

Box 5.3. Simulating crop yield for different irrigation allowances, soils and irrigator types.

A rotation of winter-sown wheat » autumn-sown cereal forage » spring-sown kale » spring-sown barley was used as the basis of these simulations. Provision of adequate nitrogen was assumed. Weather data was used from the A2 scenario (see Chapter 2). Simulations were run from 2030–2049 and replicated three times with each model run being offset by one year, so each crop in the rotation was present in each of the 20 years of sampled weather. This 'in-silico' experiment with the APSIM model (Box 5.1) used a factorial combination of soil type (288 and 93 mm available water capacity), irrigator type (centre-pivot and roto-rainer) and annual irrigation allocation (0, 100, 200, 300, 400, 500, 600 and 1000 mm/ha). The two irrigator types have differing efficiency (65% and 90% of applied water retained in the soil). The centre-pivot was also able to apply water at a variable frequency to maintain soil water content above specific trigger levels where as the roto-rainer was only able to apply water at a 10-day frequency.

These results highlight the potential benefits of upgrading and expanding irrigation systems to sustain arable crop yields under climate change. Important consideration has to be made regarding regulatory policies and use of management practices to minimise potential environmental impacts such as from nutrient losses to ground water (e.g., nitrogen leaching)

4.1.6 Improved pest management

Climate change is expected to influence the development, distribution and (consequently) the infestation pressure of weeds, insects and diseases on arable crops (Section 3.5). Although quantitative understanding of the effects of climate change on pest pressure is very limited due to the difficulties in aggregating and generalising isolated impact observations (Ziska et al. 2011), recent reviews consistently highlight the importance of adapting pest management techniques to increase resilience against climate change impacts (Ladanyi & Horvath 2010; Juroszek & von Tiedemann 2011; Sutherst et al. 2011).

The most frequently suggested adaptive options reinforce the principles developed for integrated pest management (IPM) programmes (Kogan 1998). IPM is an approach to pest control that aims to maximise 'lower cost' ecosystem services while minimising unnecessary and 'more costly' pesticide use. This is done by combining biological (natural predators and parasites), chemical (selective pesticides) and cultural controls in an integrated way. Several studies identify potential adaptive options for improving biotic control in response to climate change (Boote et al. 1983; Chakraborty & Datta 2003; Hayman & Sadras 2006; Duveiller et al. 2007; Howden et al. 2007; Gerard et al. 2010) which include:

- strategic use of biotic or chemical pest control
- changing to, or developing, more pest-resistant varieties or species
- diversifying crop rotations to break pest cycle
- changing sowing and harvesting time to avoid period of highest pest pressure
- managing irrigation to avoid creating micro-climate for pest development
- maintaining suitable habitat and corridors for natural enemies
- improving pest monitoring, early warning and predictive systems
- adapting cultivation and residue management techniques

The strong climatic influence on pest population dynamics and impact (Section 3.5) implies that early-warning and modelling tools can be used to anticipate and plan the level of intervention. The management of pests is a dynamic process of decision making based on the past history of the crop involved, seasonal climate, and prospective economic returns (Sutherst et al. 2011). A key component for the implementation of successful adaptive options is the maintenance of ongoing 'monitoring and evaluation' of populations and geographic distributions of vectors, pests, and hosts (Sutherst et al. 2011). This can be improved by the use and development of simulation models to predict geographical distribution, seasonal phenology and population dynamics of pests at a range of spatial and temporal scales. Initial progress has been made by using pest distribution models such as CLIMEX (Sutherst et al. 1999) to identify global regions with greater potential to be sources of insect invasion to New Zealand due to climatic similarities (Peacock & Worner 2006); and to categorise potential invading species and their geographical range of dispersion (Kean 2009). For example, lowland and montane regions in the South Island of New Zealand were found to be the most susceptible to the invasion of the weed hawthorn (*Crataegus monogyna*), a shrub originally native to Europe.

However, to predict pest damage to crops, and risk of pest outbreaks realistically – and to plan optimum timing and intensity of interventions – it is necessary to develop linked pest-crop models (Boote et al. 1983). The diversity of pests, their complex interaction with crops (and other species) and their simultaneous response to climatic drivers makes it impossible to design global or national strategies of pest control, given the variability and spatial heterogeneity of climatic changes (Sutherst et al. 2011). Therefore, spatial heterogeneity in climate and management aspects must be considered. For example, Duveiller et al. (2007) have suggested that conservation agriculture (CA), which is also an adaptive option to climate change (Section 4.1.3), may create more favourable micro-climatic conditions for the development of residue-borne necrotic pathogens (e.g., tan spot or septorias) or head blight in wheat. Adaptive measures should take in consideration the development of resistance to synthetic chemicals and crop defence mechanisms to avoid maladaptation.

4.2 Strategic adaptation options

Strategic adaptation options require additional investment and use of technologies already available but not yet incorporated into most production systems. Benefits occur in the mid-term and risks are greater than for tactical options. Such adaptive options are expected to be most effective at higher levels of climate change.

4.2.1 Changing crop species

Changing crop species can be seen either as a 'tactical' or 'strategic' adaptation depending on the costs and risks involved to incorporate a given new species into the crop rotation system. Changing to already locally available crops is a 'tactical' adaptation often applied by New Zealand broad acre farmers to minimise market and pest outbreak risks. The same method can be used to adapt to climate change by diversifying the crop mix either 'tactically' from currently (easily) available species or 'strategically' by bringing new species from other regions or from abroad.

Changing to an alternative crop species has agronomic and market consequences. While it enables farmers to diversify commercialised products, it also may demand new infrastructure to process and commercialize alternative products. For example, as temperature increases due to climate change, tropical species such as maize can potentially migrate further south in New Zealand gaining competitive advantage over temperate species such wheat and barley. Currently, silage maize is the most productive forage option in crop rotations both in the South and North Island (de Ruiter et al. 2009a; de Ruiter et al. 2010). However, although earlier maize harvests at silage stage are feasible, the short growth season in the South Island restricts later harvests for grain production (Wilson et al. 1994). With longer growth seasons and reduced risk of frosts, maize crops may be a new economically viable crop species for both silage and grain production at higher latitudes in New Zealand. Similar potential was identified for growing sweet corn in Canterbury (Wilson & Salinger 1994). A simulation exercise using the APSIM model (Box 5.1) tested the potential benefits of growing silage maize in Southland in the 'middle year' 2040 considering the A2 climate scenario (Figure 5.15).

The analysis results suggest that not only the yield (Figure 5.15a) but also the quality (Figure 5.15b) of maize silage may be improved in Southland by the middle year 2040. Longer growth cycles also enabled an increase in the grain fraction of silage. Therefore, a warmer climate in Southland by the middle year 2040 would potentially enable higher yields with better quality silage (higher energy and lower moisture content).

In addition, other tropical and subtropical crop species such as rice and soybean, previously not adapted to the cool temperate climate of New Zealand, may become economically viable with global warming. This may be particularly true in the warmer climate of the northern regions if investments in new infrastructure are justifiable. To adapt to increasing drought in the East Coast of New Zealand, crops such as sorghum (e.g., Mutava et al. 2011) which are more resilient to water stress could be used either as forage or as grain.

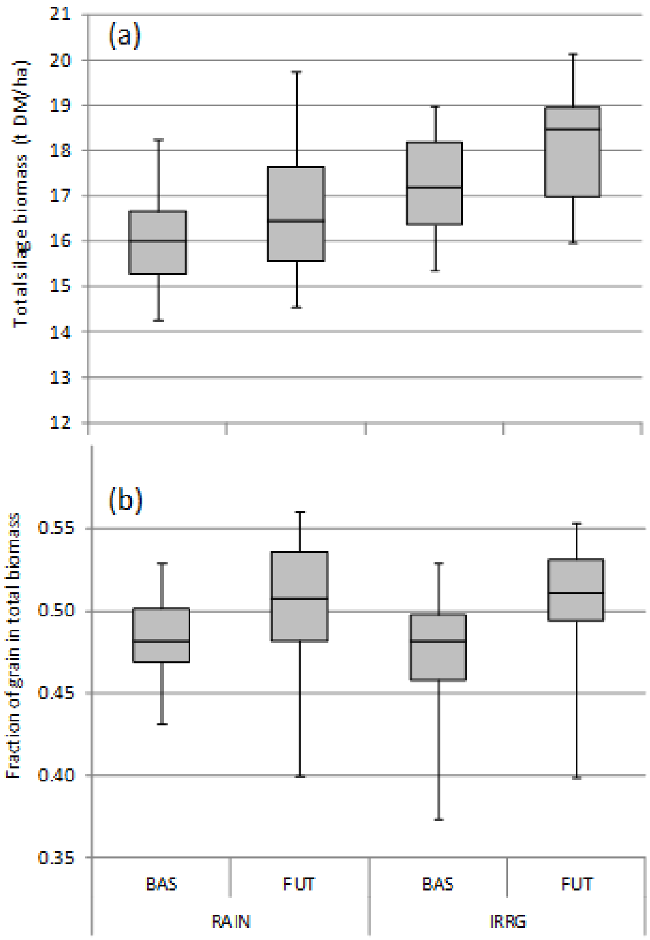

Figure 5.15. Silage maize simulation with APSIM (Box 5.1) in Southland for a base (BAS, 1980–1999) and future (FUT, 2030–2049) climate assuming the A2 climate scenario under rain-fed (RAIN) and irrigated (IRRG) conditions. (a) Total yield. (b) Quality (fraction of grain in total biomass. The box line represents the 50th percentile, box boundaries indicate 25th and 75th percentiles, whiskers show the 5th and 95th percentiles.

As the climate becomes suitable to new crop species in New Zealand, market and risk assessments must be taken in consideration to evaluate economic viability before the implementation of new industries (Howden et al. 2010a). Many of these changes are, therefore, likely to be demand-driven by the market, rather than supply-driven by the grower. The effectiveness of changing species must also be evaluated considering the likely southern migration of weeds, insects and diseases previously constrained by cold temperatures (Section 3.5).

4.2.2 Developing resilient genotypes

Most commercial genotypes currently used in broad acre cropping have been developed and selected for a relatively stable climate during the past century. New varieties will need to adapt to new climates at a much faster pace. This means that, instead of only selecting from already available varieties (Section 4.1.2), it will be necessary to develop new genotypes with agronomic traits that enable a maintaining or increasing yield and quality in the future climate.

The genetic improvement in yield of cereal varieties since the 1960's green-revolution can be largely attributed to the increase in harvest index (HI; i.e., fraction of biomass allocated to harvested organs) and pest resistance (Messina et al. 2011). However, physiological limits may have been reached in many crops for further increases in HI (Hay 1995; Sinclair 1998). Future yield gains may require increases in potential biomass accumulation, through faster canopy development or photosynthetic rates. Simultaneously, these genotypes will need to adapt to the different pest pressures (Section 3.5) and to a higher magnitude and frequency of high temperatures (Section 3.1) and drought (Section 3.2) imposed by climate change.

This demand for adapting to multiple stresses and a fast-changing environment imposes a challenge to conventional breeding. A possible adaptation measure to speed the rate of development of new genotypes is to combine techniques of genome sequencing, quantitative genetics and bioinformatics. In conjunction with crop simulation modelling, these can help determine the plant traits required for future climates (Semenov & Halford 2009). The use of genetic modification (GM) can be another technological option to shorten the time to develop more resilient crop varieties, for example with specific pest resistance (Bruce 2012). However, this is provided that the technology is proven safe, gains widespread acceptance and provides clear economic benefits for New Zealand (Saunders et al. 2003).

Some of the traits most frequently considered as advantageous to adapt to climate change (e.g., Ceccarelli et al. 2010) include:

- different maturity characteristics (e.g., thermal-time sum to reach flowering)
- different maturity responses to photoperiod and vernalisation
- resilience against high temperatures (including heat stress events)
- resilience to drought stress
- pest and disease resistance
- higher resource use efficiency for water and nitrogen
- higher harvest index
- altered quality aspects (e.g., nitrogen partitioning to grains, and drying characteristics).

It is uncertain how effective breeding for multiple stresses can be, given the complexity of traits and the interaction between genotype and environment (Araus et al. 2008; Chenu et al. 2009; Habash et al. 2009; Slafer 2010). Crop traits such deeper and more abundant root systems might have a yield advantage in one environment but a yield penalty in another. Most plant traits for conferring different aspects of drought tolerance have a dual effect; positive in very severe drought conditions and negative under milder stress levels, or vice-versa (Tardieu 2011). The relative change of individual traits is also not directly translated to yield benefits once scaled up to the crop level (Sinclair et al. 2004). For example, these authors infer that by enhancing leaf concentration of the enzyme Rubisco (Section 3.3.1) by 50%, crop yields would only increase by 6%. Thus, the likely benefit of any isolated new trait for future climate needs to be objectively evaluated at the scale of field production.

Genetic diversity is an essential building block for developing crop varieties adapted to future climates. To ensure resilience against an uncertain future climate it is important to preserve crop diversity by maintaining and enhancing seed-banks.

4.2.3 Increasing use of precision agriculture techniques

Precision agriculture (PA) encompasses a variety of technological options to optimise resource use efficiency, profitability and sustainability of farming systems. This is commonly achieved by using detailed spatial data collected from within farm fields (e.g., yield and soil fertility) to improve decision making. A combination of technologies can be used for this purpose including: global position systems (GPS); aircraft or satellite remote-sensing data collection; automated yield monitoring at harvest; and crop and soil sensing technologies (e.g., infrared spectrometry, soil inductance metering and leaf-chlorophyll metering). Based on spatially explicit information, spot-specific farm operations such as fertiliser and pesticide application can be done using variable rate technology (VRT) to deliver profit-maximising application rates and minimise environmental impacts (Robertson et al. 2009; Pinaki et al. 2011).

Practical examples of the role of PA in helping farmers adapt to future climate change scenarios include: VRT irrigation approaches to reduce water wastage in environments that may have less allocable water; VRT fertiliser approaches to reduce over application and potential nutrient losses in heavy rainfall environments; auto-steer/GPS technologies to confine soil compaction to smaller zones in environments that may have more frequent and heavier rainfall events (so less energy is subsequently required to cultivate soils; precision drilling techniques to improve the physical condition of the soil, making it more resilient to heavy rainfall events and wind erosion (and less cultivation also reduces moisture loss from the soil, reducing the risk of drought in drier areas); and precision contouring and levelling technologies improve soil drainage in wetter environments, reducing the likelihood of crop losses related to surface pounding.

4.2.4 Implementing monitoring and forecasting programmes

It is possible to adapt to increasing climate variability by more frequently and accurately monitoring different aspects of broad acre cropping systems. The value of improved weather and seasonal climate forecasts was identified for short-term tactical and medium- to long-term strategic decisions for both intensive (Calanca et al. 2011) and low input cropping systems (Patt et al. 2005). The relationship between major climatic events and inter-seasonal climate variability suggests that seasonal forecasting and early-warning systems can be implemented as a tool for better decision making. For example, the El Niño–Southern Oscillation (ENSO) was shown to be related to variability of rainfall (Zheng & Frederiksen 2006) and temperature (Zheng & Renwick 2003) in New Zealand. Better seasonal rainfall forecasts could potentially improve decision making on how much crop to grow and additional feed to buy and reduce production risks. For example, projection of annual rainfall was shown to be a key predictor of silage yield for dry-land maize in the North Island of New Zealand (Teixeira et al. 2011a).

An example of monitoring programmes that can benefit adaptation to climate change relate to soil moisture. In-farm soil moisture readings, done within stationary farm probing or frequent visits by specialised consultants, can improve irrigation efficiency by rationalisation of irrigation (Section 4.2.5). Irrigation scheduling can optimise the temporal match between plant demand and soil water supply, reducing water consumption, energy use and optimising fertiliser application and pest control programmes. Many of the leading farmers in the irrigated areas of New Zealand are already using widespread soil moisture monitoring to schedule irrigation and development and uptake of this technology is likely to provide additional resilience to climate variability. In addition, the use of decision supporting tools to better schedule irrigation application such as Aquatrac™ (Brown et al. 2010) in New Zealand and FAO's Aquacrop (Steduto et al. 2009) can support better irrigation scheduling.

4.2.5 Expanding and improving access to irrigation

The uncertainty concerning future rainfall variability and frequency of drought from climate change is a main risk component for broad acre cropping (Chapter 8). The potential of irrigation systems to increase resilience to these factors has been identified as a key adaptive measure for different regions and broad acre crops (Travasso et al. 2009, Tubiello et al. 2000, van der Velde et al. 2010).

In addition to 'tactical' improvements in water management (Section 4.1.5), 'strategic' adaptive options such as the development of irrigation schemes in areas currently not irrigated in New Zealand would allow farmers to minimise drought severity and the potential increase in rainfall variability due to climate change. In 2006, around 976,000 ha were under irrigation in New Zealand, with more than 65% of that in the Canterbury plains (Ministry for the Environment 2006).

The overall benefits of expanding irrigation potential areas are illustrated in Figure 5.16. Pooled yield gains, simulated with the APSIM model (Box 5.1), for several typical crop rotations were projected to increase from 5% in heavy soils of Southland to nearly 60% in light soils of Canterbury.

The potential for irrigation expansion can be exemplified by the Canterbury region, where less than half of the ~1.2 million hectares potentially suitable for irrigation were actually developed in 2008 (Bright 2008). Naturally, this potential expansion has to be analysed considering the long-term preservation of ecosystems services, economic viability and sustainability of rural and urban activities which depend on common and limited water resources, to be regulated by water allocation policies (see simulation study in Figure 5.12). Irrigation allocations from new irrigation sources will be carefully calculated for the specific location and operation assuming high utilisation efficiency. This will make it necessary to install on-farm equipment capable of applying water more evenly and efficiently (such as centre-pivots) to ensure high production can be achieved with capped allocations (Section 4.1.5.2).

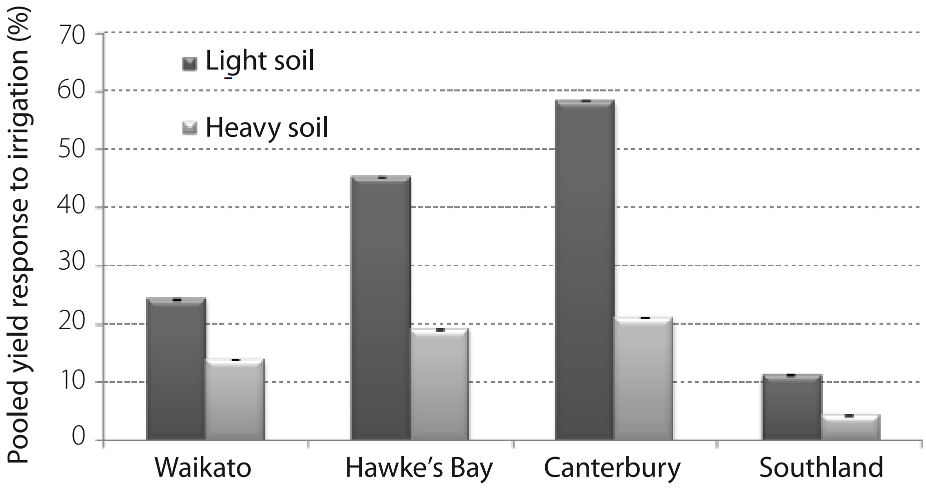

Figure 5.16. Average yield increase in yield due to the use of irrigation for crop mixes in four New Zealand arable crop regions in light and heavy soil types pooled for the baseline and future climates used in APSIM simulations (Box 5.2).

4.3 Transformational adaptation options

Transformational adaptation options, characterised by greater risk and longer-term investments and returns, are required when ecological, economic or social conditions become untenable (Park et al. 2012). They are likely to occur in response to intense changes. Implementation of these options may require large-scale investment in research and infrastructure or demand considerable structural changes in agricultural production systems.

4.3.1 Designing new broad acre cropping systems

The design of new broad acre cropping systems may be necessary to adapt to new climatic conditions and exploit new market opportunities. Global changes in population, consumer quality standards, eating habits and purchasing power, particularly in large emerging import markets such as China and India, may require strategic restructuring of the New Zealand arable industry (FAR 2011b). Under such a scenario, demand may drive the arable industry to produce a wider range or different types of grain or enhance the forage components of rotation mixes to supply more intense livestock production. Alternatively, a more 'environment-conscious' humanity may demand more vegetarian diets and production systems with fewer inputs. This range of possibilities is in alignment with the rationale used to build the emission scenarios used in Chapter 2 and also with the new scenarios for future IPCC assessment reports (Moss et al. 2010). Possible 'bottom-up' drivers of change in broad acre industry would be the changes in New Zealand population ethnicity that are likely to influence eating habits and the demand for specific types of foods. Emerging niche markets, for example, small grain cereals in Asian nations, may create an opportunity for high specialisation of industry to attend quality demands. Pressure for changing crops grown and their management may also be driven 'top-down' via the implementation of regional or national environmental protection regulations or additional production costs associated with, for example, carbon trading schemes. These drivers are interlinked to climate change through the socio-economic conditions that also influence emissions and mitigation measures. Thus, the impacts of climate change will need to be factored into the development of these potential land use and food industry changes.

4.3.2 Development and adoption of innovative technologies

There is a range of riskier long-term but potentially high-impact technological advances that could be used to transform the arable sector. Historically, technological advances have revolutionised the productivity of broad acre crops and ensured sufficient food to cope with the pace of global population increase. Examples include the development of synthetic nitrogen fertilisers (Erisman et al. 2008) and pesticides made feasible due to access to 'low cost' fossil fuel, and also targeted breeding programmes (e.g., semi-dwarf cereal varieties) developed since the 1960's green revolution (Borlaug 2003). By their very nature it is difficult to predict if future technological advances will enable a similar pace of yield increase and if the identified technologies will be of value in the future.

4.3.2.1 *Improving crop uptake and conversion efficiency potentials*

The exploitable gap between current yields achieved at intensive cropping systems and crop genetic potential for further increase is closing (Cassman 1999), with prospects of reaching a ceiling in crop productivity (Fischer & Edmeades 2010). However, some authors suggest that there is still scope for further increases in potential yields. For example, by manipulating photosynthetic enzymes to improve RUE (Loomis & Amthor 1999; Ewert et al. 2006). The development of crop genotypes with higher uptake and conversion efficiency for water, light and nutrients could be a breakthrough in resource use. For example, by transferring the biochemical pathway of C_4 crops into C_3 crops, as currently attempted for rice crops (Mitchell & Sheehy 2006), it would be possible to produce more biomass per unit of solar radiation intercepted and water transpired. However, the current challenges involved in the transfer of multiple genes suggest that this technology will not be available in the short term (Peterhansel 2011).

4.3.2.2 *Developing perennial cereals*

Greater resilience to extreme climatic conditions could be achieved by incorporating perennial characteristics into annual cereal crops (Glover et al. 2010). The benefits include increased access to water due to a more abundant root system and reduction in mechanisation requirements (Bell et al. 2010). Trade-offs may include lower harvest index due to having roots as stronger sinks for photosynthates. This is a long-term challenge that may allow production in marginal environments for annual crops (Lakew et al. 2011). This technology seems more suited to marginal cropping areas and is therefore unlikely to be of widespread use in New Zealand, unless stress conditions (e.g., drought) reach unforeseen magnitudes.

4.3.2.3 *Increasing crop resistance through micro-organism association*

It is possible to achieve increased resilience to both biotic and abiotic stresses by the application of plant-associated micro-organisms (e.g., bio-agents such as rhizoplane and endophytic bacteria or symbiotic fungi) on arable crops (Grover et al. 2011). In New Zealand, the success already obtained with ryegrass endophytes conferring tolerance to insect damage is encouraging (Popay & Thom 2009). Future research is required to extend the technology to cereal crops. Tolerance to future pest pressures (Sections 3.5 and 4.1.6), high temperatures and drought seem the primary targets for this technology. This work has been already embraced by the Foundation for Arable Research (FAR 2011a).

4.3.3 *Migrating to different land uses and economic activities*

If climate and other regional/global changes compromise the economic viability of broad acre farming, it will be necessary to explore other possibilities of land use or else to completely abandon agriculture. One possible driver of such changes could be the increase in competition for resources with other farming enterprises due to climate change. For example, in Canterbury, the demand for ever scarcer irrigation water may mean that it is more economical for one farming enterprise to trade an irrigation allocation with another– and return to a dry-land cropping situation (or other land use). There may also be opportunities to develop closer integration with other farming enterprises for reducing environmental and economic pressure catalysed by climate change. For example, closer integration between arable and dairy farms could see an increase in forage and feed grains supplied to the dairy herd and also arable farmers taking effluent from milking sheds and feeding pads to use as an alternative fertiliser source (and also helping to manage the environmental impacts associated with disposing of effluent).

As an example of fast land use change in New Zealand, the recent southern migration of the dairy industry has converted 'extensive dry-land' livestock production farms into 'intensive irrigated' dairy production systems in a few years (Pangborn & Woodford 2011). This movement was mainly driven by economics (e.g., lower land prices in Canterbury) but illustrates how fast and effective land use change can be as an adaptive option. This example also highlights the cascade of carry-over effects to production systems caused by land use changes. The migration of dairy farming to the lower rainfall and cooler winters of Canterbury fostered the implementation of large-scale irrigation systems and the development of supplementary feed production systems (e.g., maize silage and forage brassicas) to feed cows during winter.

4.4 *Identifying maladaptation risks*

Maladaptation to climate change may occur when the impact of a certain technology is over-estimated or when its side effects are unforeseen. The recent rush for biofuel production from maize crops in the USA is an example of maladaptation to mitigate climate change within a broad acre cropping context (Cassman & Liska 2007). The use of bioethanol from maize, as a substitute for fossil fuel to reduce CO_2 emissions, largely ignored potential negative socio-economic impacts such as the rise of food prices due to competition for land and other production resources (Fischer et al. 2009).

It is possible to identify and minimise the risk of maladaptation by testing adaptive options beforehand at smaller scales or through simulation exercises. For example, we used the APSIM model (Box 5.1) to explore the potential benefits of delaying sowing and increasing fallow period for dry-land kale crops within a pasture rotation in Canterbury (Figure 5.8). The null hypothesis was that increasing the preceding fallow period from 1 day (i.e., no-fallow) to 2 or 4 months, would increase kale yield and be less variable in response to greater soil water storage. The analysis shows that lengthening the fallow period was not effective in improving yields. In addition, higher costs and risks due to the shortening the preceding pasture regrowth cycle and management requirements to control weeds during longer fallow periods would make this an example of maladaptation. A very late sowing date in April was also identified as an ineffective adaptation option because of large yield declines in response to lower temperatures and available solar radiation (Figure 5.8).

Integrated assessments that include both biophysical and socio-economic drivers of adaptive responses are more suitable to identify maladaptation options. For example, ideally the implementation of adaptive measures should take into account the net balance in greenhouse gas emissions and the overall ecological footprint of the new production systems (Howden et al. 2010b).

5 Evaluating net benefit of adaptation options

The benefits of adaptation options can be measured in terms of the economic, environmental and societal gains. Some technologies enable adaptation to multiple climate drivers (Table 5.3), but the greatest benefits are likely to come from combining different options into ‘technological-bundles’ to adapt to climate change.

The potential benefits of adapting cropping systems to climate change vary with location and intensity of climate change. When summarised for several international studies, yield increases due to adaptation ranged from 10% to up to 18% (Howden et al. 2010b; IPCC 2007a). For these aggregated global values, Howden et al. (2010b) showed that benefits (percentage gain from non-adapted yields) tended to increase until moderate warming (<2°C) and then level off, with more positive responses under non-limiting water conditions. A thorough quantitative analysis of adaptation benefits for cropping systems is still impractical due to the complex nature of decision making at farm level and the large diversity in management and climatic conditions (IPCC 2007a). However, general insights can be drawn from the options presented in Table 5.3.

For New Zealand, the wide range of ‘tactical’ adaptive measures suggests that there are potential benefits and flexibility to cope with moderate climatic changes. These options are in fact the widespread application of currently available ‘best management practices’ to cope with current climate variability. For example, by changing sowing dates, varieties and crop species, farmers can manipulate the matching between crop development stages and prevailing weather. The development of new genotypes, using traditional breeding or molecular/genetic techniques, is a ‘strategic’ option to enlarge the pool of better adapted varieties. The improvement in the efficiency of water and nutrient use (Sections 4.1.4 and 4.1.5), resources that trend to become more limited and expensive, will certainly be of benefit to enable increased yield potentials to be realised (e.g., CO_2-fertilization) and reduce environmental impacts. This can be achieved, for example, ‘tactically’ by improving the efficiency of irrigation equipment (Figure 5.12) or ‘strategically’ by expanding the irrigated area and its infrastructure (Section 4.2.5). Consistent yield benefits are expected under the provision of adequate water supply, particularly for light soil conditions (Figure 5.16).

Finally, the benefits of transformational adaptive options (Section 4.3) are highly uncertain and depend on external factors such as market responses, technological advances and availability of production resources (land, water, energy) in New Zealand and also in other global cropping regions.

Table 5.3. Summary of adaptation knowledge for the broad acre cropping sector.

Driver	Impact	Tactical	Strategic	Transformational
Increase in CO_2	- Increased photosynthetic rates - Decreased transpiration rates	- Manage nutrient and water supply to enable higher yield potentials and to maintain crop quality	- Ensure access to irrigation to enable higher yield potentials	- Develop new varieties with enhanced yield potential
High temperature	- Shortening crop cycles - Increased/decreased photosynthetic rates - Increased respiration rates -Increased/decreased canopy expansion rates -Increased/decreased pest pressure	- Change sowing date - Change crop variety	- Change crop species - Develop new varieties better adapted to warm environments	- Change location - Change farming activity
Low rainfall	- Reduced canopy expansion rates - Reduced RUE - Limit nutrient uptake	- Change in sowing date - Change in crop variety - Use irrigation and/or increase its efficiency - Conservation agriculture to increase soil water retention	- Change species - Develop varieties better adapted to drought - Develop new irrigation infra-structure -Precision agriculture (e.g., VRT irrigation)	-Change location -Change farming activity
High rainfall	-Limited soil workability -Limited root respiration - Increase in pest pressure - Plant lodging -Nutrient losses to groundwater	-Change in sowing date -Change variety -Soil management (e.g., conservation agriculture, drainage)	-Develop more resilient varieties and species -Develop drainage systems	-Change location -Change farming activity
Heat stress	-Impairment of reproductive processes causing low harvest index	-Change sowing dates -Change to more resistant crop varieties	-Develop heat-stress resilient varieties -Irrigate to ensure transpirational cooling	-Prospects of improved resistance with microorganism association -Change farming activity
Extreme climate (storms, severe droughts, high winds and floods)	-Yield damage	-Change in sowing date -Change to more resistant varieties - Implement and improve biotic control techniques	-Change species -Develop new varieties -Develop forecasting and monitoring programmes	-Change to alternative cropping systems -Change farming activity

6 Knowledge gaps

There is very little 'practical' information available from field experiments and pilot-studies specifically designed to quantify the effectiveness and costs of the different adaptation options. This is a critical knowledge gap that makes it difficult for practitioners to compare the benefits of different innovations or decide when to implement them. Currently, most insights into adaptive options for future climates are gained from modelling studies. There is a need to continue improving the capability of crop models to assess impacts and identify adaptation options (Rotter et al. 2011). Current uncertainties are being identified through international model inter-comparison initiatives and minimised through the use of ensemble model assessments (Rosenzweig & Wilbanks 2010; Palosuo et al. 2011). The main knowledge gaps identified for this type of studies include:

- Changes in the frequency and intensity of rainfall have a large impact on crop yield but are still not well captured in climate models (Sinclair 2011).
- The frequency and magnitude of extreme events such as heat stress and severe droughts are not well represented in climate change data projections; and the mechanisms of yield damage are not yet considered in most crop models (Tubiello et al. 2007b).
- The magnitude of the CO_2 fertilization effect to materialise under farm conditions is still under debate (Long et al. 2006; Tubiello et al. 2007a). The understanding of the interactions between CO_2, temperature and water availability is still limited.
- The impact of climate change on yield damage caused by biotic factors (insects, diseases and weeds) is likely to change but is still difficult to quantify and not coupled to most crop models (Section 3.5).

In particular, the impact of future technological advances on future crop yields is unknown (Ewert et al. 2006). These authors have shown the substantial influence that technological advances have on simulated projections of crop production, either by reducing yield gaps (i.e., differences between actual and potential yields) or increasing potential yields. In New Zealand, achieved yields are closer to genetic potential than elsewhere in the world (Section 2.1), as illustrated by the record wheat yields achieved in the country (Armour et al. 2004). Uncertainty about the pace of technological advances, as illustrated in Section 4.3, makes it difficult to predict if current yield plateaus (Cassman 1999) can be surpassed in the future.

In addition to these findings, key research areas to improve the assessment of impact and adaptation for broad acre cropping include:

Development of methods to link multiple geographic scales (i.e., from point-based to regional to national). For that, methods that enable spatially explicit quantification of impacts and adaptation benefits are required (e.g., see discussion in Ewert et al. 2011).

- Methods for quantifying and communicating assessment uncertainties.
- Addressing cost–benefits from adaptive options by objectively considering the value of ecosystems' services (e.g., clean water, clean air and sustainable use of land resources) in linked biophysical/economic assessments.

7 Concluding remarks

This review suggests that there is a wide range of adaptive measures to harness the opportunities and mitigate the threats of climate change on broad acre cropping systems in New Zealand. The effectiveness of adaptive measures is specific to each production system. Benefits depend on local weather, crop choices, soil types, available technology and socio-economic conditions.

Given the global relevance of grain production for both human consumption and livestock feeding, adaptation decisions in New Zealand cannot ignore changes also occurring in other parts of the globe. Climate impacts are geographically heterogeneous with larger yield losses projected for the tropics than for temperate and mid-latitude countries (Fischer et al. 2008). Climate change impacts on cropping regions overseas will certainly impact New Zealand's arable sector through global market and trade effects. The selection and potential benefits from adaptation measures will, therefore, be influenced by external factors including global food supply/demand, commodity prices and trade policies (Howden et al. 2007; Meinke et al. 2009; Huang et al. 2011) affecting economic performance of broad acre cropping in New Zealand.

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Chapter 6. Horticulture

Adapting the horticultural and vegetable industries to climate change

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