Potential impacts of climate change on agricultural land use suitability: barley

Dennis Van Gool

Luke Vernon

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POTENTIAL IMPACTS OF CLIMATE CHANGE ON AGRICULTURAL LAND USE SUITABILITY:
BARLEY

Dennis van Gool and Luke Vernon

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Barley

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Summary

A relatively simple model was developed to generate climate change scenarios for a variety of agricultural crops. The model was only partially validated against real data, hence it is best used as a decision support system that allows people with land resource, crop and climate knowledge to determine potential impacts of climate change on crop growth and production.

Land use capability data and climate information for the agricultural zone of Western Australia were combined with a modified French and Schultz equation to produce a potential yield map for barley. Another yield map was then produced for 2050 based on SRES marker scenario A2, CSIRO Mark II, which is considered a good model for the south-west of WA.

Climate change in WA may result in relatively large reductions (>30 per cent) in potential barley yield in the northern agricultural region (around Mullewa) by 2050 due to reduced rainfall and higher maximum temperatures. Although current barley production is not very high in the northern agriculture region, significant reductions are predicted for Mullewa and Northampton. Of the major barley growing areas, Lake Grace stands out as having both a high total reduction (>10,000 tonnes) and an 11 per cent reduction in yield potential.

The CSIRO model predicts a small increase in both maximum and minimum temperatures, of around 0.8 degrees Celsius. Both 2050 temperature prediction and crop response to temperature are uncertain. High temperatures will reduce soil moisture, change disease risk and have direct effects on growth. We believe a high temperature effect is likely, though the amount of actual temperature increase and the effect on barley yield are uncertain. It is possible that the temperature effect on barley growth may be offset by increased CO2 levels in the future, but this is not considered in our model.

The model predicts that an extensive area encompassing much of the eastern, central, southern and south-eastern wheatbelt may experience a 10-30 per cent yield reduction by 2050 mainly due to reduced rainfall.

There is a large area where little change is anticipated in the western area of the agricultural zone, between the current 350 mm rainfall isohyet and the State Forest. However within this region it is likely that low lying areas will perform better in the future as reduced rainfall results in less waterlogging, but drier areas are likely to lose some production.

Overall, this modelling found that 41 per cent of the agricultural zone may experience a decrease in yield potential greater than 10 per cent as a result of climate change. The actual reduction will be less as farmers adapt by altering their planting strategies and changing barley cultivars.

The model is independent of an economic analysis. Our use of the term 'yield potential' is indicative, as farmer adaptation occurs anyway and it is difficult to predict how much flexibility there is in this adaptation. This decision support system shows areas of risk, where the capacity to adapt may be strained. Under our specific model assumptions, it identifies the best places to grow barley in 2050 and shows areas, such as Lake Grace, Mullewa and Northampton which will most likely need significant adaptation to overcome yield reductions as a result of climate change. Examples include the development of new cultivars, such as short season varieties of barley, improvements in management or alternative crops.
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Acknowledgements

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Introduction

This is one of five climate change reports covering wheat, barley, lupins, canola and oats. Wheat is grown extensively throughout the agricultural region, hence the wheat model described in the first report provides a useful comparison for barley.

Barley (*Hordeum vulgare*) is the second major crop grown in Western Australia behind wheat (Young 1998). Over 1.5 million tonnes (t) of barley is produced annually (Garlinge 2005). In 2001-02, 1.1 million hectares were planted for grain and 2.2 million tonnes harvested (ABS 2005). Its value is also significant to the State, representing $467 million of the total $5.5 b gross value of agricultural production in 2001-02 (ABS 2005). Figure 1 shows the main barley growing regions, based on CBH grain receivals from 1995 to 1999. This period was selected because it is considered to be an average expectation by the Farm Business Development Unit at the Department of Agriculture. This value has been used for Exceptional Circumstances guidelines since 2000 (Allan Herbert, pers comm.).

Barley grown in WA is used for malting, shochu production, human consumption or stock feed (Garlinge 2005). Malting barley is used for brewing beer and other foodstuffs. Malting varieties account for almost 90 per cent of the land sown to barley. Only those with malting classification can be used for malting (Garlinge 2005).

Premium quality Stirling barley is used in Japan to make shochu, a distilled spirit. Barley is also used for stock feed. Barley grown for malting but not meeting the quality requirements of the malting grade can also be used for feed (Garlinge 2005).

Climate variability presents a significant challenge to cropping. Records show that rainfall has declined in the south-west, undergoing a sharp and sudden decrease since the 1970s (IOCI 2002). Day and night-time temperatures, particularly in winter and autumn, have...
increased gradually over the past 50 years. Although climate is not static even in the absence of human influence, the changes experienced do not appear to have been caused exclusively by natural climatic variability (Sturman and Tapper 1996, IOCI 2002).

In order for the cropping industry to adapt to future variability, it is important to identify likely impacts of climate change. This study aimed to assess how current climate change scenarios in the agricultural zone of WA will impact on barley suitability and growth. This will help identify areas where future management and research efforts should be focused.

**Climatic requirements and influences**

The most important climatic factors influencing the growth of barley in WA are rainfall and temperature. Traditionally, barley was grown in areas receiving less than 400 mm annual rainfall (Young and Elliot 1994). With the release of later maturing varieties, barley is now grown in areas receiving 750 mm to less than 325 mm annual average rainfall, covering all of the low, medium and high agroclimatic zones (Young 1998).

Highest yields are attained in the high rainfall zones, however, the cool moist climate and long growing season also favour development of pests and foliar diseases, with the root disease take-all being a major constraint to yield in these areas (Young 1998). Barley is more tolerant of foliar and root diseases than wheat. Hill and Wallwork (2002) commented that barley generally shows half the yield penalty of wheat to take-all. As such, barley has potential to be a more reliable and higher yielding crop than wheat in high rainfall areas (Young 1998). Indeed, Zhang et al. (2004) and Gregory et al. (1992) found barley to yield 10 and 20 per cent higher than wheat in trials near Kojonup and East Beverley respectively.

Temperature is also a major yield determinant as it controls development. Optimum temperature for growth varies depending on the stage. For example, Tamaki et al. (2002) found that leaf emergence rate was greatest at around 22°C, whereas leaf growth rate had its optimum at 20°C. High temperatures (>35°C) post-anthesis have been shown to significantly reduce grain weight and change malting performance (Savin et al. 1996, Wallwork et al. 1998, Passarella et al. 2002). Savin and Nicholas (1999) showed grain weight reduction was greater under heat stress than drought. This means that in warmer areas short season varieties of barley should yield better.

**Soil requirements and influences**

Barley is well adapted to a wide range of soils. In general, high yields are obtained where soils are coarse-textured with relatively low nitrogen supply (as low protein is preferred for malting), well drained and non-acidic (Young 1998). However, if nitrogen is too low there will be significant reductions in total grain yield.

Barley is the most tolerant cereal to salinity, but EC levels above 800 mS/m result in yield reductions (Young 1998).

Soil acidity is a major constraint to crop growth (Carr et al. 1991), and barley is particularly sensitive compared with other cereals. Soils with low pH invariably have high levels of aluminium in the soil solution, to which barley is extremely sensitive (Scott et al. 1997). Generally, soils with pH_{Ca} <4.5 are unsuitable (Young 1998).

Barley is more tolerant of alkalinity than other cereals (Young 1998), however, boron toxicity is often associated with alkaline soils and will limit yields. Barley grown with pH_{Ca} >6.5 in the subsoil often experience symptoms of boron toxicity (Garlinge 2005).

Waterlogging can be an important constraint to production, and has been identified as the major constraint in the high rainfall zone of the south-west (Zhang et al. 2004). Setter et al. (1999) showed that yields can be reduced by 51-84 per cent due to waterlogging, depending on the stage of growth. Barley is able to withstand short periods of waterlogging without
significantly affecting yield (Young 1998). For further information on soil factors affecting productivity, refer to Appendix 1.

**Model development**

To estimate yield, the model uses the rainfall-driven French and Schultz (1984) equation, to which adjustments are made to take into account land capability, waterlogging and maximum and minimum temperatures.

The French and Schultz equation has been accepted as a useful model for grain crops in WA, even though reporting has been informal or anecdotal (e.g. Tennant 2001, Hall 2002). Some detailed work has been undertaken for grain legumes (Siddique *et al.* 2001).

The model as reported here was first developed in conjunction with Peter White for use with pulses and legumes in WA and reported by van Gool *et al.* (2004a,b).

When our yield predictions seem reasonable, the effects caused by climate change are predicted by re-running the model for a selected 2050 climate scenario.

The model is a good tool for combining complex data and expert knowledge. It bridges the gap between a number of scientific disciplines and several audiences, including:

- People involved in planning and policy
- Land users and managers, including research agronomists, technicians and farmers.
Materials and methods

The data

- Bureau of Meteorology (BoM) climate surfaces for rainfall, maximum and minimum temperatures. These are mean daily values for each month for 1961 to 1990 shown on 0.25 x 0.25 degree grid cells (approx. 2.5 km).
- Department of Agriculture map unit database and land resource maps to create land capability maps for each crop. Mapping scales range from 1:20,000 to 1:250,000. See Schoknecht et al. (2004) for an overview of soil-landscape mapping methods and outputs and van Gool et al. (2005) for an explanation of land qualities and land capability.
- Ozclim climate scenario (SRES Mark II) available from CSIRO Atmospheric Research which predicts changes in rainfall plus maximum and minimum temperature.
- BoM Patched Point climate data.
- Published and unpublished information about the crops.
- CBH grain bin receivals information for 1995 to 1999 summarised for local government areas prepared by the Farm Business Development Unit, Department of Agriculture.
- Expert and local knowledge.

Software

The mapped information was prepared using Arcview 3.2 and Spatial Analyst. The gridded BoM climate and Ozclim climate change information was matched to the centroid of each soil-landscape map unit by a unique identifier. Only matching grid cells were used and no attempt was made to further summarise the information. The information was then exported to an Access 97 database, where all the yield calculations were carried out. The information was then exported back to Arcview for display, but any other GIS package could be used.

Method

Yield

Initial estimates of water use efficiency were derived from the literature. After a review of this study by staff from the Australian Greenhouse Office it was requested that this information be scaled to real data. We had mean values for yields based on CBH grain receivals and corresponding Bureau of Meteorology rainfall records 1995-1999 readily available (Figure 2).

Grain receival figures provide more conservative estimates of water use efficiency than others reported (e.g. French and Schultz 1984, Tennant 2001, Hall 2002). The yields represent averages achievable in the south west agricultural region in 1999. It should be noted that the mean yields are then scaled both up and down for good and poor cropping land as indicated by the land capability which considers both the soil type and the position in the landscape.
To analyse the CBH figures, in the interests of simplicity, and because there were insufficient data to warrant using a more complex model, the equation was partitioned using two linear regressions of yield and rainfall (Figure 3). For 150-285 mm rainfall the regression line is similar to the French and Schultz (1984) equation and for 285-600 mm there is a line showing much lower water use efficiency. The lines were drawn where they best represented the data (the $R^2$ values were maximised). Up to 285 mm there was a very good fit of the data but beyond 285 mm the data fitted poorly. The use of two linear regressions instead of a polynomial equation is generally not condoned, however it is a pragmatic solution for our decision support tool. The ‘$x$’ intercept of the line from 150 to 285 mm was also used to estimate the evaporation water loss (90 mm).
Figure 3: Linear regressions on mean barley yields 1995-99 based on CBH grain receivals (scaled to 1999 figures)

Mean yield was estimated using a modified equation of French and Schultz (1984). Adjustments for excessive rainfall (WAc), soil capability class (LCc), minimum temperature (Mintc), maximum temperature (Maxtc) were added.

\[ \text{MY} = \text{WUE1} \times (\text{GR} - \text{WL}) \times \text{WAc} \times \text{LCc} \times \text{Mintc} \times \text{Maxtc} \]

\[ \text{MY} = \text{WUE2} \times \text{GR} + \text{YI} \times \text{WAc} \times \text{LCc} \times \text{Mintc} \times \text{Maxtc} \]

MY = mean yield
WUE1 = water use efficiency which is approximately 9.2 (from CBH grain receivals)
WUE2 = water use efficiency which is approximately 0.5 (from CBH grain receivals)
YI = Yield at the intercept of the two regression equations = 1793 kg
GR = growing season rainfall 1 May to 31 October, plus 20% of rainfall for 1 November to 30 April (the 20% accounts for initial soil moisture available to the crop)
WL = water loss
   If GR ≥150 mm/yr THEN WL = 90
   If GR < 150 mm/yr THEN WL = GR × 0.6
WAc = waterlogging constant (see below)
LCc = land capability class constant (see below)
Mintc = minimum temperature constant (see below)
Maxtc = maximum temperature constant (see below)

Waterlogging constant (WAc)

In this scenario, growing season rainfall above 285 mm was approximately where the water use efficiency of barley growth declines dramatically for several reasons. Excess water is removed by run-off or leaches beyond the root zone, and increased disease can reduce yields. Waterlogging and increased incidence of disease will result in yield reductions when rainfall becomes very high. In the absence of better data, yield potential was decreased for
increasing rainfall above 600 mm (Table 1). Further data were not sought because of time constraints and because it was felt that it would have only a small impact on our model as 600 mm occurs near the edge of the State Forest, a distinct physical boundary for cropping. (State Forest areas are shown on Figure 13.)

Table 1: Waterlogging constants for adjusting yield potentials for annual rainfall

<table>
<thead>
<tr>
<th>Annual rainfall (mm)</th>
<th>Waterlogging constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>600*-700</td>
<td>1.00 of the yield achieved at 600 mm</td>
</tr>
<tr>
<td>700-800</td>
<td>0.9 of the yield achieved at 600 mm</td>
</tr>
<tr>
<td>800-1000</td>
<td>0.8</td>
</tr>
<tr>
<td>1000-1200</td>
<td>0.7</td>
</tr>
<tr>
<td>1200-1400</td>
<td>0.5</td>
</tr>
<tr>
<td>&gt;1400</td>
<td>0.3</td>
</tr>
</tbody>
</table>

*600 mm occurs near the edge of the State Forest creating a distinct physical cropping region boundary.

Land capability constant (LCc)

'Law of the Maximum' (Wallace and Terry 1998) states that a large yield response is possible if there is only a single limiting factor, but as the capability table indicates (Appendix 2), if one limitation is overcome, others soon come into play. This suggests that only when all limiting factors are addressed simultaneously does plant production have a chance of reaching biological potential. For this reason using land capability maps based on many factors for this yield model we believe is superior to models driven from only one or two more readily available or better understood properties, such as soil water storage or pH. Lower capability means greater constraints for plant growth and reduced yield, hence the average crop yield is scaled using the values listed in Table 2.

Table 2: Land Capability Class constants for adjusting yield potentials on each soil capability class

<table>
<thead>
<tr>
<th>Land Capability Class</th>
<th>Land Capability Class Constant (LCc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Higher than average yields

Average yields

Lower than average yields

Land capability ratings for barley were based on Young (1998), van Gool, Tille and Moore (2005) and Maschmedt (unpublished), with fine-tuning in consultation with barley agronomists from the Department of Agriculture. The ratings can be best described as considered judgements taking into account local experience and the research data that was available (both published and unpublished).

The development of the ratings involved several iterations. Ratings were modified until there was consensus that the maps of land capability provided a good general representation of reality (see Figure 4) in the context of a subjective evaluation of survey quality using the date of publication, survey methods and the mapping scale (see Figure 5). See Appendix 2 for the final capability table.
Figure 4: Land capability for barley

Figure 5: Subjective assessment of reliability based on mapping scale and survey methods
Temperature constants (Mint, Maxt)

Maximum and minimum temperatures for barley growth were collated from Ecocrop (FAO 1996) and the Australian software program PlantGro™ (Hackett 1999). These temperature values suggest that barley experiences significant yield reductions when the temperature exceeds 35°C and may die when temperatures exceed 38°C. At the low temperature extreme, yield is depressed significantly at -5°C and plants normally die at -8°C.

These temperature values were then related to averages of the daily monthly maximum and minimum temperatures on the BoM climate surfaces (see Tables 3 and 4).

Because we are using daily temperatures averaged for an entire month there will be a significant fluctuation of temperature around this value, hence the temperatures reported in Tables 3 and 4 may seem higher or lower than expected. Refer to Appendix 3 for how the yield limiting temperature values in Tables 3 and 4 were estimated.

For maximum temperature, the months August to October were used. During this time temperature increase is fairly linear, and more warm days occur in October than August.

For minimum temperature, -5°C is rare, but frosts are common in some regions. September was selected because crops are highly vulnerable to frost damage at this time. Our minimum temperature restriction is loosely related to the likelihood of frosts (see Figures A4 and A5 in Appendix 3).

A maximum temperature was selected using a monthly mean about 13°C less than the point at which significant plant stress was thought to occur. For the minimum temperature, the monthly minimum was about 9°C higher than the point at which significant plant stress was thought to occur. Other than FAO (1996) and Hackett (1999), there were little real data to support these selections in WA. However, the model iterations, discussed below, were used to fine-tune the temperature adjustments.

The tables show how yield is decreased as average maximum temperature increases (Table 3) and average minimum temperature decreases (Table 4) below critical levels. See Appendix 3 for further information on selection of temperature limitations using monthly averaged data.

Table 3: Temperature constants for adjusting yield potentials for average maximum temperatures (August to October)

<table>
<thead>
<tr>
<th>August-October average maximum temperatures (°C)</th>
<th>Temperature constant (Tc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;22.8</td>
<td>1.0</td>
</tr>
<tr>
<td>22.8-23.0</td>
<td>0.95</td>
</tr>
<tr>
<td>23.0-23.2</td>
<td>0.9</td>
</tr>
<tr>
<td>23.2-23.4</td>
<td>0.85</td>
</tr>
<tr>
<td>23.4-23.6</td>
<td>0.8</td>
</tr>
<tr>
<td>..........and so on to 24.8. (24.7 is the maximum value under the 2050 climate scenario)</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4: Temperature constants for adjusting yield potentials for average minimum temperatures (September)

<table>
<thead>
<tr>
<th>September average minimum temperatures (°C)</th>
<th>Temperature constant (Tc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;5.0</td>
<td>1.0</td>
</tr>
<tr>
<td>4.8-5.0</td>
<td>0.95</td>
</tr>
<tr>
<td>4.6-4.8</td>
<td>0.9</td>
</tr>
<tr>
<td>4.4-4.6</td>
<td>0.85</td>
</tr>
<tr>
<td>...and so on to 4.0. (4.1 is the minimum value for the current climate)</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The initial minimum temperature value was 5.6. This was reduced to 5 in the model iterations.

### Model iterations

As described above, considerable effort went into reaching land capability maps that accorded with 'expert' opinion. Maps underwent several iterations and the results were discussed until consensus was reached that they were a reasonable representation of reality.

When yield maps have been prepared the results can be verified against actual yield data. However, this is complicated by huge diversity in trial information, including the methods adopted for the trial, the reporting methods and the lack of detailed climate and soil information at the trial sites. A visual assessment of the mapped areas indicates that the modelled maps show high yields where existing trials yield well and vice versa. Trials should be considered because it would minimise variability due to management and farm economics. Trial information yields higher than achievable on most operational farms and is not readily available over extensive areas. Early wheat research trials reported by Davidson and Martin (1968) indicate that farm wheat yields for selected sites in WA achieve between 57 and 72 per cent of experimental yields. The model considers a mean yield based on 1995-1999 CBH yields (Figure 2) as such data were readily available. Because there is a gradual increase in yield over time, the CBH figures are scaled to 1999 yields.

It is instructive to view the comparison of modelled and shire yields spatially. Figure 6 shows where the model predictions were out by more than plus or minus 10 per cent. It was noted that the model underestimated yield in several LGAs toward the middle of the map because the minimum temperature restriction was too severe. Figure 7 shows the result when the minimum temperature where yield penalties occur is adjusted from 5.6 to 5°C.
Figure 6: Areas where the model varies from CBH 1995-99 data by more than ±10%

Figure 7: Areas where the model varies from CBH 1995-99 data by more than ±10% when yield penalties for minimum temperature are adjusted from 5.6 to 5
Figure 8a shows yield predicted by the model, averaged for each local government area against CBH yield. Figure 8b shows the yield predicted by the model against ABS crop yield figures for 1983-87 (ABS figures are comparable to CBH figures). A linear regression is not ideal, as CBH yields are not an ideal ‘known’ value. They will have a significant amount of variability. There is uncertainty in assessing which locations deliver to particular storage bins. Also some crops do not go via the storage bins at all. Even if the yield figures are reliable there is variation in management, varieties grown, planting times and differences in climate and soil types. The graph indicates the model has a fairly low predictive ability, which is not surprising given the general assumptions made (discussed under Model assumptions). Particular attention is drawn to the assumption that all soils in a local government area are considered. It should be remembered that:

*the model attempts to predict where the productivity of cropping land for barley is likely to change as a result of climate change, irrespective of whether it is being cropped for barley currently (e.g. see Figure 1).*

This allows you to predict possible shifts in productive areas over time.

Even though it was helpful in assessing gross temperature changes the CBH data are used more to scale the information rather than for accurately validating the model.

Figure 8a: Modelled versus actual yield - average value for 1995-99 in tonnes
**Figure 8b: Modelled versus actual yield - average value for 1983-87 in tonnes**

The graph shows the modelled yield (y = 0.96x) of barley with an R² value of 0.47. The data points indicate a positive correlation between modelled and actual yields, with most points falling close to the linear trend line.
Model assumptions

This model/decision support tool assumes:

- Management practices, whether improvements or a result of a response to climate change such as different planting times, do not alter over the course of the scenario. It should also be noted that barley production was dominated by the Stirling variety from 1995 to 1999.

- Carbon dioxide concentrations remain constant. This is important when considering the results, as modelling by Howden et al. (1999) showed that wheat yields would more than likely increase at all sites studied in WA (Geraldton, Wongan Hills and Katanning) under future climate change scenarios with a doubling of current carbon dioxide levels.

- Plant growth responses to temperature extremes or excessive rainfall are generally not linear except over a small portion of the response curve, Tables 2, 3 and 4 show a linear relationship of waterlogging and temperature to growth. This is because the lowest September daily mean temperature is 4.1°C and the highest August to October daily mean is 24.7°C. Most of the region appears to have only slight temperature limitations for barley and the 50 year climate change scenario climatic adjustments are relatively small. Waterlogging/disease limitations apply after 600 mm, but this occurs mostly in forest/water catchment areas (shown on Figure 13) that are not available for cropping. The model would need temperature and waterlogging responses checked for other regions, or if climate change was much greater than presently predicted.

- All soils within a local government area are considered. In reality some soils would simply not be cropped e.g. saltland or bare rock. The maps indicate high and low productivity land and show where productive land might be lost as a result of climate change. Because there is no record of which soils are actually being cropped, validating the model against grain yield records based on local government areas can only be indicative. Because the model considers all land in a local government area, if there is a large amount of class 5 land the model would predict reduced yield. This would be misleading if barley is only grown in parts of the shire where class 1 to 3 land dominate.

Mean values and the French and Schultz equation

The model only deals with average conditions. It does not consider climate extremes (droughts and floods) reported to be more frequent with climate change (e.g. IPCC 2001).

The French and Schultz equation is an appropriate tool for dealing with average climate values (e.g. BoM 1961-1990). It is not suitable for looking at crop growth in a single season because it only considers if there is adequate rainfall over the growing season. If the rain falls too early or too late in the season there will be a large effect on crop growth that cannot be predicted. Over a longer time period these seasonal differences are averaged out.

Temperature-related assumptions

- The temperature requirements for different cultivars can vary greatly. However, the model assumes a single cultivar for a given scenario.

- There are interactions between temperature and moisture availability. For example, barley will tolerate 38°C if soil moisture is not limiting, and the plant is not under moisture stress. The temperature/moisture interaction can be built into the model (and has been trialled), but was not used for the scenarios generated for this report.

- There are critical temperatures for different stages of crop development. For example, a minor frost risk in May, when plants have germinated, could be more important than a much higher frost risk in July. This model presently uses the September coldest
temperatures. Adding temperature criteria for other months to account for critical plant
growth periods would be straightforward.

- Frosts can reduce crop yields by damaging plants, but cooler temperatures are beneficial
  for consistent grain filling, hence the response to minimum temperature can be difficult to
  predict.
- When it is warmer, barley has short grain-filling period, hence there is less opportunity to
  achieve good yields, and any moisture or temperature stresses will reduce yields more
  than in cooler areas. The model assumes a single cultivar, though a new scenario could
  be generated for each cultivar if the climatic or soil requirements were known to be
  significantly different.
- Temperature may not be a direct problem for the plant, but evaporation and evapo-
  transpiration may dry soils out before the crop has finished growing. This was considered
  when making high temperature selections.
- Higher temperatures are generally correlated with increased numbers of plant pathogens.
  This was considered when making high temperature selections in the model.
- Finding relatively detailed climate information for barley suitable for preparing regional
  summaries using monthly averaged temperature data proved difficult. It is generally
  accepted that temperature affects growth and yields. However, we are unaware of any
  regional temperature modelling that has been quantified, hence our initial predictions are
  largely based on estimates from the literature and field knowledge from barley
  agronomists. Model iterations were then used to adjust these values.
Results

Changes in potential yield over the 50 year climate scenario due to rainfall only are displayed in Figures 9 and 10. These show a broad reduction in yield potential particularly noticeable east and north of the 350 mm annual rainfall isohyet.

Changes due to rainfall plus temperature are displayed in Figures 11 and 12 and a final difference map is displayed in Figure 13. These maps indicate a further decrease in yield potential in the northern wheatbelt around Mullewa and north of Dalwallinu compared to Figures 9 and 10 as a result of higher temperatures. Figure 13 shows that in this area the model predicts the largest yield reduction (>30 per cent) compared with any other area in the agricultural zone.

The changes in yield for the 2050 climate scenario are easiest to see on Figure 13. In three regions a 20-30 per cent yield reduction is predicted. These areas are east of Three Springs and Bencubbin, and north of Salmon Gums.

The rest of the wheatbelt east of the current 350 mm annual rainfall isohyet and a band south of the 350 mm isohyet and north of Jerramungup shows a 10-20 per cent reduction in yield.

The west of the wheatbelt adjacent to the State Forest shows a large area where no change (±10%) is predicted.

Of the land area, 43 per cent or 11.6 million ha showed a reduced potential yield of 10 per cent or more. The remaining 15.1 million ha of land did not change (i.e. more than ±10 per cent). This was the second largest decrease predicted for the crops studied in this series, behind canola (45 per cent) shown in Table 5.

Table 5: Area experiencing change in potential yield for crops analysed in this study (van Gool and Vernon 2005, van Gool and Vernon 2006, Vernon and van Gool (2006a,b))

<table>
<thead>
<tr>
<th>Reduction</th>
<th>Area of agricultural zone experiencing change of potential yield (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Barley</td>
</tr>
<tr>
<td>Large (&gt;30%)</td>
<td>2</td>
</tr>
<tr>
<td>Moderate (20-30%)</td>
<td>4</td>
</tr>
<tr>
<td>Small (10-20%)</td>
<td>37</td>
</tr>
<tr>
<td>No change ±10%)</td>
<td>57</td>
</tr>
</tbody>
</table>

(a) updated values when wheat is re-run using the current model (utilising two linear regressions).

(b) values published in van Gool and Vernon 2005. Note this model predicts a small area of yield increase because it assumes yield penalties when growing season rainfall exceeds 400 mm. The current model uses 600 mm.

* Total area of the agricultural region is approximately 26.7 million hectares.
Figure 9: Current potential barley yield based on rainfall

Figure 10: 2050 potential rainfall based on rainfall
Figure 11: Current potential yield based on rainfall and temperature

Figure 12: 2050 potential yield based on rainfall and temperature
Figure 13: Barley yield change over the 50 year scenario when current potential yield was greater than one quarter of the maximum potential yield achieved by the model (692 kg/ha). Note: the isohyets are current annual rainfall contours.
Discussion

The large decrease (more than 30 per cent) in potential yield in the northern wheatbelt is due to a combination of reduced rainfall plus increased maximum temperatures predicted to 2050.

Temperature change is less reliably predicted by climate scenarios, plus the specific impact of high temperature on barley yield is subject to debate. Further uncertainty is cast by modelling by Howden et al. (1999), which indicated that under a doubling of CO₂ concentrations wheat (hence barley) yields might actually increase with climate change. It should be noted that in our generic model high temperature effects are estimated based on grain yield, and not dry matter production. High temperatures will reduce soil moisture stores more rapidly, and increase the likelihood of some diseases, as well as impact directly on barley growth. The main effect of rising temperature is a shorter growing season. Development of short season varieties could potentially offset yield reductions more than for a total reduction in rainfall. However, in combination reduced rain and higher temperature will impact on barley growth and farmers’ ability to adapt to these changes. It is likely that with a temperature increase in the hottest parts of the agricultural region, there will be anything from a negligible effect to a significant reduction in yield.

The 10-30 per cent decrease in potential yield over an extensive part of the wheatbelt (shown in light red as 10-20 per cent and bright red as 20-30 per cent in Figure 13) is due largely to the predicted reduction in rainfall for the 2050 year scenario.

There is a large area of no change west of the State Forest and south of the 350 mm rainfall isohyet. There is speculation that less rainfall in these areas will result in less waterlogging and disease, and hence increased yields. Stephens (1997) and Stephens and Lyons (1998) indicated a negative impact of waterlogging in higher rainfall areas. However this is not supported by the data used to scale our model for this study, particularly the simple linear regressions (Figure 3). Our model would show a positive impact from reduced rainfall in these regions if waterlogging constraint occurs at considerably less than 600 mm rainfall. It is possible that the data used lacks the detail required, as it is based on LGA averages. Within an LGA, higher portions of the landscape and well drained soils are likely to experience yield reductions with decreased rainfall. This could be completely offset by areas that are less well drained which would be less waterlogged and have increased yield. Hence the area of no change is likely to be misleading because within this region there are likely to be some farmers who benefit, and others who lose out depending on the soils on their farms.

We have assumed a small yield reduction in cold areas due to incidence of frost. With slightly increased temperatures due to climate change yields may go up a little. However, in cooler areas there appear to be benefits for consistent grain filling, so yields may actually decline due to increased temperature. It is likely that the net effect of slightly increased minimum temperature is going to be small.

Results show a significant overall decrease in yield over a large portion of the agricultural zone. This may be significant to barley growers, particularly those in the northern wheatbelt, who would need to (continue to) adapt to climate change more than in other regions. Adaptation includes management, but these results may also present some direction for breeders for continuing development of new cultivars for this region.

Climate change predictions

We have mentioned that not considering CO₂ change is a major limitation of the model. The uncertainty surrounding prediction of future climate change needs to be considered in this modelling. Indeed, recent studies have highlighted other sources of uncertainty surrounding climate change. Stanhill and Cohen (2001) described the phenomenon of a widespread
decrease in solar radiation, termed global dimming, and at first this appears to be contrary to the undeniable evidence for increases in temperature during the past four decades. Studies such as these have resulted in much debate among the scientific community about the validity of past climate change predictions and the potential processes and mechanisms causing global warming under global dimming. Supporting this phenomenon, Roderick and Farquhar (2004) found that, similar to the northern hemisphere, pan evaporation rates in Australia have actually decreased over the last 30 years. Liepert et al. (2004) provided a potential explanation for global warming under a global dimming situation. They concluded that “a radiative imbalance at the surface leads to weaker latent heat and sensible heat fluxes and hence to reductions in evaporation and precipitation despite global warming”.

The lack of suitable temperature information about barley to improve the relationship with the monthly mean climate surfaces certainly affects the credibility of this model. However, we would argue that even with insufficient data the strength of this model is its simplicity. It is a useful decision support tool for predicting likely climate change effects on agricultural crops based on any combination of data, available literature and ‘expert’ opinion. Additionally as shown in the model iterations the model can be run several times and matched against available yield data to overcome gross errors in the temperature adjustments.

**Model improvements**

A better reliability estimate would occur if the model was quantified and calibrated against existing yield information from controlled trials. Preliminary investigation is underway which is collating (initially) pulse trial data over a number of years with adequate information on trial methods and soil types. Funding will dictate how far this work progresses.

The model could be improved by factoring in a ‘confidence’ or ‘reliability’ estimate with each of the inputs (e.g. see Figure 5). It is also worth noting the two predicted yield decreases for wheat in table 5. Even though different equations were used (the 2005 wheat report utilised French and Schulz figures derived from the literature) the areas predicted remained quite similar. This suggests that our updated model gives little extra value for the regional predictions, particularly when the increased complexity of using the two linear regressions is considered.

We used the model as a decision support tool, and our test was whether the maps reflect reality against expert opinion or local knowledge. Feedback is important to the success of this process and local credibility. It may be advantageous to formalise this process further, and investigate how to incorporate uncertainty measures based on the feedback.

The important point to note is that if expert opinion changes, or there are several likely scenarios these could all be generated fairly readily.

**Economic implications**

If you have just skipped to this section to discover the potential dollar value of the effects of climate change, we believe this has little practical value and would be misleading without a detailed look at many aspects of barley production – which is beyond the scope of this report. It is a simple task to summarise our modelled change for each local government authority (Figure 14 and Table 6 for corresponding LGA names) and then calculate a dollar value for lost production. But what does this really tell us? Because there is considerable flexibility for adjustment in management practices e.g. planting times, row spacing and different varieties, the actual change in productivity will be less than predicted by the model. What the map does indicate are those LGAs which are likely to experience the greatest pressures to make adjustments because of climate change.

From Figure 14 the LGAs with highest pressure for change are in the northern region, including Mullewa (No. 30), Morawa (37), Perenjori (38). However all these LGAs have mean annual production of less than 15,000 tonnes. The shires with the highest yields in the
northern region are Northampton (No. 26) and Mullewa. Table 7 shows the yield potential reductions predicted by the model, given our assumptions, e.g. if no adaptation occurs and 1999 management and varieties are still used. It is likely that in some areas adaptation may not fully offset yield reductions caused by climate change. For example Lake Grace (131) has mean production of >100,000 tonnes and predicted reduction of 11 per cent. On the other hand Esperance (129) has a high total yield reduction (4,800 tonnes), but the percentage reduction is small (2%), hence adaptive changes may be able to overcome negative impacts of climate change.

Figure 14: Barley yield change for each LGA
Table 6: LGAs and corresponding identification numbers

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>No.</th>
<th>Name</th>
<th>No.</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>Northampton (S)</td>
<td>68</td>
<td>Cunderdin (S)</td>
<td>130</td>
<td>Cuballing (S)</td>
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<td>30</td>
<td>Mullewa (S)</td>
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<td>Wanneroo (C)</td>
<td>131</td>
<td>Lake Grace (S)</td>
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<tr>
<td>32</td>
<td>Chapman Valley (S)</td>
<td>70</td>
<td>Northam (S)</td>
<td>132</td>
<td>Ravensthorpe (S)</td>
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<tr>
<td>35</td>
<td>Greenough (S)</td>
<td>71</td>
<td>Swan (S)</td>
<td>133</td>
<td>Waroona (S)</td>
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<tr>
<td>36</td>
<td>Geraldton (C)</td>
<td>73</td>
<td>York (S)</td>
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<td>Williams (S)</td>
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<td>37</td>
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<td>Bruce Rock (S)</td>
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<td>Narrogin (S)</td>
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<tr>
<td>38</td>
<td>Perenjori (S)</td>
<td>75</td>
<td>Mundaring (S)</td>
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<td>Harvey (S)</td>
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<td>39</td>
<td>Mingenew (S)</td>
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<td>Narembeen (S)</td>
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<td>Dumbleyung (S)</td>
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<td>40</td>
<td>Irwin (S)</td>
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<td>Three Springs (S)</td>
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<td>Stirling (C)</td>
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<td>Wagin (S)</td>
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<td>Carnamah (S)</td>
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<td>Bayswater (C)</td>
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<td>West Arthur (S)</td>
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<td>Mount Marshall (S)</td>
<td>84</td>
<td>Belmont (C)</td>
<td>142</td>
<td>Kent (S)</td>
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<tr>
<td>44</td>
<td>Yilgarn (S)</td>
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<td>Kalamunda (S)</td>
<td>143</td>
<td>Dardanup (S)</td>
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<td>45</td>
<td>Dalwallinu (S)</td>
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<td>Beverley (S)</td>
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<td>Bunbury (C)</td>
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<td>Coorow (S)</td>
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<td>Canning (C)</td>
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<td>Capel (S)</td>
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<td>Melville (C)</td>
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<td>Moora (S)</td>
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<td>Gosnells (C)</td>
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<td>Donnybrook-Balingup (S)</td>
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<tr>
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<td>Koorda (S)</td>
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<td>Corrigin (S)</td>
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<td>Jerramungup (S)</td>
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<tr>
<td>54</td>
<td>Wongan-Ballidu (S)</td>
<td>111</td>
<td>Serpentine-Jarrahdale (S)</td>
<td>151</td>
<td>Busselton (S)</td>
</tr>
<tr>
<td>55</td>
<td>Victoria Plains (S)</td>
<td>112</td>
<td>Kwinana (T)</td>
<td>152</td>
<td>Kojonup (S)</td>
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<tr>
<td>56</td>
<td>Dowerin (S)</td>
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<td>Kondinin (S)</td>
<td>153</td>
<td>Gnowangerup (S)</td>
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<td>Gingin (S)</td>
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<td>Brookton (S)</td>
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<td>Nungarin (S)</td>
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<td>Wandering (S)</td>
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<td>Bridgetown-Greenbushes (S)</td>
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<td>Trayning (S)</td>
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<td>Rockingham (C)</td>
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<td>Nannup (S)</td>
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<tr>
<td>60</td>
<td>Wyalkatchem (S)</td>
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<td>Pingelly (S)</td>
<td>157</td>
<td>Augusta-Margaret River (S)</td>
</tr>
<tr>
<td>61</td>
<td>Goomalling (S)</td>
<td>124</td>
<td>Murray (S)</td>
<td>158</td>
<td>Tambellup (S)</td>
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<tr>
<td>62</td>
<td>Chittering (S)</td>
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<td>Mandurah (C)</td>
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<td>Cranbrook (S)</td>
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<tr>
<td>63</td>
<td>Merredin (S)</td>
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<td>Kulin (S)</td>
<td>160</td>
<td>Manjimup (S)</td>
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<tr>
<td>65</td>
<td>Toodyay (S)</td>
<td>127</td>
<td>Boddington (S)</td>
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<td>Albany (S)</td>
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<tr>
<td>66</td>
<td>Kellerberrin (S)</td>
<td>128</td>
<td>Wickepin (S)</td>
<td>162</td>
<td>Plantagenet (S)</td>
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<td>67</td>
<td>Tammin (S)</td>
<td>129</td>
<td>Esperance (S)</td>
<td>163</td>
<td>Denmark (S)</td>
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</table>
Table 7: Total yield change for 10 LGAs with largest predicted reduction

<table>
<thead>
<tr>
<th>Region</th>
<th>No.</th>
<th>1999</th>
<th>2050</th>
<th>Reduction (t)</th>
<th>Predicted % yield reduction IF NO ADAPTATION OCCURS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Grace (S)</td>
<td>131</td>
<td>101,500</td>
<td>90,200</td>
<td>11,300</td>
<td>11%</td>
</tr>
<tr>
<td>Ravensthorpe (S)</td>
<td>132</td>
<td>89,000</td>
<td>84,200</td>
<td>4,800</td>
<td>5%</td>
</tr>
<tr>
<td>Esperance (S)</td>
<td>129</td>
<td>266,400</td>
<td>261,600</td>
<td>4,800</td>
<td>2%</td>
</tr>
<tr>
<td>Gnowangerup (S)</td>
<td>153</td>
<td>92,400</td>
<td>87,700</td>
<td>4,700</td>
<td>5%</td>
</tr>
<tr>
<td>Kent (S)</td>
<td>142</td>
<td>51,200</td>
<td>46,900</td>
<td>4,300</td>
<td>8%</td>
</tr>
<tr>
<td>Mullewa (S)</td>
<td>30</td>
<td>14,200</td>
<td>10,500</td>
<td>3,700</td>
<td>26%</td>
</tr>
<tr>
<td>Northampton (S)</td>
<td>26</td>
<td>16,100</td>
<td>13,000</td>
<td>3,100</td>
<td>19%</td>
</tr>
<tr>
<td>Jerramungup (S)</td>
<td>150</td>
<td>94,800</td>
<td>92,100</td>
<td>2,700</td>
<td>3%</td>
</tr>
<tr>
<td>Kondinin (S)</td>
<td>113</td>
<td>20,500</td>
<td>18,200</td>
<td>2,300</td>
<td>11%</td>
</tr>
<tr>
<td>Corrigin (S)</td>
<td>109</td>
<td>20,700</td>
<td>18,400</td>
<td>2,300</td>
<td>11%</td>
</tr>
<tr>
<td><strong>Total (all ag region)</strong></td>
<td>1,436,700</td>
<td>1,356,700</td>
<td>80,000</td>
<td>6%</td>
<td></td>
</tr>
</tbody>
</table>

**Future opportunities**

There may be opportunities in the future for:
- Higher yields in less well drained parts of the high rainfall zone due to decreased rainfall, less waterlogging and lower disease risk
- Development of new cultivars to counter the high temperatures and shorter growing season that could be the dominant constraint to barley growth in the future, particularly in the north of the agricultural zone
- Further improvements to land and crop management, in terms of retaining soil moisture available to crops (e.g. wider row spacings in dry areas or dry years, improving soil properties such as compaction, pH, fertility, water repellence, structure etc.)
- Possible shifts in important barley growing regions.
Conclusion

This model is a useful tool as a decision support system for rapidly predicting likely climate change effects on agricultural crops based on a combination of data, available literature and ‘expert’ opinion. The results draw attention to areas of risk and opportunity.

The area suitable for barley may decrease in future over an extensive area encompassing much of the eastern, central, southern and south-eastern wheatbelt. If our high temperature constraints are valid, then large (>30 per cent) reductions in the region north of Three Springs are predicted. However these are not presently major barley growing areas.

A significant factor determining the adaptation required to deal with the expected climatic changes is how quickly they occur. It might be argued that plant breeders and agronomists have dealt with previous changes without knowing it, simply by selecting genotypes and practices that yielded well at the time. This adaptation will probably continue provided the climatic changes are no faster than in the past.

Of the areas with current high production (>50,000 tonnes) Lake Grace stands out as an LGA which will experience a relatively large (11 per cent) reduction in yield potential. It is debatable whether adaptation by growers can completely overcome this.

These results can help target research effort to assist farmer adaptation, as it highlights where management may need to be improved or adjusted, for example, different planting times, fertiliser regimes, farming systems, alternative crops or traits which could be desirable in new cultivars.

Finally, our model increased in complexity during the project. Although this appeared logical it is doubtful if the increased complexity was warranted by the marginal improvements.
References


IOCI (2002). ‘Climate variability and change in south west Western Australia’. Indian Ocean Climate Initiative Panel, Perth.


Appendix 1: Soil conditions affecting barley

Source: Young (1998)

<table>
<thead>
<tr>
<th>Soil conditions</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil water deficit</strong></td>
<td>Barley is often regarded as having a high level of drought resistance. There is little evidence to suggest that it has higher water use efficiency than wheat. It is more a case of drought avoidance through early maturity, than drought resistance.</td>
</tr>
<tr>
<td><strong>Waterlogging</strong></td>
<td>Susceptible, although it can withstand transient waterlogging. When waterlogging is only short, crops can still yield more than 3 t/ha. The development stage at which waterlogging has its largest effect on yield has not been defined clearly. The most sensitive stages appear to be between germination and emergence, the early seedling stage and when plants are elongating rapidly, which is the most rapid growth stage.</td>
</tr>
<tr>
<td><strong>Soil salinity</strong></td>
<td>Has the highest tolerance of the cereals. Under controlled conditions yield is decreased when electrical conductivity (ECe) &gt;800 mS/m, with a yield decrease of 5%/100 mS/m increase above 800 mS/m. Less tolerance during emergence and the seedling stage.</td>
</tr>
<tr>
<td><strong>Salinity and waterlogging</strong></td>
<td>Saline areas are often waterlogged and dominated by barley grass which is a host of the root disease, take-all. If barley is grown on saline areas there must be an attempt to drain the area and reduce root disease. The most practical method may be applying a high rate (approx. 200 kg/ha) of a compound fertiliser containing ammonium sulphate at seeding.</td>
</tr>
<tr>
<td><strong>Acidity: minimum pH_{Ca}</strong></td>
<td>More sensitive to aluminium toxicity than other cereals. Acid sandplain soils (e.g. wodjil) that increase in acidity with depth and have high Al levels are unsuitable. In the medium/high rainfall areas, high yielding crops are commonly grown on coarse-textured soils that are mildly acid at the surface. These soils generally become neutral with depth and have naturally low levels of Al. If the pH_{Ca} is &lt;4.5 and crops have a history of poor yields, barley is likely to respond to liming.</td>
</tr>
<tr>
<td><strong>Alkalinity: maximum pH_{w}</strong></td>
<td>More tolerant than other cereals, but most cultivars are very susceptible to boron toxicity. A feature of some alkaline soils in WA is increasing concentration of boron with depth. On these soils there is a significant yield advantage for boron-tolerant varieties such as Skiff from SA. This advantage tends to be greatest in drier years confirming the SA observation that root growth of boron-susceptible varieties into the subsoil is impeded, reducing their capacity to extract moisture from depth in a season with a dry finish.</td>
</tr>
<tr>
<td><strong>Key nutrient requirements</strong></td>
<td>The amounts of major and trace elements for optimum growth are very similar to those required by wheat. An important consideration is the optimum grain protein content for malting barley. High protein is desirable in wheat, but not in malting barley as it leads to low malt extract and a protein haze which must be precipitated out of the resulting beer. Therefore, soils and rotations which result in low protein are more suited to malting barley than bread wheat.</td>
</tr>
<tr>
<td><strong>Compacted soils</strong></td>
<td>Roots are restricted by traffic pans, so barley can respond to deep ripping.</td>
</tr>
<tr>
<td><strong>Root growth into clayey subsoils</strong></td>
<td>There is little information on the extent of root growth into clayey subsoils in WA. A study on the Esperance sandplain in 1993 (D. Tennant and K. Young unpublished) showed that barley extracted moisture to a depth of 1.3 m on a gravelly sand that had a clayey subsoil at 50 cm. On alkaline mallee soils, tolerance to high boron is likely to influence root penetration in the subsoil.</td>
</tr>
<tr>
<td><strong>Soil properties affecting germination</strong></td>
<td>Crop establishment principles are essentially the same as for wheat. Barley experiences the same problems with crusting surface soils and water repellent sands.</td>
</tr>
<tr>
<td><strong>Erosion risk</strong></td>
<td>Appears more susceptible to sand blasting than wheat.</td>
</tr>
</tbody>
</table>
Appendix 2: Barley capability and land qualities

Table A1: Barley capability

<table>
<thead>
<tr>
<th>Land quality</th>
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<th>LC3</th>
<th>LC4</th>
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<td>Flood hazard (f)</td>
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<td>L</td>
<td>M</td>
<td>H</td>
<td>XX</td>
</tr>
<tr>
<td>pH at 0-10 cm (zf)</td>
<td>Slac</td>
<td>N</td>
<td>Mac</td>
<td>Malk</td>
<td>Sac</td>
</tr>
<tr>
<td>pH at 50-80 cm (zg)</td>
<td>Slac</td>
<td>N</td>
<td>Mac</td>
<td>Malk</td>
<td>Salk</td>
</tr>
<tr>
<td>Phosphorus export risk (n)</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>V H</td>
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<tr>
<td>Salinity hazard (y)</td>
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<td>PR</td>
<td>MR</td>
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<tr>
<td>Surface salinity (ze)</td>
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<td>S</td>
<td>M</td>
<td></td>
<td>H</td>
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<td>Salt spray exposure (zi)</td>
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<td></td>
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<td></td>
<td>S</td>
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<tr>
<td>Surface soil structure decline susceptibility (zb)</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>XX</td>
<td></td>
</tr>
<tr>
<td>Subsurface acidification susceptibility (zd)</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Subsurface compaction susceptibility (zc)</td>
<td>L</td>
<td>M</td>
<td>XX</td>
<td></td>
<td>H</td>
</tr>
<tr>
<td>Traficability (zk)</td>
<td>G</td>
<td>F</td>
<td></td>
<td>P</td>
<td>VP</td>
</tr>
<tr>
<td>Rooting depth (r )</td>
<td>V D</td>
<td>D</td>
<td>M</td>
<td>MS</td>
<td></td>
</tr>
<tr>
<td>Water erosion hazard (e)</td>
<td>VL</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>VH</td>
</tr>
<tr>
<td>Waterlogging / inundation risk (i)</td>
<td>N</td>
<td>VL</td>
<td>H</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>Water repellence susceptibility (za)</td>
<td>N</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>XX</td>
</tr>
<tr>
<td>Soil water storage (m)</td>
<td>H</td>
<td>M</td>
<td>ML</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Wind erosion risk (w)</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A2: Land quality rating descriptions

<table>
<thead>
<tr>
<th>Land quality</th>
<th>Subscript</th>
<th>Rating description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of excavation</td>
<td>x</td>
<td>H (high), M (moderate), L (low), VL (very low)</td>
</tr>
<tr>
<td>Flood hazard</td>
<td>f</td>
<td>N (nil), L (low), M (moderate), H (high)</td>
</tr>
<tr>
<td>Land instability</td>
<td>c</td>
<td>N (nil), VL (very low), L (low), M (moderate), H (high)</td>
</tr>
<tr>
<td>Microbial purification</td>
<td>p</td>
<td>VL (very low), L (low), M (moderate), H (high)</td>
</tr>
<tr>
<td>pH at 0-10 and 50-80 cm depth</td>
<td>zf</td>
<td>V sac (very strongly acid), Sac (strongly acid), Mac (moderately acid), Slac (slightly acid), N (neutral), Malk (moderately alkaline), Salk (strongly alkaline)</td>
</tr>
<tr>
<td>Phosphorus export hazard</td>
<td>n</td>
<td>L (low), M (moderate), H (high), VH (very high) E (Extreme)</td>
</tr>
<tr>
<td>Rooting depth</td>
<td>r</td>
<td>VS (&lt;15), S (&lt;30), MS (30-50), M (50-80), D (&gt;80), V D (&gt;150) cm</td>
</tr>
<tr>
<td>Salinity hazard</td>
<td>y</td>
<td>NR (no hazard), PR (partial or low hazard), MR (moderate hazard), HR (high hazard), PS (saline land)</td>
</tr>
<tr>
<td>Salt spray exposure</td>
<td>zi</td>
<td>S (susceptible), N (not susceptible)</td>
</tr>
<tr>
<td>Site drainage potential</td>
<td>zh</td>
<td>R (rapid), W (well), MW (moderately well), M (moderate), P (poor), VP (very poor)</td>
</tr>
<tr>
<td>Land quality</td>
<td>Subscript</td>
<td>Rating description</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>-----------</td>
<td>------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Soil absorption</td>
<td>zj</td>
<td>H (high), M (moderate), L (low), VL (very low)</td>
</tr>
<tr>
<td>Soil water storage</td>
<td>m</td>
<td>VL (&lt;35), L (35-70), ML (70-100), M (100-140), H (&gt;140 mm/m for 0-100 cm or the rooting depth)</td>
</tr>
<tr>
<td>Soil workability</td>
<td>k</td>
<td>G (good), F (fair), P (poor), VP (very poor)</td>
</tr>
<tr>
<td>Subsurface acidification susceptibility</td>
<td>zd</td>
<td>L (low), M (moderate), H (high), P (presently acid)</td>
</tr>
<tr>
<td>Subsurface compaction susceptibility</td>
<td>zc</td>
<td>L (low), M (moderate), H (high)</td>
</tr>
<tr>
<td>Surface salinity</td>
<td>ze</td>
<td>N (nil), S, (slight), M (moderate), H (high), E (extreme)</td>
</tr>
<tr>
<td>Surface soil structure decline suscep-</td>
<td>zb</td>
<td>L (low), M (moderate), H (high)</td>
</tr>
<tr>
<td>tibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trafficability</td>
<td>zk</td>
<td>G (good), F (fair), P (poor), VP (very poor)</td>
</tr>
<tr>
<td>Water erosion hazard</td>
<td>e</td>
<td>VL (very low), L (low), M (moderate), H (high), VH (very high), E (extreme)</td>
</tr>
<tr>
<td>Water repellence susceptibility</td>
<td>za</td>
<td>N (Nil), L (low), M (moderate), H (high)</td>
</tr>
<tr>
<td>Waterlogging/inundation risk</td>
<td>i</td>
<td>N (nil), VL (very low), L (low), M (moderate), H (high), VH (very high)</td>
</tr>
<tr>
<td>Wind erosion hazard</td>
<td>w</td>
<td>L (low), M (moderate), H (high), VH (very high), E (extreme)</td>
</tr>
</tbody>
</table>
Appendix 3: Selection of temperature limitations

Warmer temperatures tend to occur toward the end of the growing season; hence the likelihood of high temperatures in August to October was used to indicate where crops may be affected. However, monthly average figures need to be related to daily climate records.

Figure A1 shows the daily records for Salmon Gums in 1995. In the middle of the period (46 days) the average maximum temperature from the trend line is just over 20°C. On day 1 it is 15.6°C and day 92 it is 28.6°C. The daily records show that the maximum temperature can vary considerably from this mean, with maximum temperatures ranging from a low of just under 12°C to a high of 36°C.

The minimum temperatures for September (Figure A2) display a similar pattern, with an average value of about 7.3°C, and a range from 0.3 to 13.2°C.

Figure A1: August to October maximum temperatures from Salmon Gums Research Station (1995)

Figure A2: September minimum temperatures from Salmon Gums Research Station (1995)
Another way of looking at the maximum and minimum temperatures is to consider a summary of selected stations from daily records. Table A3 shows an average maximum temperature of 22.17°C at Binnu (see Figure A3) from 1961 to 1990. However, the highest temperature over this period was 39.5°C. Table A4 shows that at Binnu approximately 18 days per year are greater than 25°C, five days are greater than 30°C and it only exceeds 35°C every second year during August to October.

Table A3: Minimum and maximum temperatures from 1961 to 1990 for August, September and October

<table>
<thead>
<tr>
<th>Station</th>
<th>August-October average °C</th>
<th>Lowest minimum °C</th>
<th>Highest maximum °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binnu</td>
<td>22.17</td>
<td>13.00</td>
<td>39.50</td>
</tr>
<tr>
<td>Grass Patch</td>
<td>19.72</td>
<td>10.00</td>
<td>40.50</td>
</tr>
<tr>
<td>Mullewa</td>
<td>22.92</td>
<td>11.00</td>
<td>39.00</td>
</tr>
<tr>
<td>Salmon Gums Research Station</td>
<td>20.15</td>
<td>9.40</td>
<td>40.00</td>
</tr>
</tbody>
</table>

Table A4: Average number of days per year in August to October where the temperature values are exceeded

<table>
<thead>
<tr>
<th>Station</th>
<th>&gt;25°C</th>
<th>&gt;30°C</th>
<th>&gt;35°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binnu</td>
<td>18.4</td>
<td>5.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Grass Patch</td>
<td>11.9</td>
<td>3.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Mullewa</td>
<td>26</td>
<td>8.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Salmon Gums Research Station</td>
<td>15.9</td>
<td>4.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

From Figure A3, which shows the maximum temperature from 1961 to 1990, it can be seen that Binnu falls in the 22 to 23°C category. This is confirmed by information in Table A3.

So for the values of temperature extremes for wheat, and using knowledge in the northern agricultural region, we know that wheat growth can be reduced when temperatures exceed 23°C. From the weather station information we can see that temperatures over 30°C are not uncommon (can occur between three and eight days a year). This knowledge was used to decrease wheat yields slightly as the monthly mean temperatures increase, shown in Table A5. Note that the example below shows a linear reduction, but any increments can be used. The actual temperature change over the scenarios is just less than one degree, hence only a very small portion of the high or low temperature adjustments is used. Temperature effects outside of this range are probably not valid, but are included as a starting point in case the model is used in other regions, or for crops with more severe temperature constraints.
The logic for the low temperatures is the same as for high temperatures, as described above. Low temperatures affect growth rates, however there is also increased frost risk (see Figure A5), which can result in direct plant damage. Note that although it is colder in July, frosts in September are more damaging, hence the minimum temperatures in September are used in the model.
Table A6: Minimum September temperatures 1981 to 1990

<table>
<thead>
<tr>
<th>Station</th>
<th>Average</th>
<th>Lowest minimum</th>
<th>Highest minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bodallin South</td>
<td>6.5</td>
<td>-0.5</td>
<td>15.0</td>
</tr>
<tr>
<td>King Rocks</td>
<td>6.2</td>
<td>-0.5</td>
<td>15.0</td>
</tr>
<tr>
<td>Wandering Comparison</td>
<td>5.4</td>
<td>-2.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Williams Post Office</td>
<td>6.5</td>
<td>-2.0</td>
<td>13.0</td>
</tr>
</tbody>
</table>

Table A7: Average number of days in September when temperature is less than stated

<table>
<thead>
<tr>
<th>Station</th>
<th>&lt;10°C</th>
<th>&lt;5°C</th>
<th>&lt;0°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bodallin South</td>
<td>25.1</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>King Rocks</td>
<td>26.7</td>
<td>10.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Wandering Comparison</td>
<td>25.8</td>
<td>13.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Williams Post Office</td>
<td>25.6</td>
<td>8.8</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Figure A4: Climate surface of September mean monthly minimum temperatures
Table A8: Wheat yield reduction as mean minimum temperatures decrease

<table>
<thead>
<tr>
<th>September average minimum temperatures</th>
<th>Yield reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;5.6</td>
<td>No reduction</td>
</tr>
<tr>
<td>5.4-5.6</td>
<td>0.95</td>
</tr>
<tr>
<td>5.2-5.4</td>
<td>0.90</td>
</tr>
<tr>
<td>5.0-5.2</td>
<td>0.85</td>
</tr>
<tr>
<td>………….and so on to zero yield</td>
<td></td>
</tr>
</tbody>
</table>

Figure A5: Frost days in September between 1980 and 2004

For wheat and barley more temperature information was available and hence more confidence in the selection of temperature values. As wheat is the most widely grown crop in the region, field knowledge within the Department of Agriculture gave further confidence to these selections.

The crops were then ranked in terms of temperature sensitivity, as the actual Ecocrop (FAO 1996) and PlantGro™ (Hackett 1999) numbers were only a rough guide. The temperature constraints were then simply scaled up or down in relation to the wheat (but also barley) temperature values. This method is similar in principle to the way crop agronomists often use wheat as a reference point for comparing other crop yields.