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Costs of climate change - impacts on farm incomes in English GO regions

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Costs of climate change - impacts on farm incomes in English GO Regions

Report

Submitted to

Department for Environment, Food and Rural Affairs

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Table of Contents

1. INTRODUCTION 1
1.1 Objectives 1
1.2 Previous research used in this analysis 1
2. METHODOLOGY 2
2.1 Climate change scenarios and input data 3
2.2 Determining simple models of crop yield 4
2.2.1 Initial analysis - linear regressions using only Scottish data 5
2.2.2 Extended analysis - extending the dataset and simplifying variables 6
2.3 From changes in crop yield to changes in income 7
3. RESULTS 9
3.1 Predicted changes in relative yield 9
3.2 Predicted changes in farm income 11
3.2.1 Changes by GOR 11
3.2.2 Changes by scenario and crop type 12
3.3 Predicted changes in regional income from agriculture. 15
4. DISCUSSION 16
4.1 Options for future work to use and refine predictions 17
4.2 Summary 18
REFERENCES 18
APPENDIX 1 - EXAMPLES OF CROPSYST OUTPUT FOR SCOTTISH SITES 19
APPENDIX 2 - RAW DATA AND FITTED MODELS 21
APPENDIX 3 - REVENUE CHANGES BY GOR AND CROP TYPE 22

1. Introduction

1.1 Objectives

This study focuses on the impacts of climate change on the agricultural sector. The specific objectives of the current study are to transfer the results of Hanley *et al.* (2005) from Scotland to each of the English Government Office Regions (GOR). As this is not a piece of primary research it is, by its nature, unable to analyse issues not previously covered by Hanley et al. such as:

- adaptation (other than that modelled in the initial study),
- the implications of alternative socio-economic scenarios or
- interactions with other sectors of the economy.

The transfer of results can only be carried out for two UKCIP02 climate change scenarios (high and low emissions) at three different dates in the future included in the earlier study. As such it is an exercise in identifying the key climate parameters in terms of those which had the largest impact in the modelled results rather than those identified through field experimentation or other techniques. By necessity, this is an exercise in greatly simplifying and extending beyond initial limits very complicated model output, and the results reported here should be interpreted with that in mind.

1.2 Previous research used in this analysis

A recently completed study (Hanley *et al.* 2005) into the impacts of climate change on farm incomes in Scotland calculated the impacts on four sites across the country. That study had three distinct stages. Firstly, potential yields were estimated for various crops and pasture at each site under a number of climate change scenarios. A management model was then used to identify the optimal land use for farmers given economic constraints and changing potential yields. Finally, the change in relative farm income and resultant changes in regional and national GDP were calculated using multipliers calculated from regionally-disaggregated input-output tables for Scotland.

In order to estimate expected changes to yields Cropsyst, a crop yield estimation model, was used (Stockle, Martin and Campbell, 1994). For any given analysis Cropsyst requires weather, field, management and crop data. Weather data are required in daily time steps for at least maximum and minimum temperature and precipitation, and in this study solar radiation data were also provided. These data were derived for each site from two sources. Predictions of future climate change were taken from UKCIP (Hulme *et al.* 2002), which provided estimated changes on a 50 km^2 scale. Historical weather data for each site was taken from Met office data held by the British Atmospheric Data Centre (BADC). A weather generator, LarsWG, was then used to estimate daily weather for each site in each time period.

Field level data required by Cropsyst included altitude and slope of the site, and soil data such as soil texture, pH, water content etc (derived for the Scottish sites from Murphy *et al.* (1998)). Management data required are fertiliser input, irrigation, planting date and criteria for harvest or clipping. Fertiliser input data were taken from the Scottish Farm Management Handbook (SAC 2001). Planting date was chosen for each year group after an analysis of crop yield data for sample crops planted on various days (in a weekly time step). It was thought that this allowed for some adaptation by farmers to changing climatic conditions thus accounting for the "dumb farmer scenario", without assigning farmers precognisense of the coming years weather. This was the only way in which adaptation, other than that provided by the management model, was included in the analysis and it was assumed that this adaptation would take place; as such data derived from this study includes this level of adaptation. It was also possible, with additional parameterisation, for

Cropsyst to automatically compute planting dates, however, the results of this were often counterintuitive in the face of climate change[1].

Cropsyst requires a large number of crop parameters including data on crop growth, morphology, phenology, vernalisation, photo-period, harvest, nitrogen and CO_2 interactions and hardiness. The crops chosen for analysis were Winter and Spring varieties of Wheat, Barley, Oats and Oil Seed Rape, with pasture as the final 'crop'. The results for these crops appear to be accurate as can seen in the Table 1, where yield estimates derived from the model but using present climate are compared to the yield ranges from farm surveys. Sample data of the predictions obtained for Scottish sites for the change in crop yields given climatic change are presented in Appendix 1.

Table 1. A comparison of estimated yield for southern Scottish sites given 'present' UKCIP weather estimations and the Farm Management Handbook's ranges.

Crop	FMHB range* tonnes/ha	Estimated yield range tonnes/ha
Winter Wheat	6 to 10	8.1 to 9.5
Winter Barley	6 to 9	6.9 to 8.6
Winter Oats	6 to 9	6.2 to 8.5
Winter OSR	3 to 4	3.3 to 3.4
Spring Wheat	4.5 to 8.5	4.4 to 5.7
Spring Barley	4 to 7	5.3 to 6.4
Spring Oats	3.5 to 6.5	5.4 to 6
Spring OSR	1.6 to 2.6	1.6 to 1.7
Pasture**	6.7 to 11.8	8.6 to 9.2

* These ranges are taken from the ranges for which gross margin data are given.
** 120 kg Nitrogen application assumed

2. Methodology

The overall methodology adopted in this study is as follows:

- develop models to transfer Scottish crop yield results to England;
- predict changes in yield for crops in English GORs;
- predict changes in farm incomes.

It should be noted that the management component of the Scottish work is not being used in this transfer study, nor is the use of regional multipliers based upon the gross margins for each crop and existing landuse. In the former case this is because we do not have access to a suitable suite of farm management models for English GOR, and developing such a suite was far outwith the resources and timescale of this project. **The important implication of this is that our results do not allow for profit maximising adaptations to occur to land use and land management over time as climate changes. They show changes in farm incomes assuming current cropping patterns persist.** Similarly, suitable disaggregated regional I-O tables are not available for England. It was decided that other factors which could not be dealt with in this study would affect both of these components (such as farmers decisions being influenced by legislation changes, changes in farm/economic structures) and these could not be incorporated within the timescale of the present study.

[1] For a given determinate crop Cropsyst would calculate the planting date based upon mean temperature (amongst other variables). Given a warming of the climate Cropsyst would calculate earlier planting whilst it is likely that farmers will delay planting to account for lower yields caused by the increased rates of maturation and grain filling.

As a consequence, the final results in this report will be expressed in changes in income by crop and GOR, in terms of £ per ha per crop type.

2.1 Climate change scenarios and input data

Hanley *et al.* (2005) made use of the UKCIP02 scenarios for predicting the effects of future climate on crops. In particular, use was made of predicted weather data that are available at a 50 km grid-square basis for the whole of the UK. The low and high emissions output scenarios were used for each of the following dates: 2020; 2050; 2080, resulting in a total of 6 scenarios. These same six scenarios are the basis of the present study. Further details of the UKCIP02 scenarios can be found in Hulme *et al.* (2002).

The data used as the basis for analysis in this study was initially from the four sites used in the original study. However, it was immediately obvious that the data from one site (Skerray, on the north coast of Scotland) was very different to the other Scottish sites and even further removed from England, and was dropped. Initial analysis therefore used data from three sites in Scotland, shown on Figure 1 by UKCIP02 grid number (Glensaugh 163; Auchincruive 215; East Linton 218). For reasons explained later, a further site located in grid 376 in England was used to provide input data. To predict changes in each GOR, a grid square within each region was selected (Figure 1), and all data locations are summarised in Table 2. The data from all sites that were used in this study were from using 'normal' fertiliser levels in Cropsyst for each crop type (these amounts, in kg ha^{-1} are: spring barley 100; spring oats 80; spring wheat 160; spring OSR 110; winter barley 180; winter oats 120; winter wheat 200; winter OSR 185, and pasture 200.

Table 2. UKCIP02 grid squares used for all crop yield input data and predictions.

UKCIP02 GRID SQ	DESCRIPTION
163	Input data for modelling - excluded from final analysis
215	Input data for modelling
218	Input data for modelling
376	Input data for modelling - added to extend dataset
	GO Regions - predictions made for these locations
238	North East
255	North West
296	Yorkshire and the Humber
334	East Midlands
352	West Midlands
375	Eastern
412	South West
415	South East

Figure 1. The UKCIP02 grid, showing the location of data used in modelling (grids 215, 218 and 376, with 163 data excluded from the final analysis) and the grids selected as representing the different GO Regions.

2.2 Determining simple models of crop yield

Given the complexity of Cropsyst and the time required to parameterise and run the programme, it was not possible within this study to run it for each crop for each GOR. It was therefore decided that the available Cropsyst data would be analysed for broad scale patterns that could be used as the basis for yield predictions in England.

Dependant variable
Preliminary examination of all data suggested that the best dependant variable to use was relative yield, i.e. the yield at time *t* expressed as a proportion of the current yield. Note that other data examined included actual yield, and actual change in yield (both in tonnes per ha), but patterns with the independent variables were clearest using relative yield.

Independent variables
It was also not possible to collect, within the timescale of this project, any new primary data regarding all sites, so the explanatory variables used in any analysis had to be readily available for all sites. The obvious data to use was the future climate data used as input for Cropsyst, as this formed part of the basis of the predictions for Scotland and was also available for the whole of England. This also makes good agronomic sense because although there will be other factors affecting crop yield (e.g. pest incidence, soil changes, etc), climate will probably be the driving factor in potential yield changes in the future. Although actual 'average' future climate data was calculated and examined against the above dependant variables, the clearest patterns were seen when using the data that

quantified the difference between the future climate and the current climate. Climate variables at two levels were used: those that quantified the differences in each season (3-month blocks), and those that quantified the differences over the whole year. Three different climate variables were used in this way: precipitation, temperature, and solar radiation. In additional, the predicted CO_2 level (in ppm) was also used as predictor variable (note that carbon enrichment is assumed, but no account is taken of the possible mitigating impacts of O_3).

2.2.1 Initial analysis - linear regressions using only Scottish data

Initial analysis using data from the three Scottish sites used linear regression to identify the best predictors of relative yield change. Hierarchical partitioning used all the seasonal climatic variables, and also separately the annual climate variables. It was found that for this dataset, average r^2 values of 0.8 - 0.9 were obtained (by crop type), typically utilising only two weather variables (either seasonal, or more commonly annual) in a linear regression. One of these two variables was always precipitation change.[2]

The relative yield relationship with precipitation is illustrated in Figure 2A, which shows the relative yield of winter wheat against annual precipitation decline for the three Scottish sites. Glensaugh (the most northerly of the three sites) shows a strong linear increase in relative yield with decreasing precipitation. However, note that the East Linton site, the one considered closest in current and future climate to much of England, shows a decrease in yield at larger precipitation decreases (i.e. in the more extreme scenarios). This is undoubtedly due to water shortage becoming an increasing problem with more extreme climate change, and indeed it is water shortage that will become the limiting factor in crop growth in many areas in the future, particularly in England. This dropoff in yield is not shown at the other two sites due to there being enough rainfall at these sites (and indeed across much of Scotland) to sustain the increased yields driven by concurrent increased radiation, increased temperatures and CO_2 fertilisation.

[2] Defined as the average anomalies of precipitation rate (i.e. yearly or seasonally) with respect to simulated 1961-1990 climate.

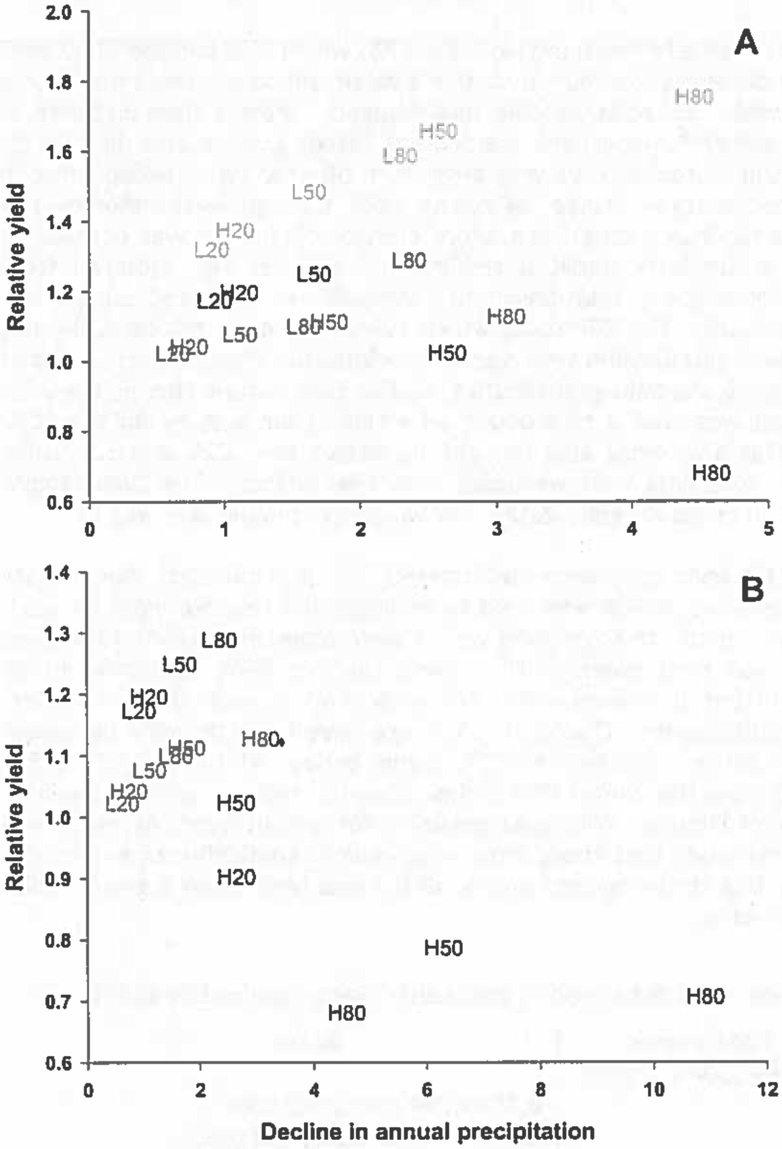

Figure 2. Relationship between annual precipitation decline (mm) and relative winter wheat yield: (A) for the three Scottish sites; (B) for the two Scottish sites and Brooms Barn used in the final analysis. Site colours: green = Glensaugh; red = Auchincruive; blue = East Linton; black = Brooms Barn. Symbol codes: H = high emissions scenario; L = low emissions scenario; number refers to year of prediction.

2.2.2 Extended analysis - extending the dataset and simplifying variables

On the basis of the above results it was felt that the Glensaugh site should be dropped from this analysis due to the strong sustained increase in yield, as sites in England are likely to suffer from water shortage as in East Linton. Note that Auchincruive, as an intermediate site, was retained. To provide more input data into the analysis an additional site, located in south-east England, was added. By incorporating the results from such a site into the analysis we hope to cover the range of precipitation drop and yield change across England. The site selected was Brooms Barn (in grid 376 Eastern GOR, see Figure 1). Cropsyst was parameterised and run for this site for each of the nine crop types, but only for the high emissions scenarios (in order to obtain results at the extreme of the precipitation decrease spectrum). The Brooms Barn site also used soil data for the SW of Scotland site, although this is not critical for analysis as soils are adaptive in the model. Carbon enrichment is assumed, but no account is taken of the possible mitigating impacts of O_3.

The results from the Brooms Barn site are shown in Figure 2B, which also has the Glensaugh data removed. It now immediately obvious that the overall shape of the relationship between precipitation decrease and relative yield has changed - after a short increase in yield (when there is still sufficient water) the yield drops rather quickly and then levels out. This shape of relationship is found to varying degrees in all crop types except oilseed rape (OSR). Given that precipitation change (affecting yield through water shortage) is likely to be the defining variable in crop growth under climate change, it was decided to use only precipitation as a predictor variable (additional variables also suffered from colinearity). Data showing the shape of relationship in Figure 2B were analysed using a log-Gaussian (log-Normal) relationship. The OSR data, which even after the addition of Brooms Barn data maintained a linear relationship with spring precipitation change, was analysed using linear regression. Due to modelling difficulties at the East Linton site in the high emissions scenarios, Cropsyst was unable to produce an estimate for pasture for the 2080 time period. The same difficulties were also thought to distort the 2020 and 2050 high emissions pasture data, so these data were excluded from that analysis. The final sample sizes were therefore 15 for all crops except pasture, for which the sample size was 12.

Once regression equations for each crop were determined, the precipitation change data for the selected grid squares in each GOR was used to estimate the relative yield for each crop type. At this stage some of the relative yield values were amended slightly (discussed in the results section). It was then intended that these relative yield values would be multiplied by the actual current (baseline) yields for each drop in each GOR. However, baseline data coverage was incomplete (Table 3), with crop-specific data (split by season and GOR) only available for three crops (winter OSR, spring barley, winter barley). Spring OSR yields were calculated from the winter OSR yields using the ratio of spring to winter yields (0.677) for the whole of England. With data available for overall yields of wheat and oats, it was assumed for this study that these data were mainly applicable to the winter varieties. To convert these data to spring data a ratio of 0.7 was used as an approximation of the spring to winter yield ratio.

Table 3. Summary of current yield data used in this study. Data supplied by DEFRA.

Crop type	Data source	Notes
Spring barley	DEFRA 2004 statistics	
Spring oats		0.7* winter oats yield used
Spring OSR		0.677 * winter OSR yield used
Spring wheat		0.7 * winter wheat yield used
Winter barley	DEFRA 2004 statistics	
Winter oats	DEFRA 2004 statistics	Assumed that statistics are applicable
Winter OSR	DEFRA 2004 statistics	
Winter wheat	DEFRA 2004 statistics	Assumed that statistics are applicable
Pasture	DEFRA advice	Max 15 t ha, 10 t ha used in this study

2.3 From changes in crop yield to changes in income

In order to move from yields to income it was necessary to analyse gross margins, i.e. the profit cost relationship for each unit of yield, detailed in Table 4. As initial data for the Cropsyst analysis was carried out using data from the FMHB 2001 this was used as the source for gross margin data in the present study. With the exception of pasture gross margins were available for all crops for a range of yields from which it was possible to calculate a value per tonne of grain output and average variable costs.

Equivalent data is not available for pasture, as grazing densities vary along with the yield of grass and different animals have different costs and values, and Cropsyst does not estimate this usage. As grazing density may not vary directly with yield it was not possible to assume a relationship in this way. Instead the revenue of hay was used along with the cost of pasture. It is also necessary to bear in mind that our initial Cropsyst analysis only considered grain yields and as such revenue from straw is not considered in this analysis. It is particularly important to consider this as it means that OSR revenues are comparatively higher as there are no straw yields from this crop.

With gross margin data it is possible to calculate the gross margins per hectare for each crop in each time period. This data is then be used to estimate the expected change in per hectare revenue for each crop type in each of the GORs, using the relative yield estimates. Note that this assumes constant real prices.

Table 4. Data used for Gross Margins calculation (source: FMHB 2001).

Crop	Revenue per kg	Cost per ha
Spring Barley	0.06	173
Spring Oats	0.06	141
Spring OSR	0.11	151
Spring Wheat	0.064	229
Winter Barley	0.06	214
Winter Oats	0.06	186
Winter OSR	0.11	299
Winter Wheat	0.064	265
Pasture	0.05	120

3. Results

3.1 Predicted changes in relative yield

The results from curve fitting and linear regression are summarised in Table 5, and an example of a fitted Log-normal curve shown in Figure 3. The average r^2 value is 0.51, with the range from 0.37 to 0.73. The remaining fitted lines/curves with confidence intervals are shown in Appendix 2.

Table 5. Summary of curve-fitting and linear regression results. Note that F and P values are only produced for the linear regression models.

Crop type	Fitted line type	F- and P-values	r^2 value
Spring barley	Log-normal	-	0.45
Spring oats	Log-normal	-	0.51
Spring wheat	Log-normal	-	0.39
Spring OSR	Linear	$F_{1,13} = 36$, $P < 0.001$	0.73
Winter barley	Log-normal	-	0.42
Winter oats	Log-normal	-	0.37
Winter wheat	Log-normal	-	0.65
Winter OSR	Linear	$F_{1,13} = 22$, $P < 0.001$	0.62
Pasture	Log-normal	-	0.43

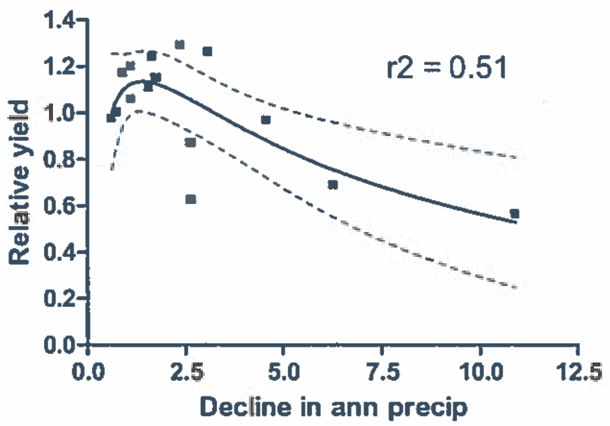

Figure 3. Example of Log-normal curve fitted to Spring oats relative yield and decline in annual precipitation data, with 95 % confidence intervals shown.

Using the curves shown in Appendix 2, relative yields were predicted for the eight GO regions in England, based on the UKCIP02 predicted changes in precipitation. However, the predicted relative yield values showed some anomalies arising from using regression equations beyond the range of their input data. The first type of anomaly is shown in Figure 4. As a result of using a log-Normal curve for most crops, the modelled line declines very sharply to the left of the peak. This means that for small decreases in precipitation very large decreases in yield result. It was therefore decided that for such predicted values the predictions would be re-set to 1, i.e. no change in yield. This is appropriate as the predictions for which this correction is required are those where little change in precipitation is anticipated, and therefore little change in yield may be expected. Out of a total of 336 relative yield predictions made, 16 were corrected in this way (most in grid square 255 in the North West, close to the Scottish study sites).

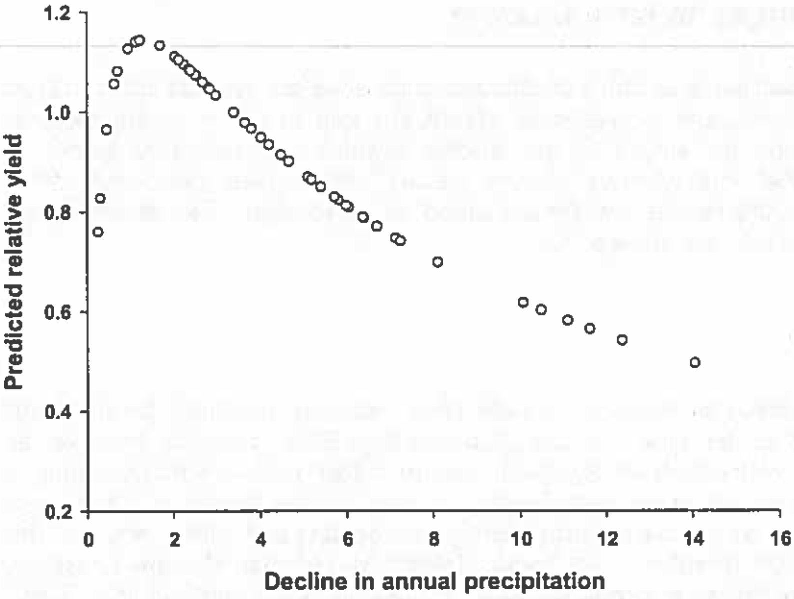

Figure 4. Example of output from predicting relative yield using a log-Normal curve (in this case, for winter wheat). Note the three points at the extreme left of the curve, where the relative yield predictions are below 1.

The second type of anomaly arises from using the oilseed rape linear regression equations, illustrated in Figure 5. Again resulting from using the regression beyond the original data, it can be seen that under higher decreases in spring precipitation (to the left hand side of the graph), the predicted relative yield falls below 0. All such values (4 in total from 42 predictions) have been set to 0 (implying crop failure). All results that arise from using the regression equations outside the input data range are highlighted in the final revenue change results, and care should be taken in subsequent interpretation, as discussed later.

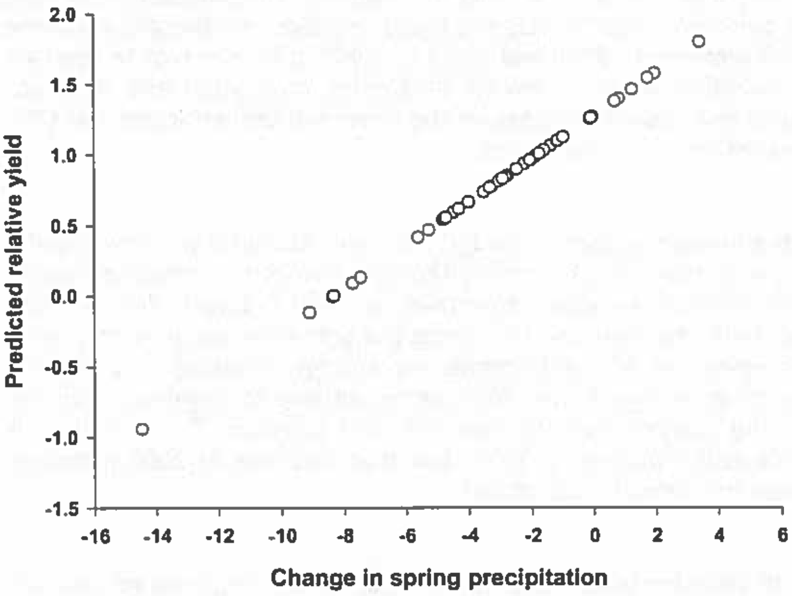

Figure 5. Example of oilseed rape predicted relative yield using linear regression equation. Note the three points at the left of the graph, showing <0 relative yield predictions.

3.2 Predicted changes in farm income

All data presented in this section is in terms of changes in revenue per hectare of each crop (compared to current income), and is presented graphically and in tables in Appendix 3. The overall trends in results for each GOR are briefly outlined and discussed below. It should be remembered that the revenue change results are derived exclusively from changes in crop yield, and the results will be described and discussed in those terms. No changes in the optimal crop mix are allowed for.

3.2.1 Changes by GOR

North East

The crops in this GOR all show an increase in yield (and therefore revenue) for the 2020 scenarios, which then tend to decrease into the 2050 and then 2080 scenarios. However as this GOR is expected, as with much of Scotland, not to suffer from water becoming a limiting factor to the same extent as southern England, some increase in yield is maintained even in the 2080's (with the exceptions of spring barley, spring oats and winter wheat). The high emissions scenario tends to suffer from lower yields/revenue than the low emissions scenario. Note that pasture shows a strong increase in yield in 2020, continuing to 2050, and although the increase continues to 2080 it is at a decreased rate.

North West

This GOR is closer in climate to the Scottish sites than even the North East discussed above, and this shows in the results. It is clear from the table in Appendix 3 that many of the relative yield predictions had to be reset to 1, resulting in predictions of no change in yield and therefore income. This is because the initial relative yield predictions were on the steep initial part of the log-Normal graph, as a result of the precipitation changes in this GOR being very little from the baseline climate. These values were therefore reset to 1 resulting in no change. Note also that there are also several predictions resulting from precipitation data outwith the range of the input data, but which were not small enough (i.e. falling below a relative yield of 1) to be reset. In the case of OSR, the values outwith the range of the equations are those where the spring precipitation increased more than the upper value used in the input data. The overall result of the climate remaining relatively wet and so there being no water shortage is that the yields and therefore income (with a couple of exceptions) increase to 2050 and again to 2080. Also note that in contrast to other GORs, the high emissions scenario results in greater crop yield and resultant income, due to plants being able to take advantage of the increased temperatures and CO_2, without water becoming restricting as in other areas.

Yorkshire and The Humber

All results for the 2080 high emissions scenario are derived from precipitation data outwith the range of the input data, with the result for winter OSR being reset to a relative yield of zero, and a consequent high income decrease (effectively a 'crop failure'). For all crops except winter oilseed rape, both the high and low emissions scenarios result in increased yields/income in 2020. However, as water becomes increasingly limiting in 2050 and increasingly in 2080, the revenue change moves from being positive to negative, with the high emissions scenario decline steeper than the low emissions scenario. The exception is pasture, which maintains increased income in 2050, but then declines in 2080 (although with a very marked difference between the scenarios).

East Midlands

All crops show an increase in yield for both scenarios in 2020. For all crops except pasture these yields then decline to 2050, although the low emissions scenario maintains a much reduced revenue increase, whereas in the high emissions scenario revenue changes become negative. The 2080 results show the scenarios diverging even more, with the revenue loss under high emissions being much more than that for the low emissions. For pasture, both emissions scenarios have increased yields and revenue in 2020, and then higher but very similar increased yields in 2050. The results then diverge in 2080, with the low emissions scenario maintaining the increased yield, but the high emissions scenario dropping sharply (though still maintaining a revenue increase).

West Midlands
All of the high emissions scenario 2080 predictions are again derived from precipitation data outwith the input data, with the same for all except the 2020 OSR predictions. In addition three of these predictions were reset to a relative yield of 0, resulting in crop failure and subsequent high revenue losses. The overall pattern of the data is similar to that of the East Midlands, with increased yields/revenue in 2020 (with the exception of winter OSR), declining to 2050 and 2080, with the high emissions scenario declining at a greater rate. The pasture data is also similar to East Midlands, with increased yield maintained in all scenarios/years, but with very divergent scenario results by 2080.

Eastern
Only two OSR predictions were derived from precipitation data outwith the range of the input data. All crops show an increase in yield in 2020, with results very similar for the two scenarios. All crops except pasture show a decreased income change to 2050, tending to result in low emissions scenario maintaining a positive income change, but the high emissions scenario becoming negative. This divergence again becomes more pronounced in 2080, with the high emissions scenario having much greater yield and revenue decreases compared to the low emissions scenario. Again, pasture is the exception, showing the same pattern as described in the previous two GORs.

South East
All crop predictions in 2080 except OSR were derived from data outwith the range of input data. The overall patterns evident in the results are the same as those described above, with a 2020 increase in yield/revenue declining to 2050 and 2080, becoming revenue losses by 2080. Again, the difference between the scenarios become more evident by 2080, and pasture also shows the same pattern as previously described.

South West
All high emissions 2080 predictions are derived from precipitation data outwith the range of the input data, with the same true for the 2050 OSR results. In addition, the winter OSR 2080 result was also reset, hence the high income loss. The overall pattern in the results is again the same as described previously.

3.2.2 Changes by scenario and crop type

The descriptions above are based on an examination of the data within each GOR individually. With such a large dataset there are obviously many ways in which the data can be compared, not all of which can be explored in this report. However, some of the results have been compared across GORs in Figures 6, 7 and 8. Figure 6 shows the results for the spring crops across all GORs, comparing the results for the years 2020 and 2080 high emissions scenario.

The most obvious pattern across these results is that the revenue changes are mostly positive for the 2020 results, in contrast to the 2080 results. The exception to this is in the North West where the 2080 results for all crops are greater than the 2020 results. This is because, as noted above, the increased growth potential in 2080 is not limited by lack of water availability in the North West as it is in other GORs. The North East is somewhat between the North West and the rest of the GORs in this regard in that, although it shows the same pattern as the other GORs, the 2020 and 2080 results are similar (almost identical in the case of oilseed rape). There is also an obvious difference in income changes for different crops. Considering the 'southern' GORs (all except the North East and North West), the 2020 revenue increase is roughly £200 per ha for spring wheat compared to about £15 per ha for spring oats.

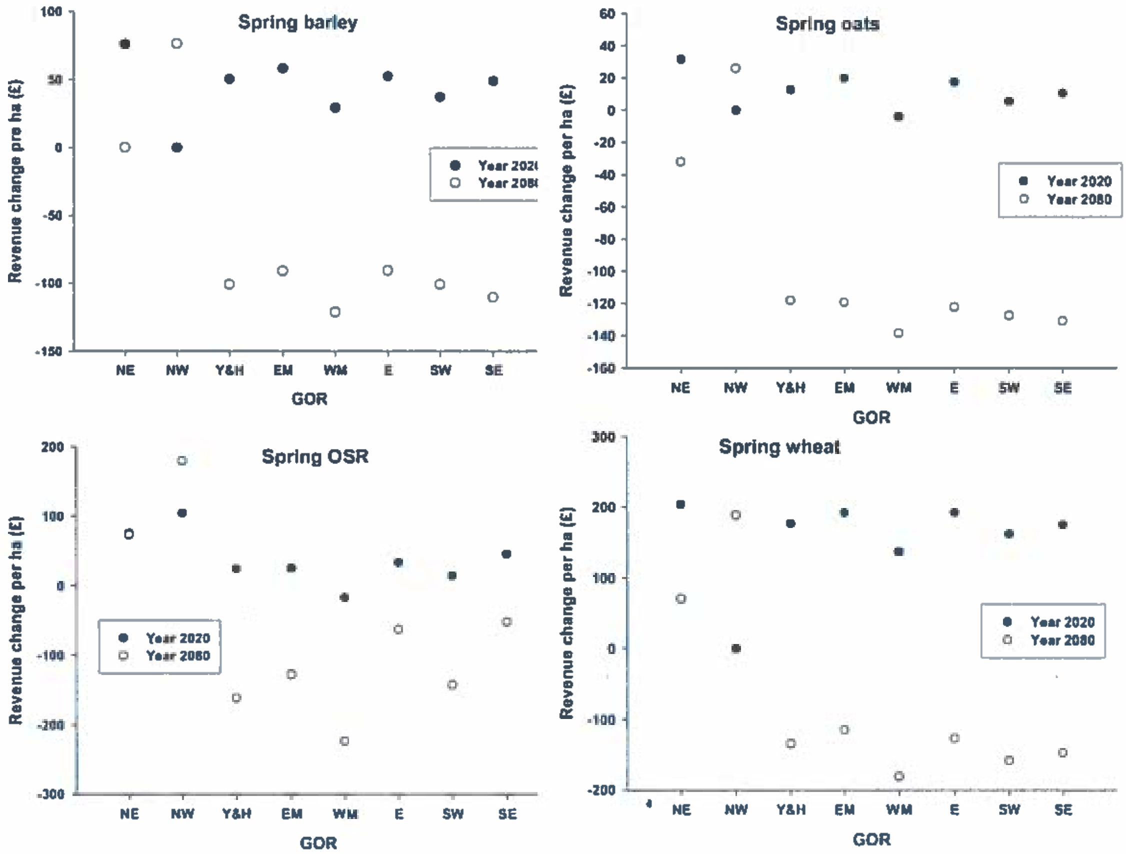

Figure 6. Revenue changes (£ per ha) for spring crops for the high emissions scenario in the years 2020 and 2080.

The same data as just described is also shown for winter crops in Figure 7. Almost identical pattern is apparent, with big 2020 to 2080 differences seen in all GORs except the North East and North West, where the latter shows the reversed pattern, and the North East is again intermediate.

The pasture results, which were obviously different when discussing each GOR results, are similarly displayed in Figure 8. It is notable that for all GORs except the North West, the difference between the years is less pronounced than for the other crops, and that both results maintain an increased yield and revenue increase. With the exception of the North West and East, the 2020 results are still slightly higher than those for 2080. In both the North East and West, the 2080 results are higher, although the 2020 result for the North West is much lower than any other (due to the relative yield prediction being reset to 1, so the predicted yield and income stayed the same).

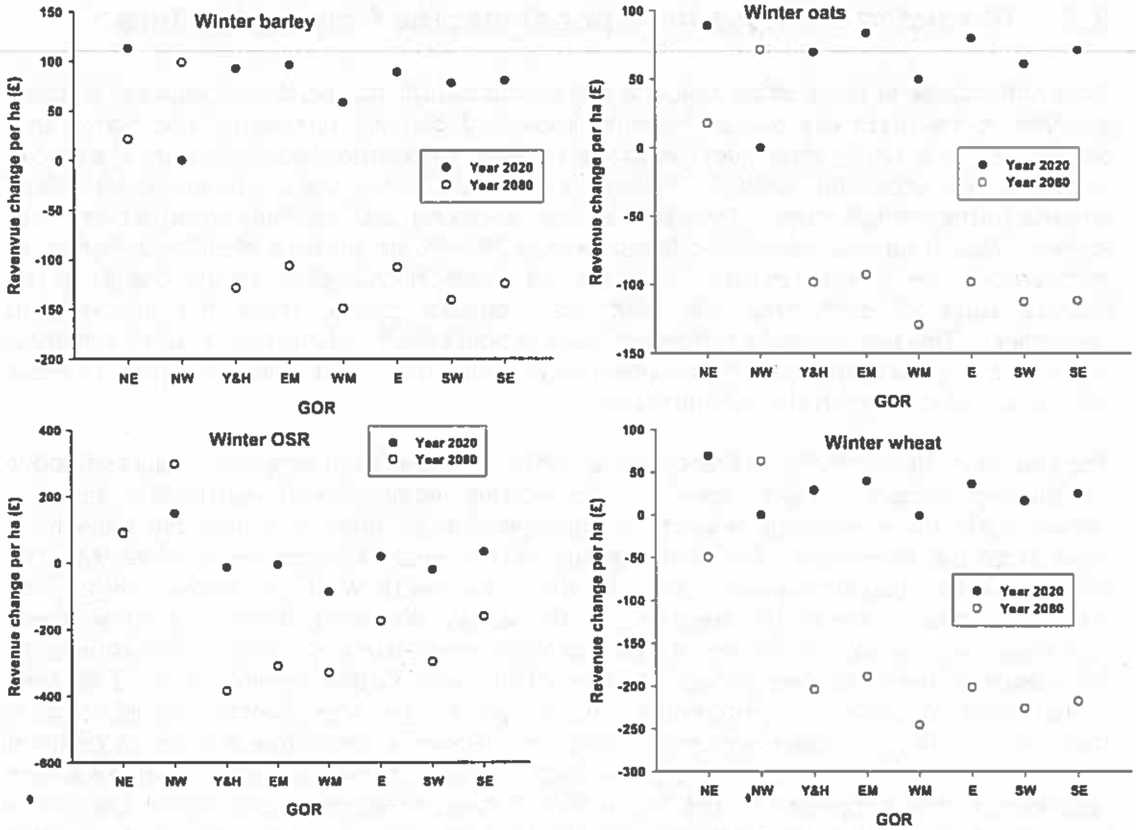

Figure 7. Revenue changes (£ per ha) for winter crops for the high emissions scenario in the years 2020 and 2080.

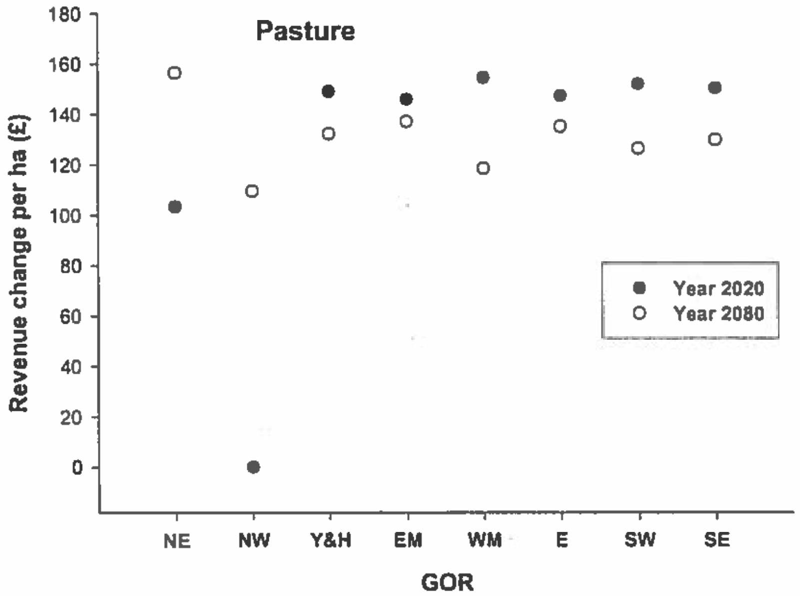

Figure 8. Revenue changes (£ per ha) for pasture for the high emissions scenario in the years 2020 and 2080.

3.3 Predicted changes in regional income from agriculture.

Once the change in per hectare values were calculated for each crop in each region it was possible to calculate the overall regional impact of climatic change on the agricultural sector through a simple multiplicative process. Strict assumptions are necessary in order to carry out this additional analysis. Firstly it is assumed that there will be no change in landuse in the regions, that is the same area of each crop will continue to be grown. This allowed data from the June Agricultural Census 2004 to be used to identify the areas of each crop in the various regions. Secondly the assumptions applied to the change in per hectare value of each crop still hold, i.e. constant prices, costs and management behaviour. This has obvious implications for the applicability of the results of this analysis and these ceteris paribus and non-adaptivity assumptions should be reported if these results are used out with the current study.

The results of this analysis, presented in appendix 4, closely follow those presented above for the per hectare changes, however, the relative importance of individual crops to a regions agricultural economy impacts in particular where there is a negative impact for some crops but not others. Regional (agricultural) revenues increase in all cases from the present to the 2020 time period (2011 to 2040), the North West site shows only a small relative increases due to the resetting of the values discussed above. In all Southern regions, all regions except the North East and North West, there is a decline in this increase in revenue to the 2050 time period (2041 to 2070) and a further decline to the 2080 time period (2071 to 2100). This relationship is stronger for the high climate change scenario than the low climate change scenario in all cases. **There is a negative impact on regional revenues by the 2080 time period given high climate change scenarios in all Southern regions with the exception of the South West.** Also presented in appendix 4 are results for impact to regional revenues net of pasture revenues. As impacts on pasture are positive in all cases this shifts the change in revenues downwards and leads to a fall in revenue for all sites given the low climate change scenario with the same exceptions identified above. In addition the negative impact on revenues occurs in both the 2050 time period and 2080 time period.

4. Discussion

A full discussion of the results is not possible in this study, given that there are so many ways in which the results can be compared - this must be left to users tailoring results analysis and display to specific questions of interest. However, the results overall display the following broad trends:

- Increases in yield and therefore also revenue occur in 2020;
- Yield and revenue then decline to 2050, with revenue change either staying positive at a lower amount or becoming negative;
- With the exception of the North West, yield and revenue change become negative by 2080;
- The North West (and to a lesser extent the North East) is notably different to the other GORs, in that yield and revenue increases are maintained in 2080 due to water shortage not becoming limiting;
- Conversely, water becomes increasingly limiting in the more southern GORs;
- Going from 2020 to 2050 to 2080, the results for the high and low emissions scenarios become increasingly divergent, with greater revenue losses evident under the high emissions scenario;
- The results for pasture are notably different to other crops, with pasture maintaining an increase in yield and revenue increase into the future.

No matter how the results are analysed however, it is important to bear in mind the caveats associated with the approach adopted. It should be remembered that the results in this report are derived using only predicted precipitation changes. Although we consider that changes in precipitation will be the main driving variable in dictating future crop yield, there may be other unknown effects that will become more prominent in the future, such as incidences of disease. In addition, there may be factors that could become locally important. Caveats to be aware of are:

- Simple approach- much of the detail in Cropsyst has been lost/ignored;
- Cropsyst does not model yield *quality*, and likewise the results here do not take quality changes into account;
- Small sample sizes - the available and usable data from Scotland was limited, and there was only time for generation of a small amount of new results for England;
- Regressions used beyond data limits - care should be taken in particular with results that are derived from precipitation data that is outwith the range of the input sites precipitation data;
- Reset data - care should also be taken with the results where the relative yield result was reset;
- Cannot handle new or changing interactions in new sites - this approach, being a simple extrapolation of yield-precipitation relationships, cannot take any account of other factors or new interactions that may occur on sites, but which may be picked up by full modelling using Cropsyst;
- Relative yield used - we cannot distinguish sites with high/low existing yields, in that an increase in yield of 25 % means very different change at a current low and current high yield sites;
- No analysis of possible impacts of changing economic conditions, including CAP reform and changes in WTO regulations;
- The time constraints on this study meant that a simplifying procedure was developed to allow the transfer of results from Hanley *et al.* (2005). This allowed the number of inputs required and analysis of those inputs to be significantly reduced. However, it was not possible to find full data for the GOR's even for this lower data requirement. Perhaps the best example of this was the lack of availability of full current yield data for the crops considered, in particular for spring crops, and fixed relationships (between winter and spring yields) were assumed;

- Given the spatial scale of the climate predictions made and the lack of any site-specific input data, this approach takes no account of factors such as soils, topography, drainage etc;
- Perhaps most crucially, the results are presented by crop type, but the lack of regionally disaggregated farm models means that we cannot translate this to income changes per farm or per ha of farmed land.

Having outlined the caveats, the advantages to this approach should also be noted:

- Quick - being simple and requiring little new data input, the generation of results was relatively quick;
- Simple - given that the methods is based on one relationship (relative yield with precipitation change), the results are relatively simple to understand and interpret. This is in contrast to Cropsyst, where the explanation for results may lie in untangling many factors that are interacting in different ways;
- Generality - the simple approach combined with ready availability of input data (climate change from UKCIP) makes this approach applicable to all UKCIP grid squares in the UK. Given the increasing resolution of climate models, this resolution may increase further in the future;
- In contrast to the point immediately above, given the uncertainties attached to climate change predictions, general models based on simple and understandable relationships may be more appropriate than more complicated models. Such more complicated approaches may be more applicable once the climate predictions improve, but at present simple models may be more appropriate.

From the data presented here it has been possible to calculate farm income for individual farms without adaptation. Given no adaptation the process is a simple multiplicative process, multiplying the area given over to each crop type by the change in per hectare revenue for the relevant crop in the relevant region. Only very simple analysis in the face of adaptation is possible using the data presented in the appendices to estimate the most profitable landuse. This is however likely to suggest a mono-cropping regime. Given the extreme changes in revenue that occur over time, and the differences in revenues between the different crops, it is obvious that farmers will adapt their crop selection to suit the prevailing climate. Such adaptation is not considered in this short study, but the revenue change results given in the tables in appendix 3 can be used to explore adaptation scenarios as required. In addition the external economic conditions that would also influence the results through affecting the intrinsic value of the various crops cannot be considered in this study.

Given the changes in climate predicted, and the decrease in yields over time in many crop types, there will obviously be opportunities for the introduction of novel crops. These opportunities will increase through time, and are also likely to be greater under the high emissions scenario than the low due to the greater climate change and greater revenue losses using current crops. The prediction of which crops will replace those considered here will be different (to greater and lesser degrees) between scenarios and year under consideration. Such crops are likely to come from areas in mainland Europe that currently experience climates similar to those predicted here, although soil, topography and cultivation differences would also influence which crops would be viable.

4.1 Options for future work to use and refine predictions

An obvious first step would be to use the gross margin/yield change predictions in regionally disaggregated farm models, giving more specific and useful results. Given the caveats described above associated with the predictions in this report, some further work would help to determine whether they are robust and reasonably accurate. An obvious way to do this would be to run Cropsyst for as many of the selected GORs as possible, and compare the new results with those obtained here. Given that running Cropsyst is a time-consuming process, consideration should be given as to which sites to run Cropsyst for. We suggest targeting sites that cover the spectrum of climate change that will be experienced across England, with sample size obviously dictated by time/money allocated to the task.

Note that it would be preferable if sites selected all had the required input data available, as well as sufficient data on crop yields to allow comparison with Cropsyst predictions for the current climate (as done in Table 1 for Scotland). A quicker way of examining the accuracy of the yield predictions used in this study would be to run Cropsyst for some of the UKCIP grid squares used in this study as representative of the GORs (Figure 1), and compare the Cropsyst results with those used here.

4.2 Summary

The results presented in this report indicate possible crop income changes across the English GOR regions, based on UKCIP changes in future precipitation. Although we have pointed out problems inherent in the approach adopted, the results are likely to be indicative of the direction and relative magnitude of yield and subsequent income changes for the considered crops. We therefore suggest that the results presented here are not used a definitive predictions of crop income in the future, but that they be used as indicators only, and indeed may also provide initial estimates against which later and more accurate predictions may be compared.

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Murphy, KJ; McCracken, DI; Foster, GN; Furness, RW; Waterhouse, A; Abernethy, VJ; Downie, IS; Wilson, WL; Adam, A and Ribera, I (1998) *Functional analysis of plant-invertebrate-bird biodiversity on Scottish agricultural land.* Final report to SOAEFD No: UGW/814/94.

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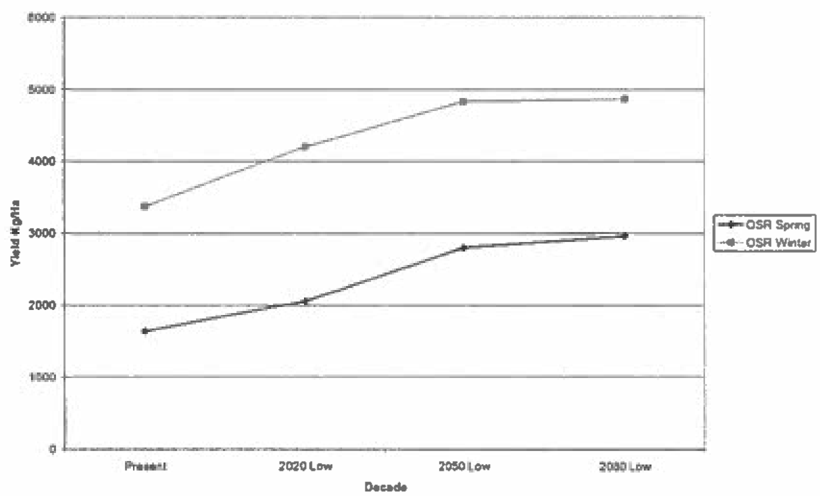
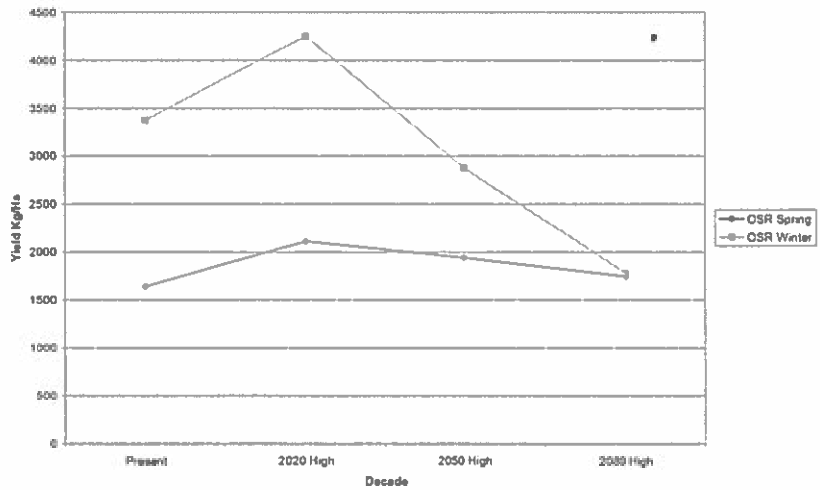
Stockle, C.O., Martin, S. and Campbell, G.S. (1994). CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. *Agricultural Systems* 46, 335-359.

Appendix 1 – Examples of Cropsyst output for Scottish sites

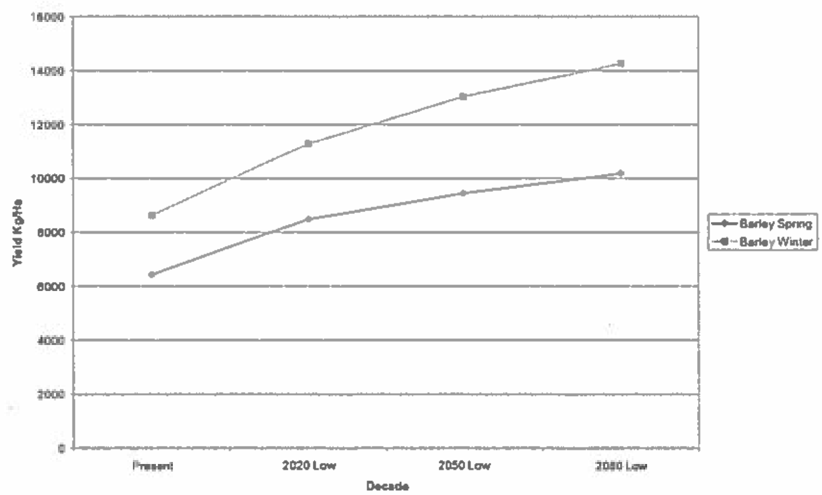
Seasonal OSR Yields SE Site Low Climate Change Scenario



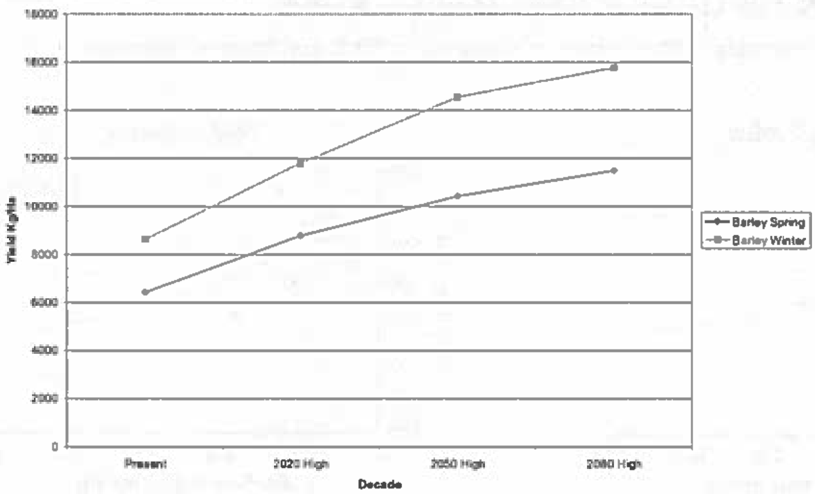
Seasonal OSR Yield SE Site High Climate Change Scenario



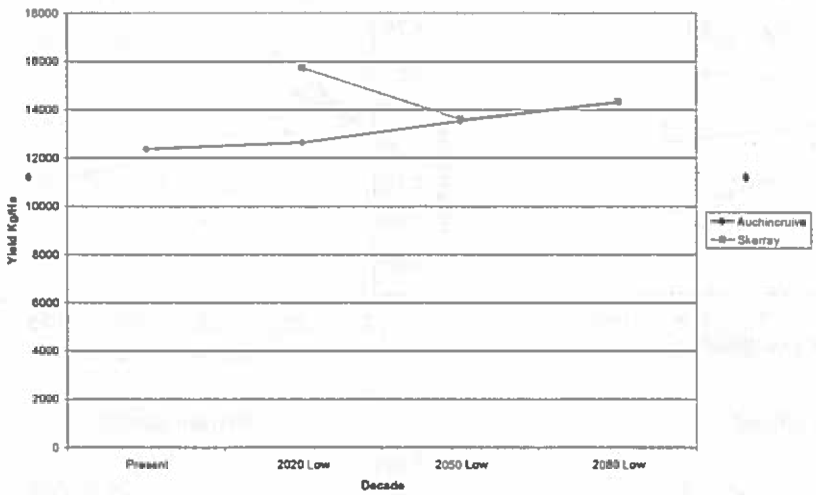
Seasonal Barley Yields NE Site Low Climate Change Scenario



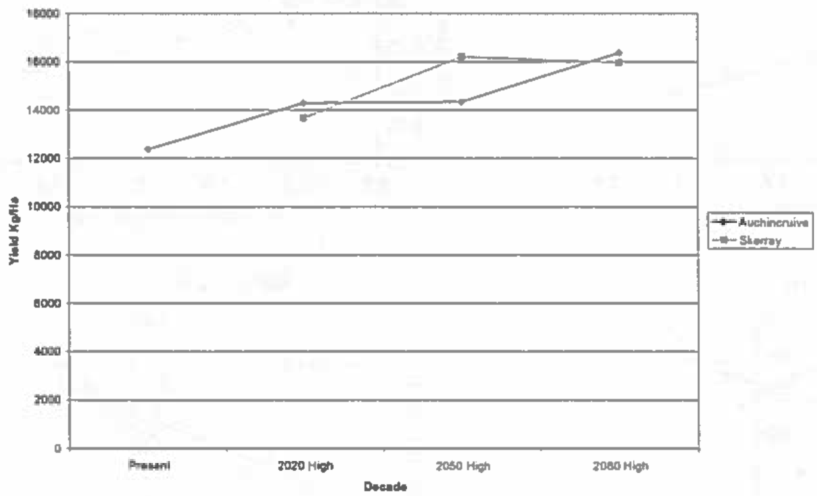
Seasonal Barley Yields NE Site High Climate Change Scenario



Pasture Yields SW and NW Sites Low Climate Change Scenario



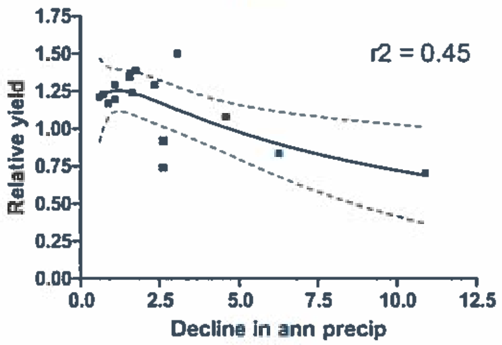
Pasture Yields SW and NW Sites High Climate Change Scenario



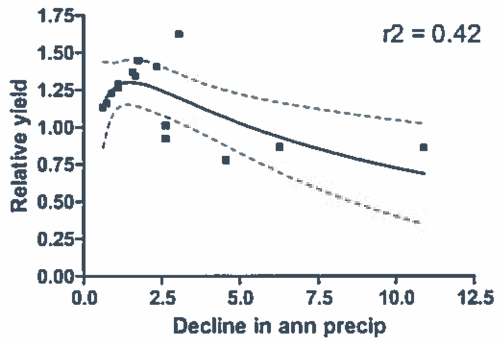
Appendix 2 – Raw data and fitted models

Graphs below show the raw data, fitted lines, r^2 values and 95 % confidence intervals.

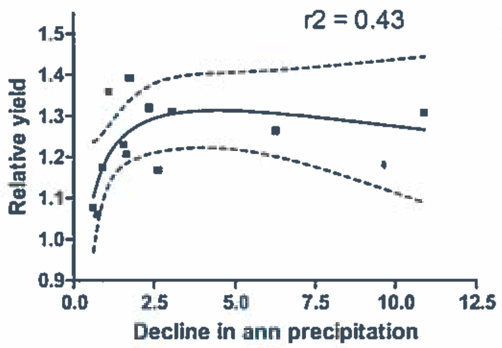
Spring barley



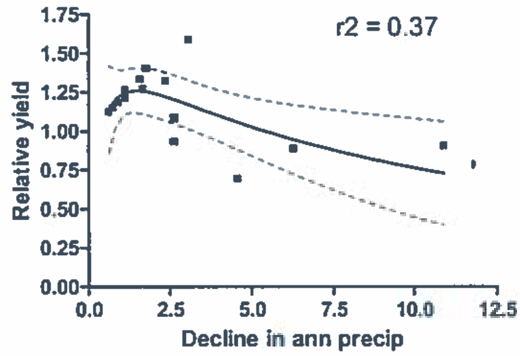
Winter barley



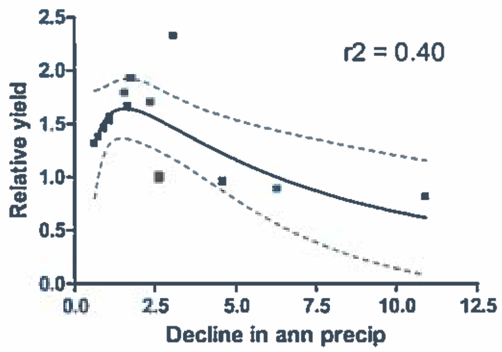
Pasture



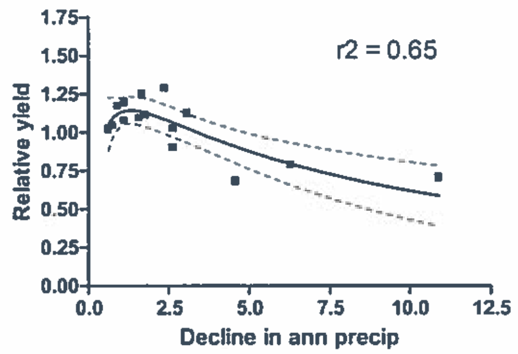
Winter oats



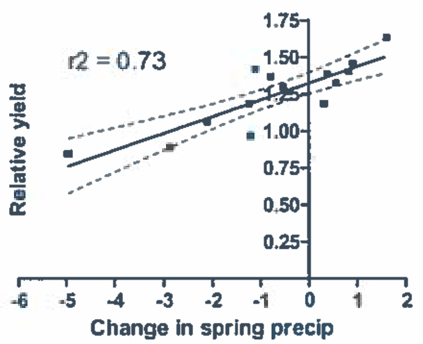
Spring wheat



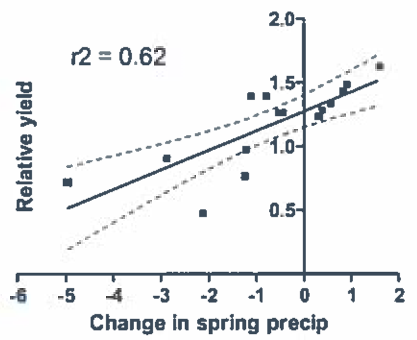
Winter wheat



Spring OSR



Winter OSR



Appendix 3 – Revenue changes by GOR and crop type

The following pages give the income changes for each crop type in each GOR, in terms of £ per ha.

Where the data used in analysis was amended in some way after prediction from the regression equations in Appendix 2 (see Methods for details), this is highlighted in the appropriate table. In the table headings, 'S' stands for summer, 'W' stands for winter, and 'OSR' for oilseed rape.

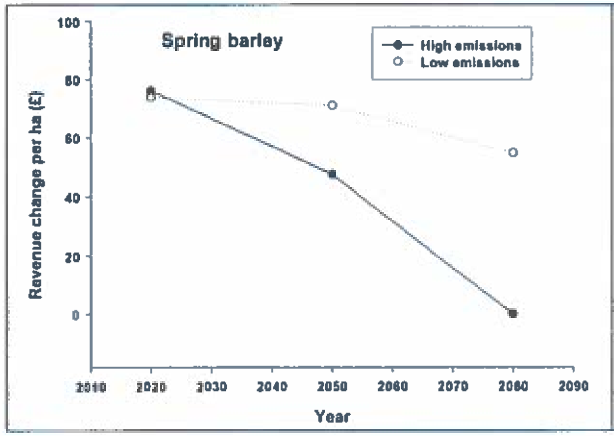
The lines on the graphs are drawn by direct extrapolation between the predicted datapoints, for the low and high emissions scenarios.

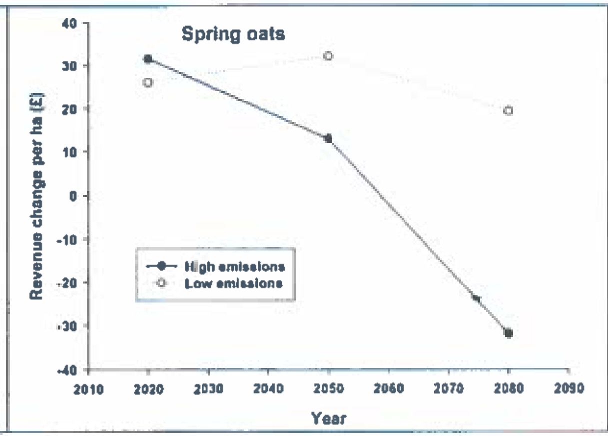
NORTH EAST

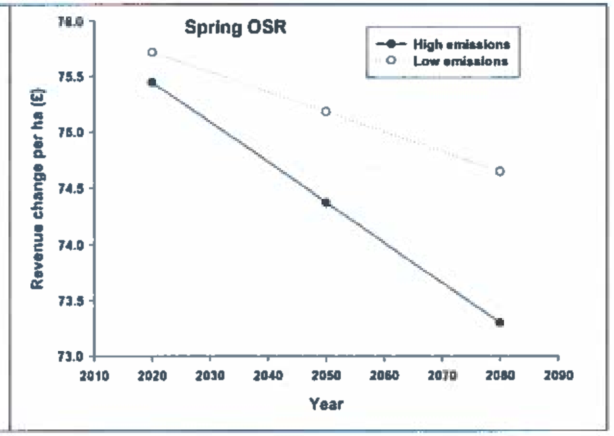
Summary results table

Scenario and year	S barley	S oats	S OSR	S wheat	W barley	W oats	W OSR	W wheat	Pasture
High 2020	76	32	75	204	113	89	93	69	103
High 2050	48	13	74	180	91	71	91	29	149
High 2080	0	-32	73	70	21	18	89	-49	156
Low 2020	74	26	76	184	103	82	94	62	90
Low 2050	71	32	75	219	118	92	93	65	130
Low 2080	55	19	75	194	100	78	92	41	146

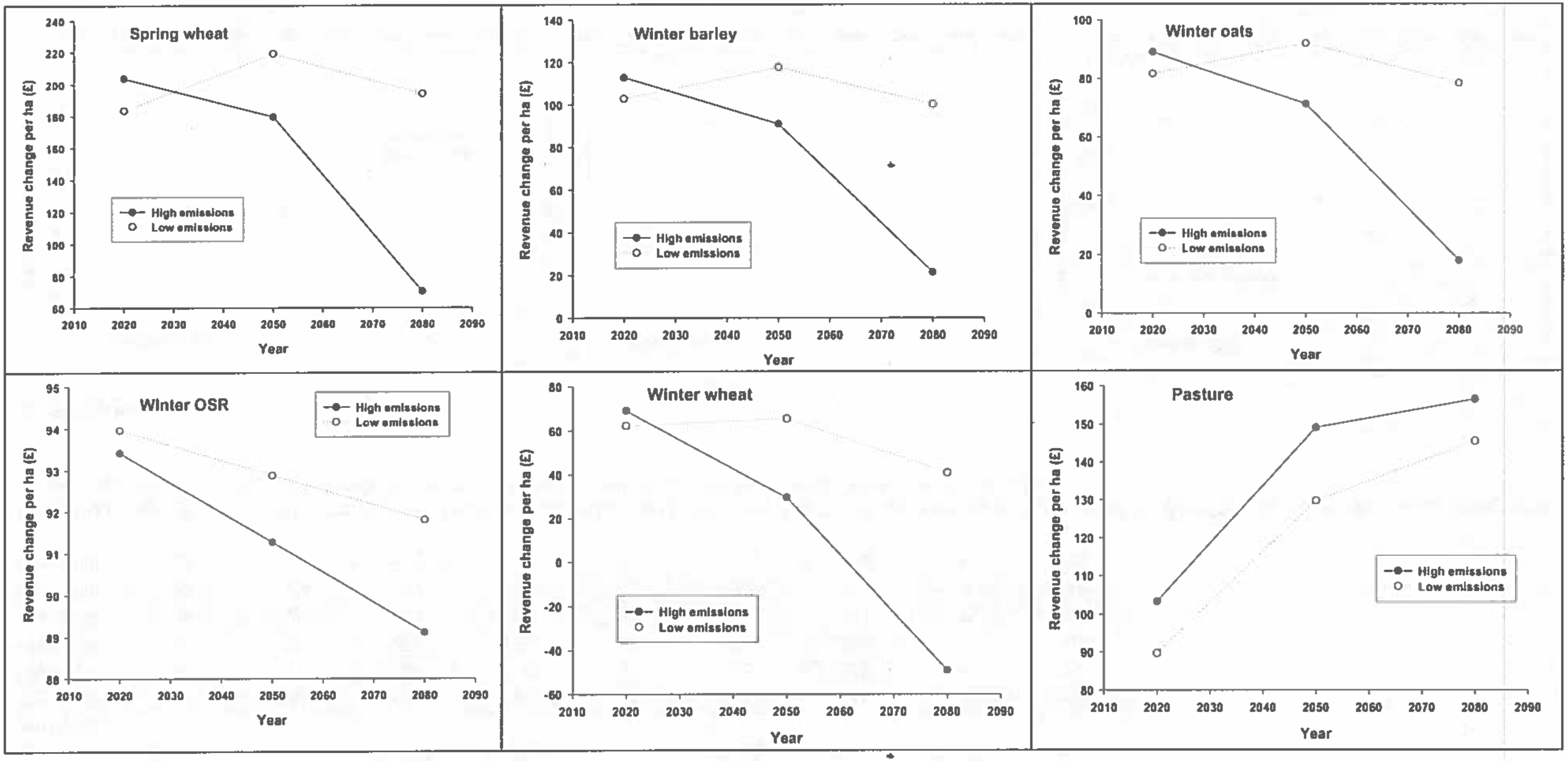
Summary graphs







North East (cont'd)



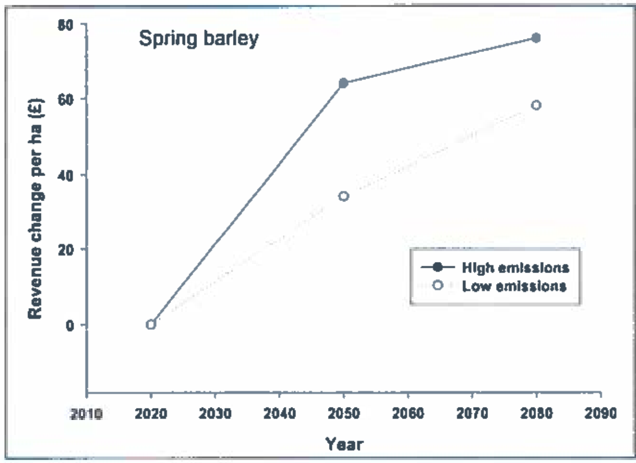
NORTH WEST

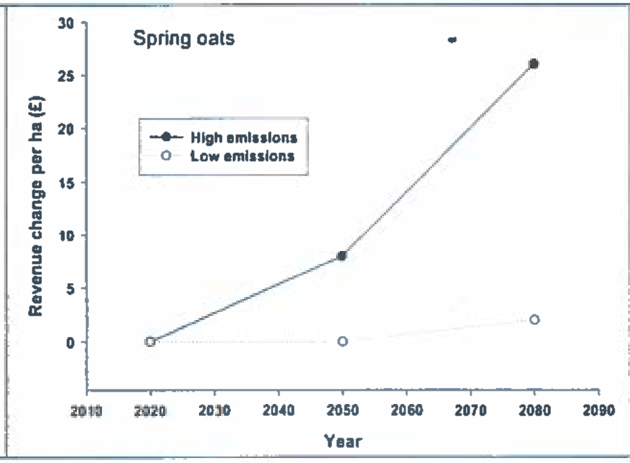
Summary results table

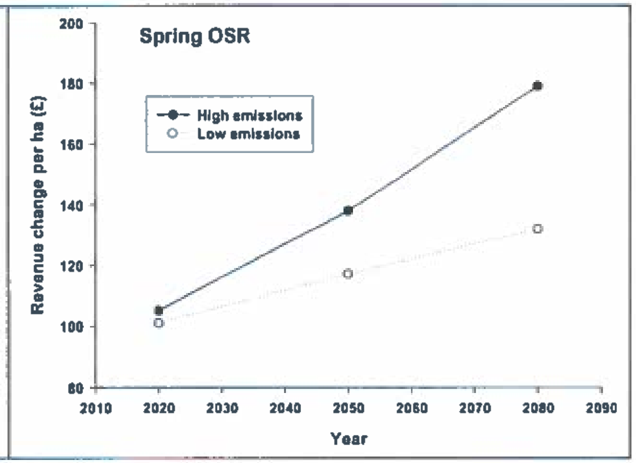
Scenario and year	S barley	S oats	S OSR	S wheat	W barley	W oats	W OSR	W wheat	Pasture
High 2020	***0***	***0***	105	***0***	***0***	***0***	148	***0***	***0***
High 2050	64	8	138	120	64	48	215	36	64
High 2080	76	26	179	189	99	72	298	63	109
Low 2020	***0***	***0***	101	***0***	***0***	***0***	141	***0***	***0***
Low 2050	34	***0***	117	27	12	12	173	***0***	18
Low 2080	58	2	132	98	52	40	202	25	53

Note that highlighted results are derived from precipitation data that were outwith the ranges of data used to develop the regression equations, and those results also in bold italics indicate where the regression result has been reset (see text for details).

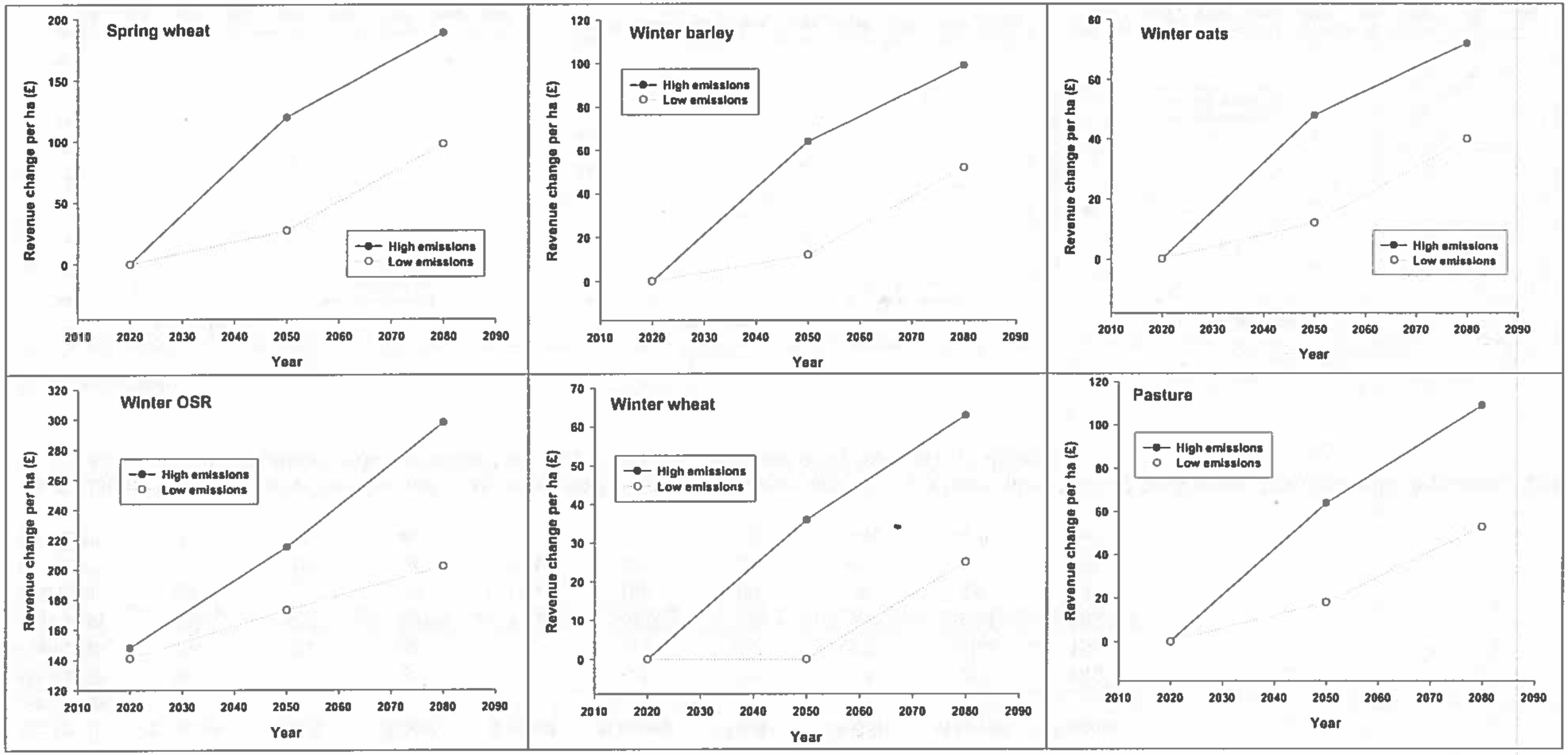
Summary graphs







North West (cont'd)



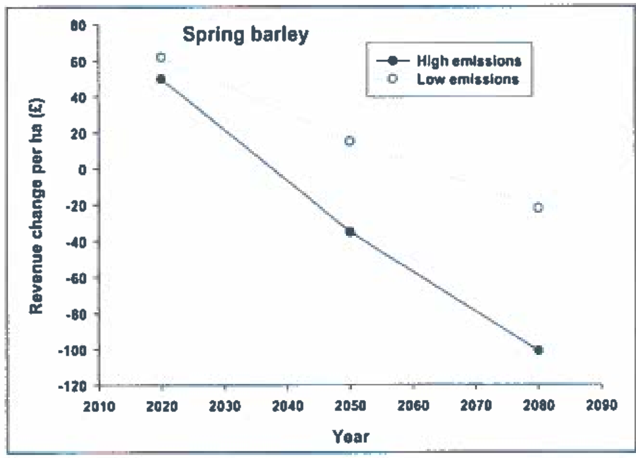
YORKSHIRE and THE HUMBER

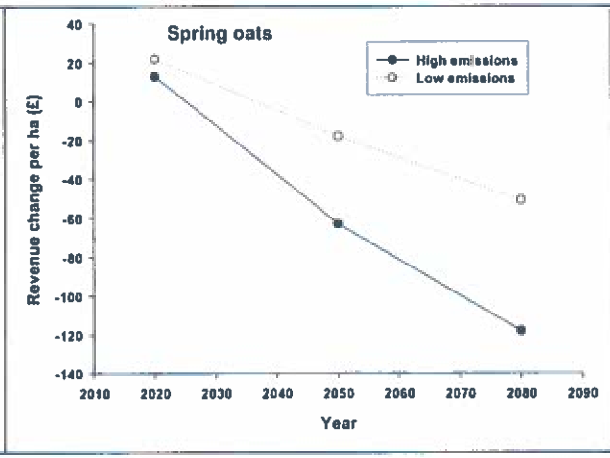
Summary results table

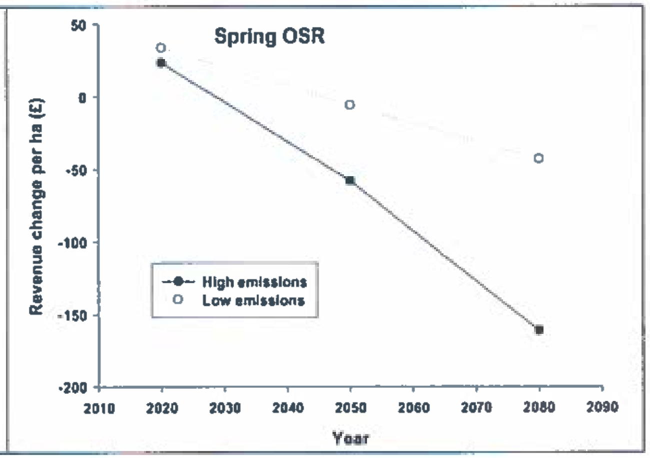
Scenario and year	S barley	S oats	S OSR	S wheat	W barley	W oats	W OSR	W wheat	Pasture
High 2020	50	13	24	177	92	70	-14	29	149
High 2050	-35	-63	-58	-7	-31	-22	-179	-104	153
High 2080	-101	-118	-161	-134	-129	-98	***-385***	-204	132
Low 2020	62	22	34	199	106	80	4	46	143
Low 2050	15	-18	-6	103	44	34	-74	-25	156
Low 2080	-22	-51	-43	21	-11	-7	-149	-83	155

Note that highlighted results are derived from precipitation data that were outwith the ranges of data used to develop the regression equations, and those results also in bold italics indicate where the regression result has been reset (see text for details).

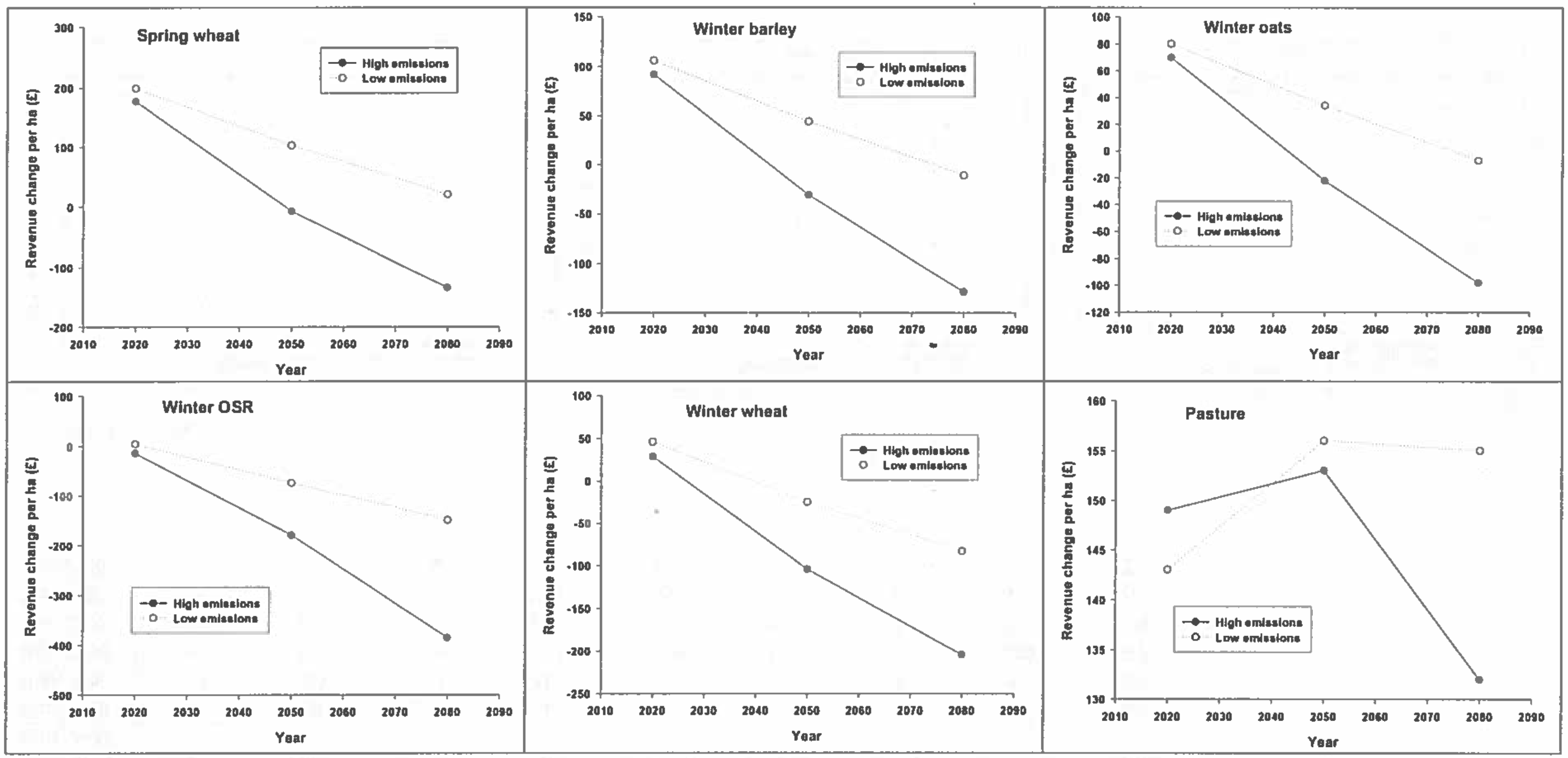
Summary graphs







Yorkshire and The Humber (cont'd)

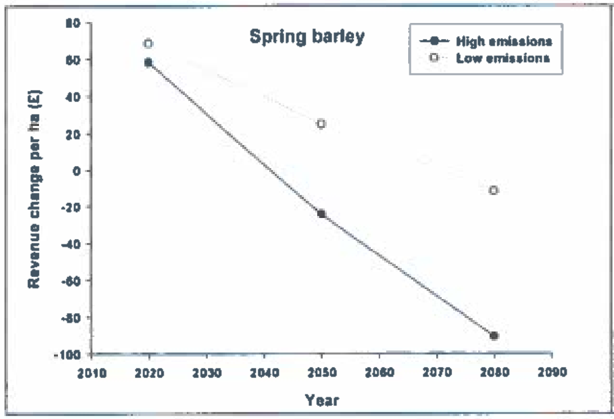


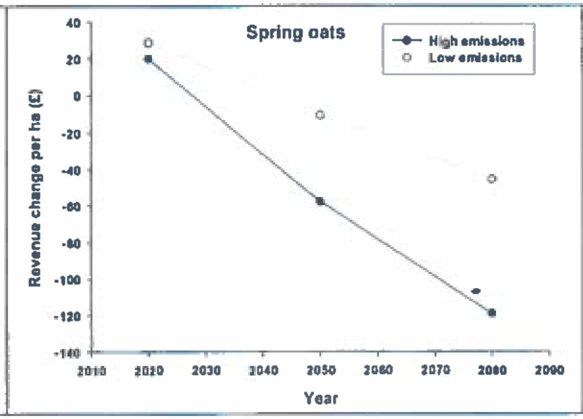
EAST MIDLANDS

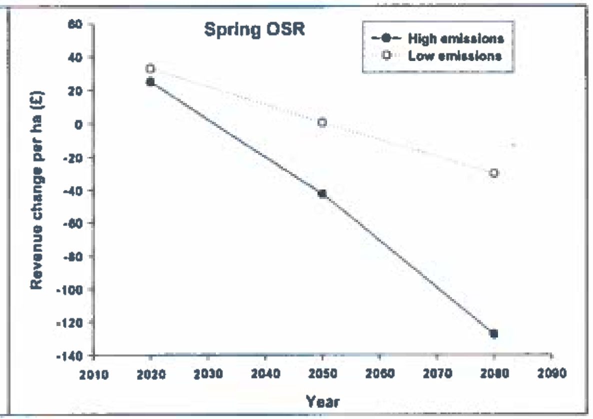
Summary results table

Scenario and year	S barley	S oats	S OSR	S wheat	W barley	W oats	W OSR-	W wheat	Pasture
High 2020	58	20	25	193	96	84	-5	40	146
High 2050	-24	-58	-42	18	-13	-10	-141	-87	154
High 2080	-91	-119	-128	-114	-106	-93	-311	-189	137
Low 2020	69	29	33	210	107	93	10	55	139
Low 2050	25	-11	1	125	55	48	-55	-11	155
Low 2080	-12	-46	-30	45	5	5	-116	-67	156

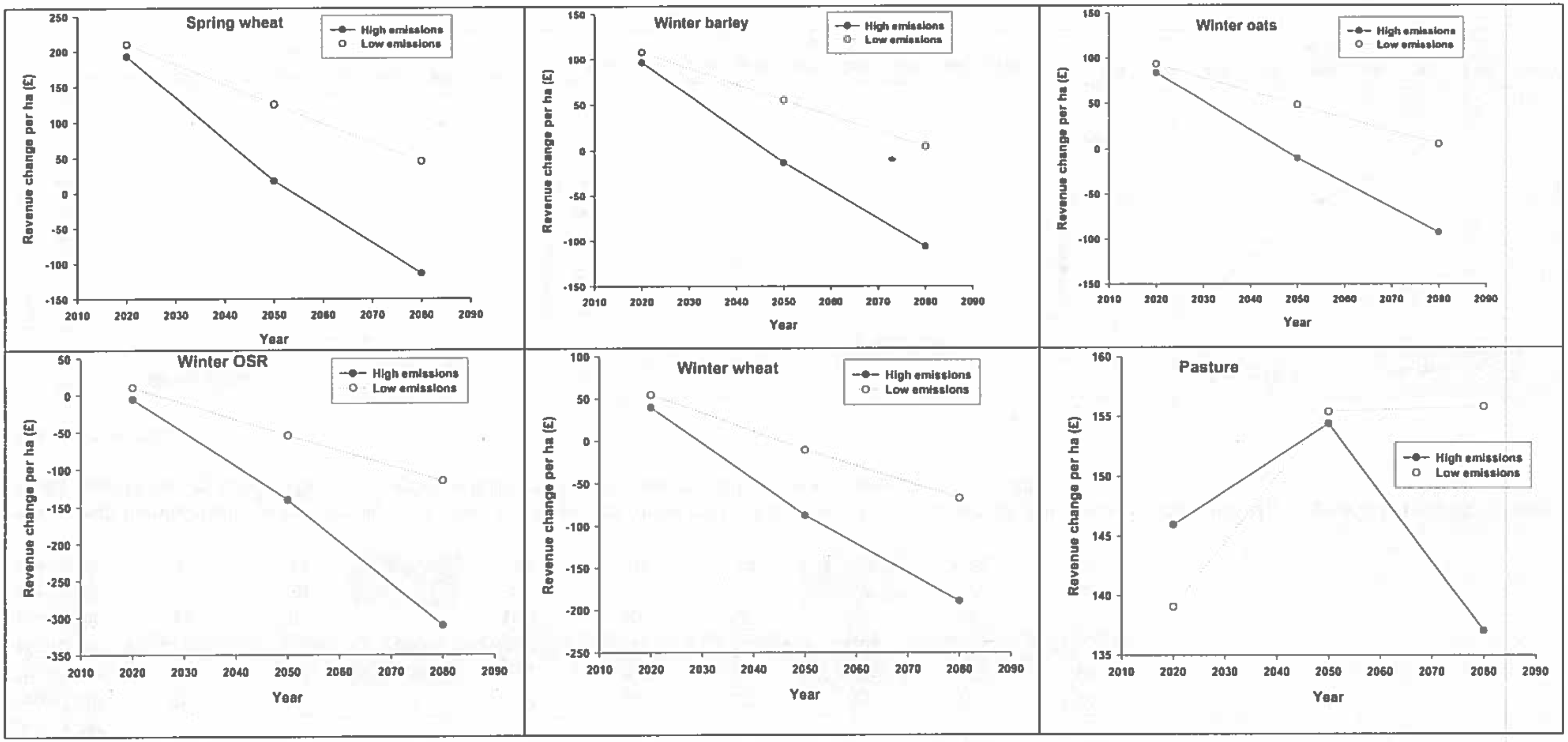
Summary graphs







East Midlands (cont'd)



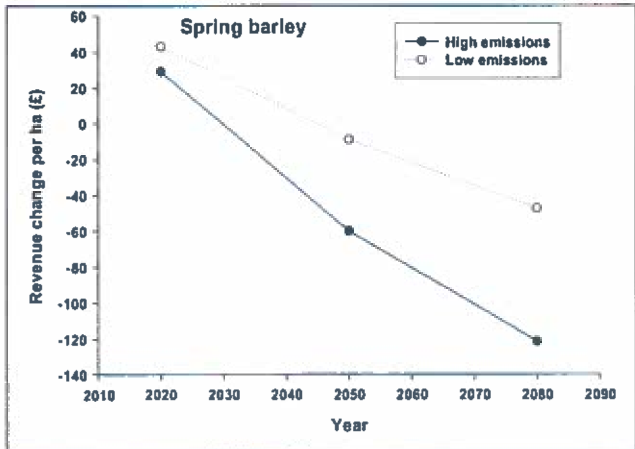
WEST MIDLANDS

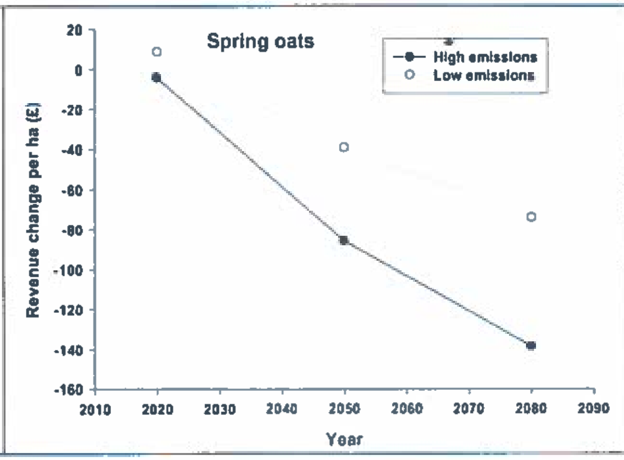
Summary results table

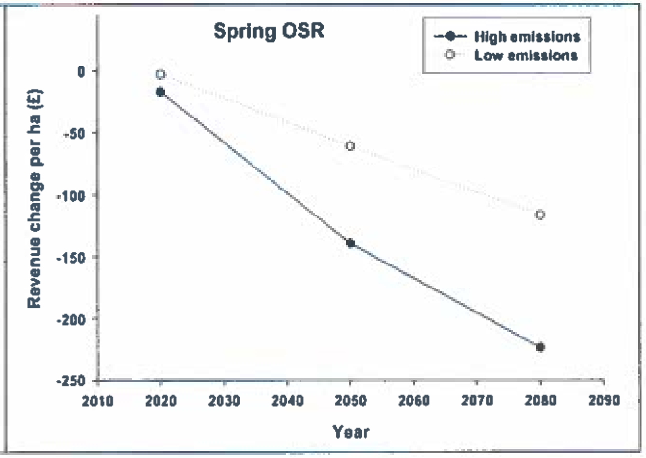
Scenario and year	S barley	S oats	S OSR	S wheat	W barley	W oats	W OSR	W wheat	Pasture
High 2020	29	-4	-17	137	58	50	-88	0	154
High 2050	-60	-86	-139	-64	-64	-54	***-330***	-147	146
High 2080	-121	-138	***-223***	-180	-149	-129	***-330***	-245	118
Low 2020	43	9	-3	168	76	65	-59	22	151
Low 2050	-9	-39	-61	48	7	7	-176	-64	156
Low 2080	-47	-74	-117	-37	-46	-38	-287	-126	149

Note that highlighted results are derived from precipitation data that were outwith the ranges of data used to develop the regression equations, and those results also in bold italics indicate where the regression result has been reset (see text for details).

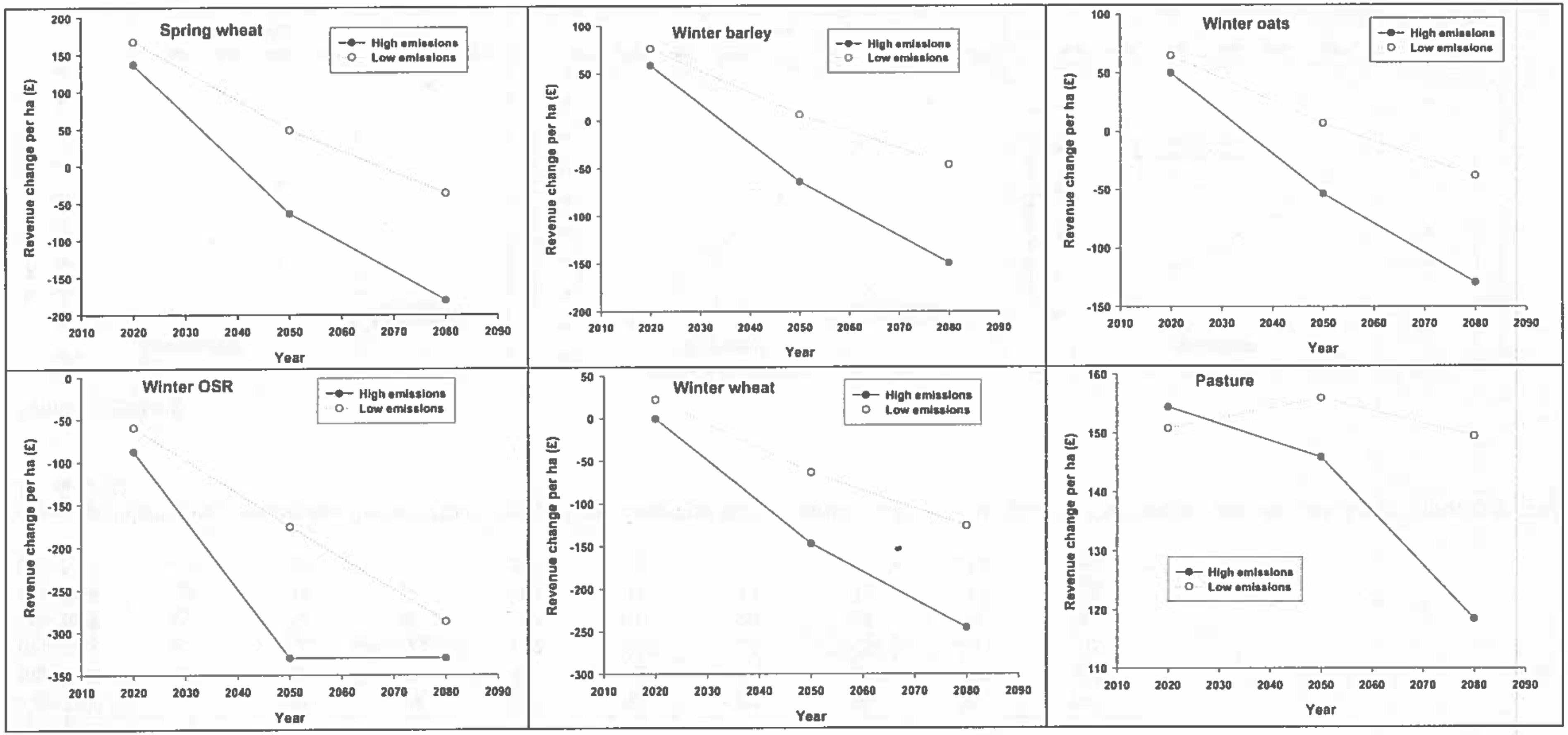
Summary graphs







West Midlands (cont'd)



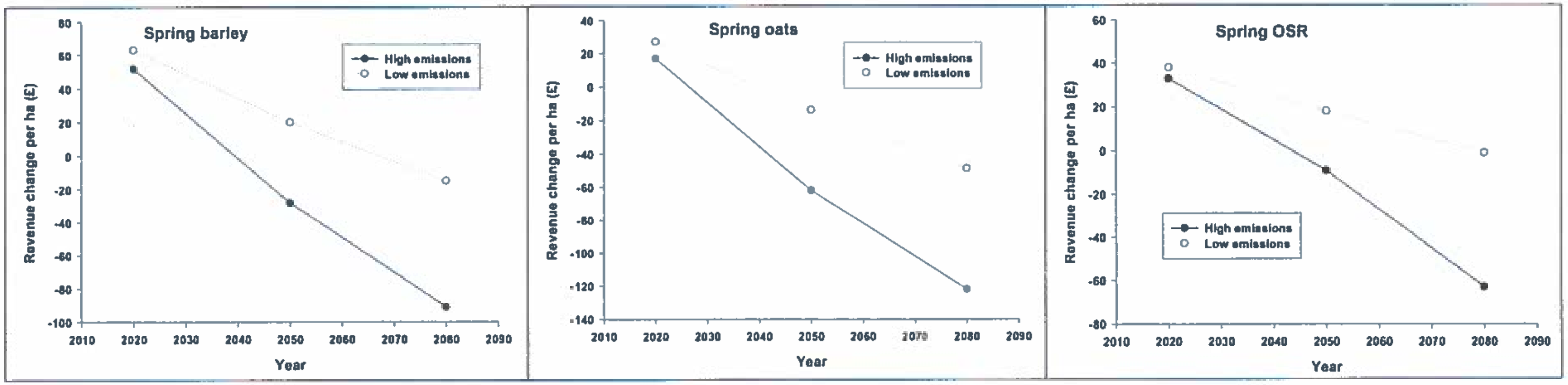
EASTERN

Summary results table

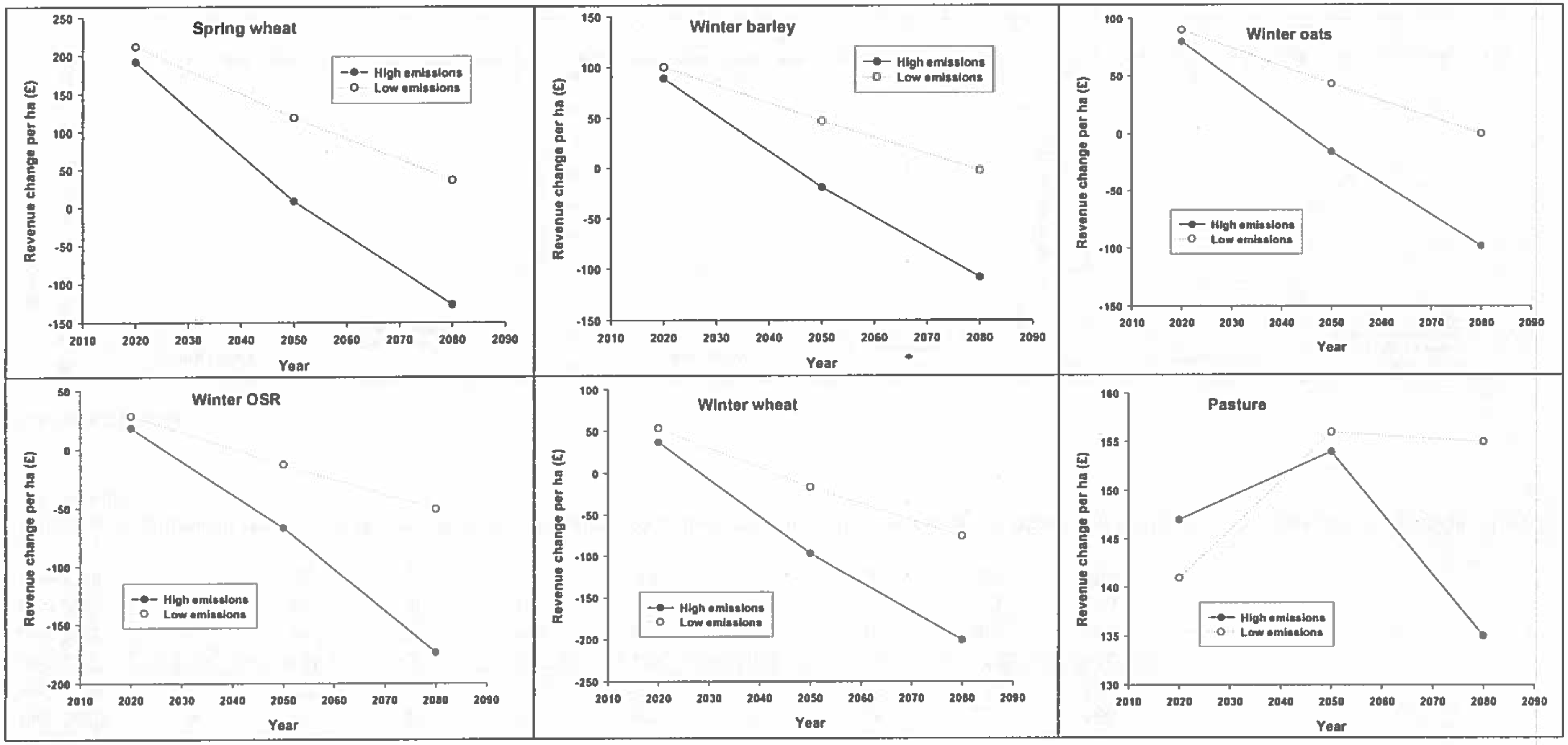
Scenario and year	S barley	S oats	S OSR	S wheat	W barley	W oats	W OSR	W wheat	Pasture
High 2020	52	17	33	192	89	80	18	37	147
High 2050	-28	-62	-9	8	-19	-16	-67	-97	154
High 2080	-91	-122	-63	-127	-108	-98	-174	-201	135
Low 2020	63	27	38	212	100	90	28	53	141
Low 2050	20	-14	18	119	47	43	-13	-17	156
Low 2080	-15	-49	-1	36	-2	0	-51	-76	155

Note that highlighted results are derived from precipitation data that were outwith the ranges of data used to develop the regression equations, (see text for details).

Summary graphs



Eastern (cont'd)



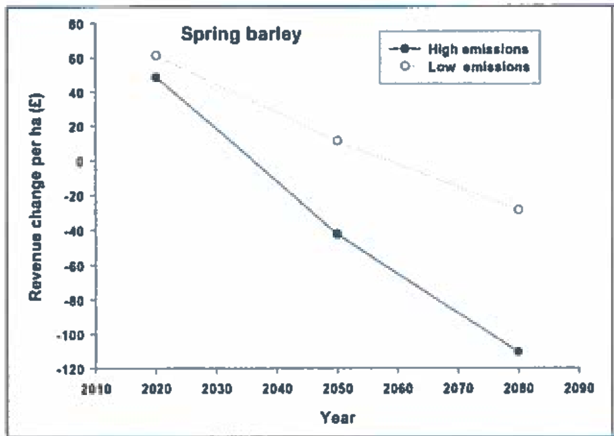
SOUTH EAST

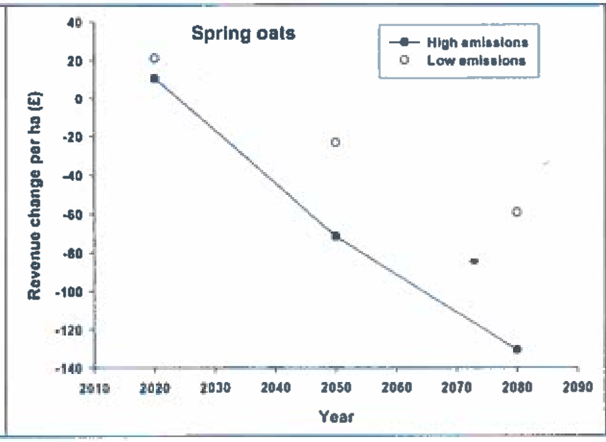
Summary results table

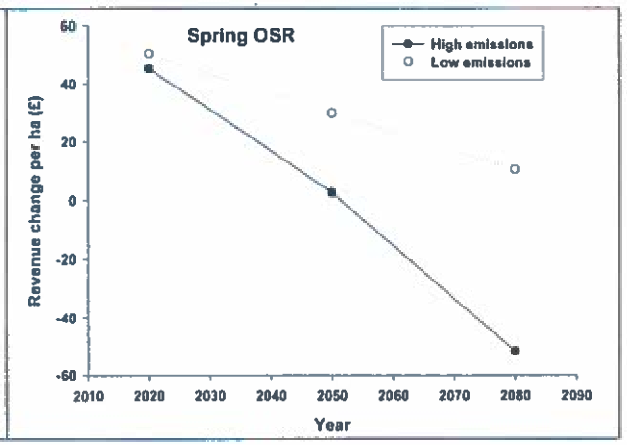
Scenario and year	S barley	S oats	S OSR	S wheat	W barley	W oats	W OSR.	W wheat	Pasture
High 2020	49	11	45	175	80	71	33	25	150
High 2050	-42	-72	2	-18	-35	-30	-53	-115	152
High 2080	-110	-131	-52	-147	-124	-112	-161	-218	130
Low 2020	61	21	50	199	94	83	43	43	145
Low 2050	11	-23	30	95	34	31	2	-33	156
Low 2080	-29	-59	10	10	-17	-14	-37	-94	154

Note that highlighted results are derived from precipitation data that were outwith the ranges of data used to develop the regression equations (see text for details).

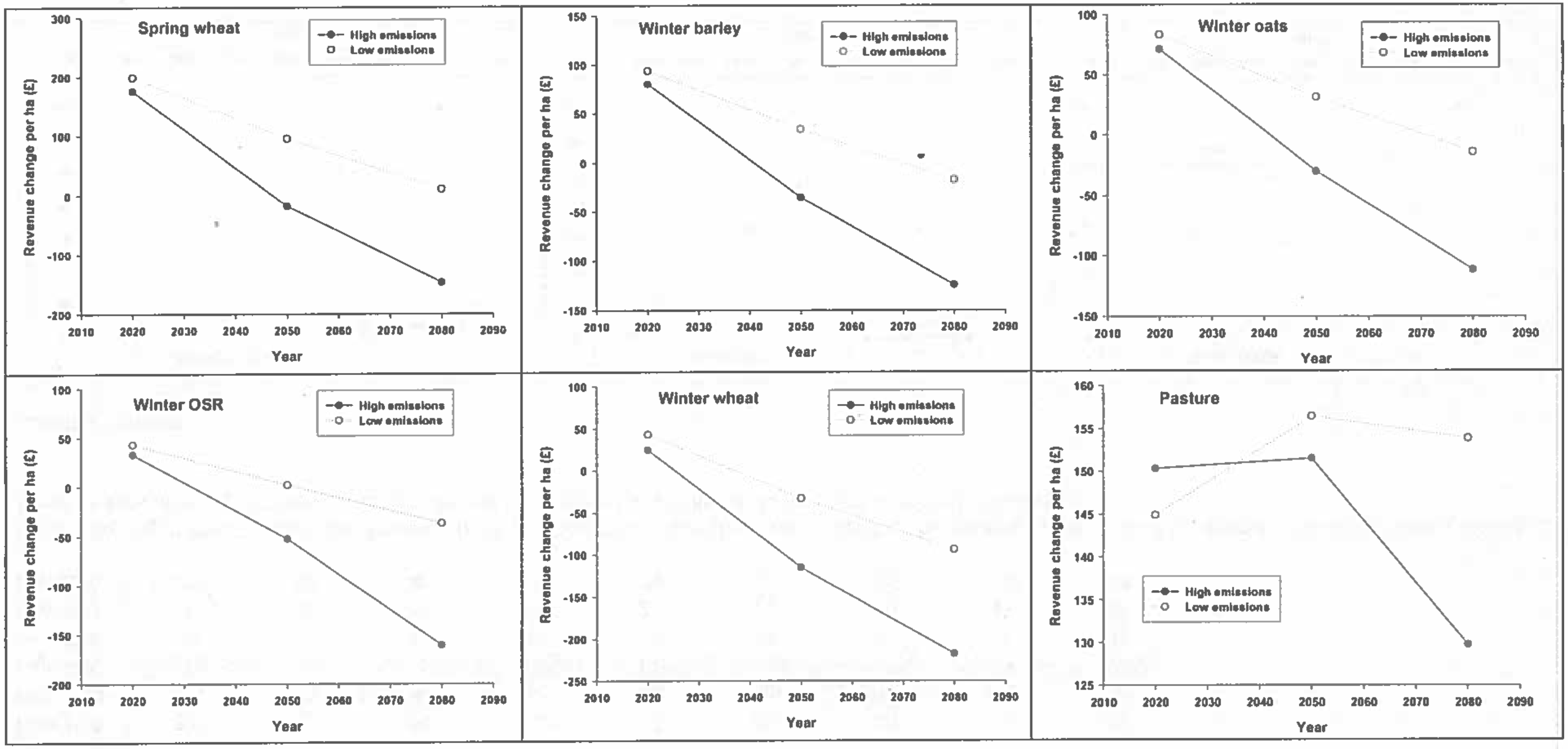
Summary graphs







South East (cont'd)



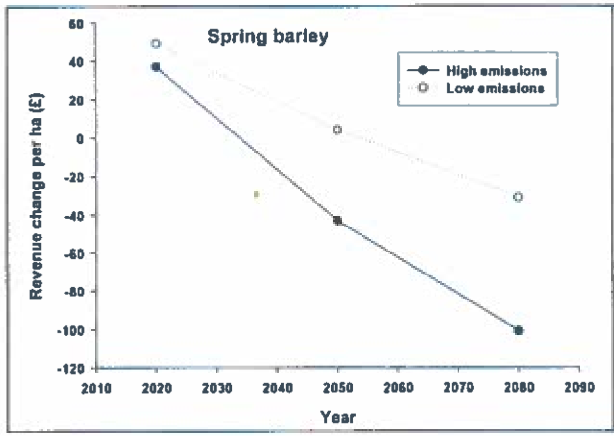
SOUTH WEST

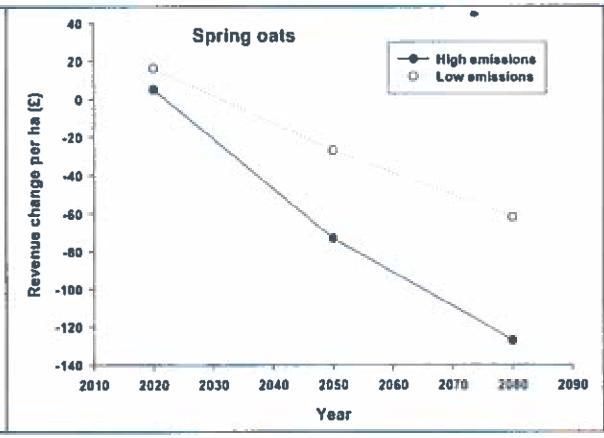
Summary results table

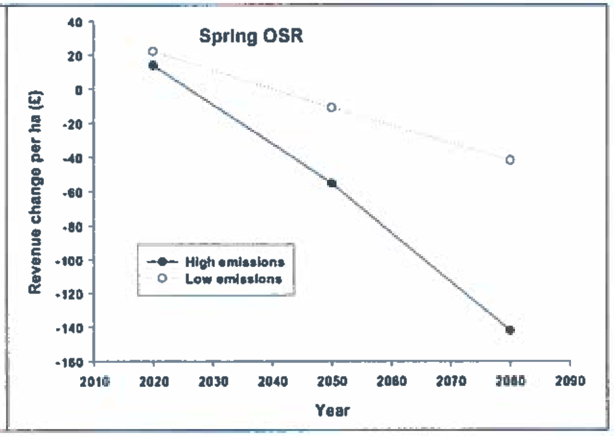
Scenario and year	S barley	S oats	S OSR	S wheat	W barley	W oats	W OSR	W wheat	Pasture
High 2020	37	5	14	162	78	61	-20	16	152
High 2050	-43	-73	-55	-33	-48	-36	-158	-125	150
High 2080	-101	-127	-142	-158	-141	-112	***-297***	-226	126
Low 2020	49	16	22	189	94	74	-4	36	147
Low 2050	4	-27	-11	80	27	22	-70	-43	156
Low 2080	-31	-62	-42	-6	-29	-21	-133	-104	153

Note that highlighted results are derived from precipitation data that were outwith the ranges of data used to develop the regression equations, and those results also in bold italics indicate where the regression result has been reset (see text for details).

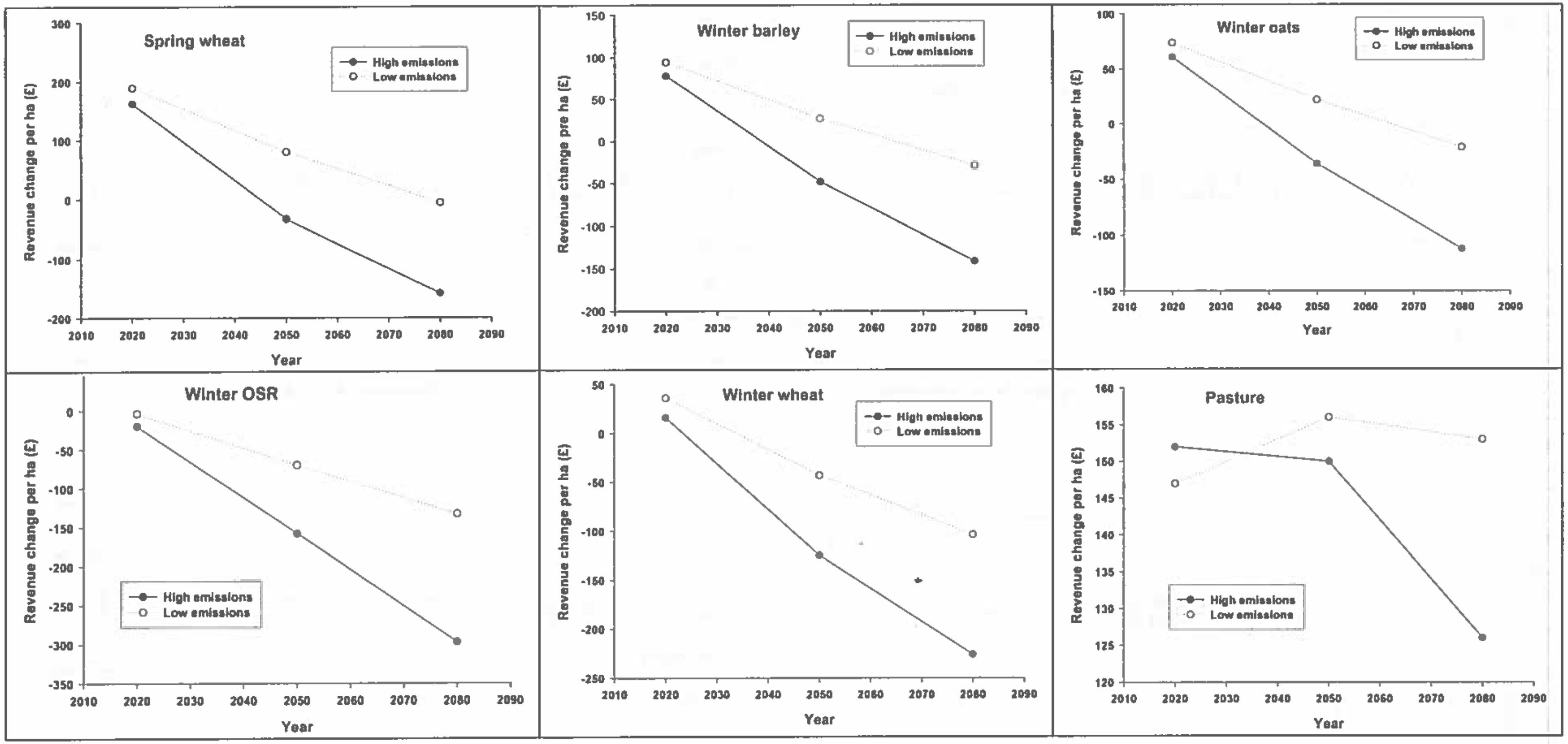
Summary graphs





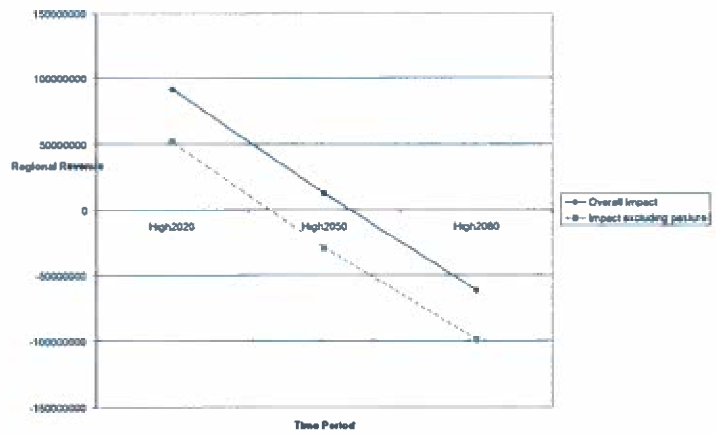


South West (cont'd)

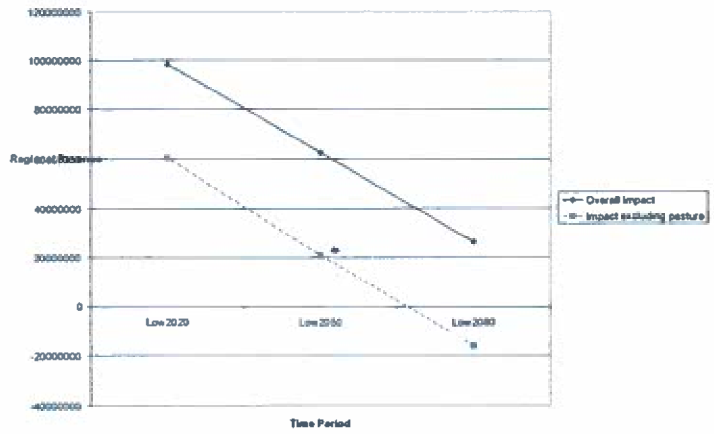


Appendix 4 Regional Revenue given unchanged landuse. Note as oats and wheat are not split into spring and winter varieties data presented is for an equal distribution of both.

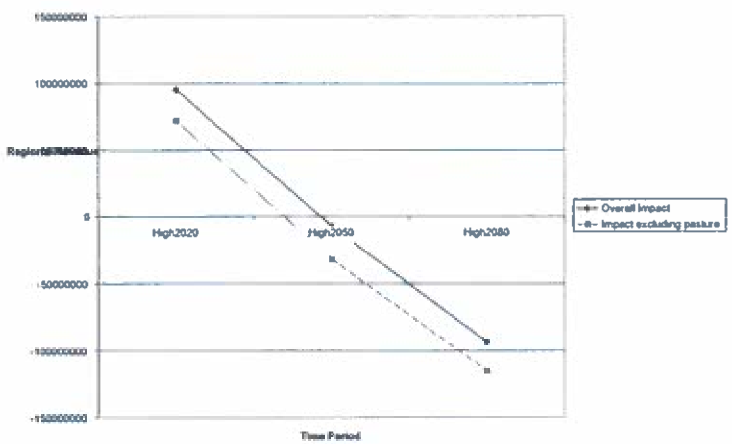
East Midlands High Climate Change Scenario



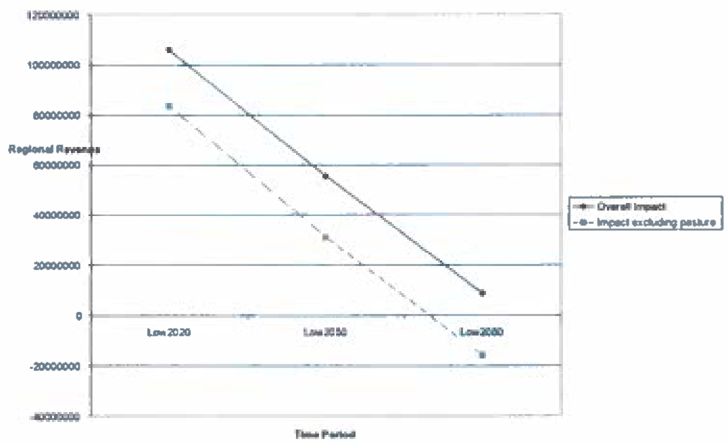
East Midlands Low Climate Change Scenario

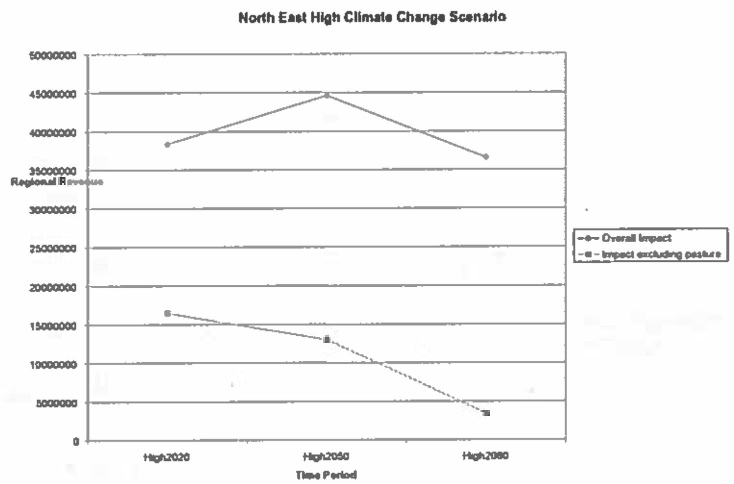


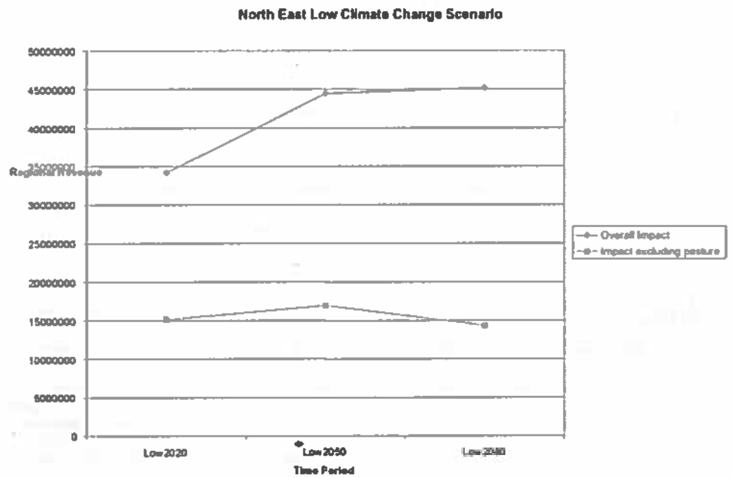
Eastern High Climate Change Scenario

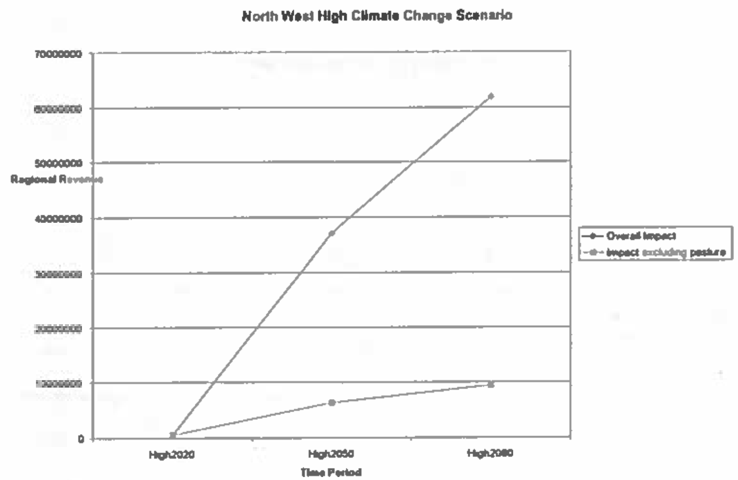


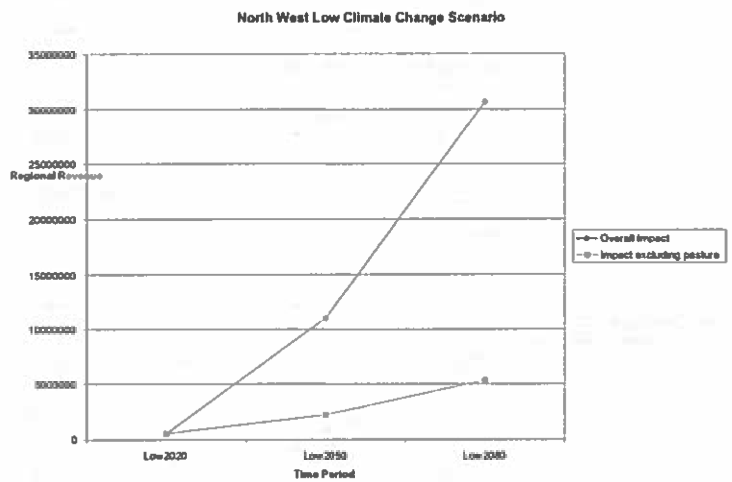
Eastern Low Climate Change Scenario

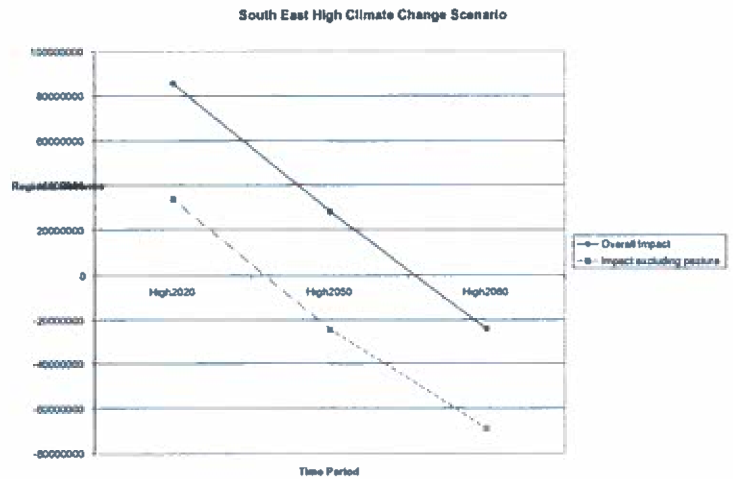


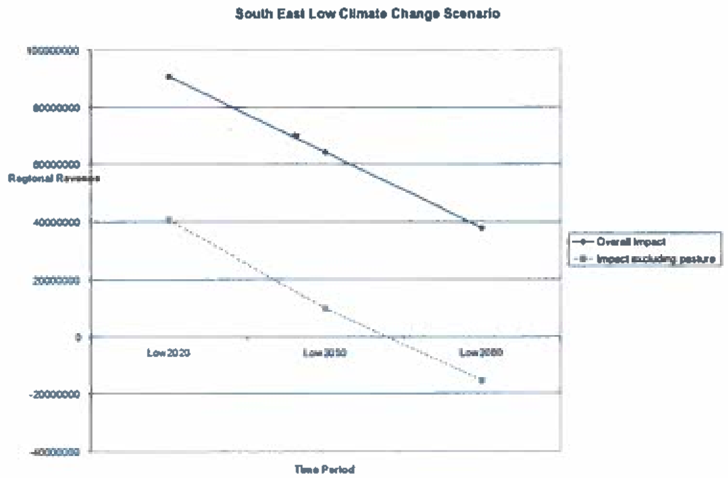

North East High Climate Change Scenario
Regional Revenue
Time Period
High2020
High2050
High2080
Overall Impact
Impact excluding pasture

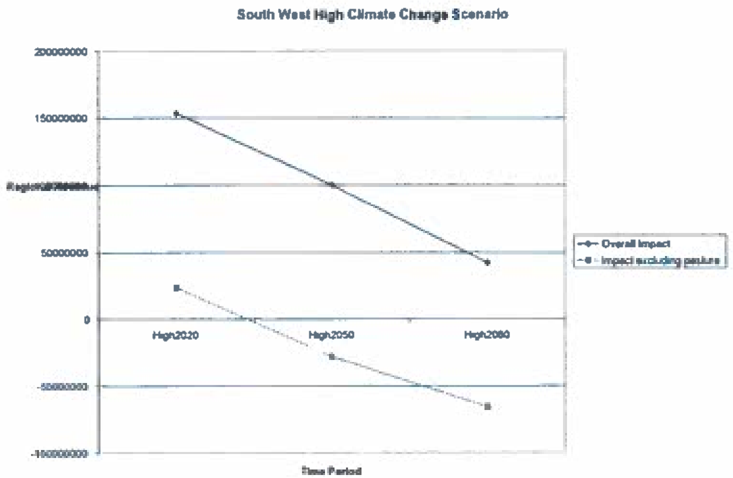

North East Low Climate Change Scenario
Regional Revenue
Time Period
Low2020
Low2050
Low2080
Overall Impact
Impact excluding pasture

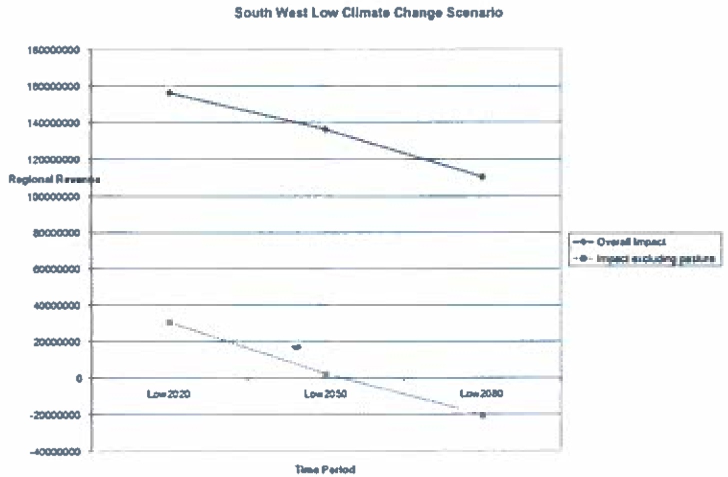

North West High Climate Change Scenario
Regional Revenue
Time Period
High2020
High2050
High2080
Overall Impact
Impact excluding pasture

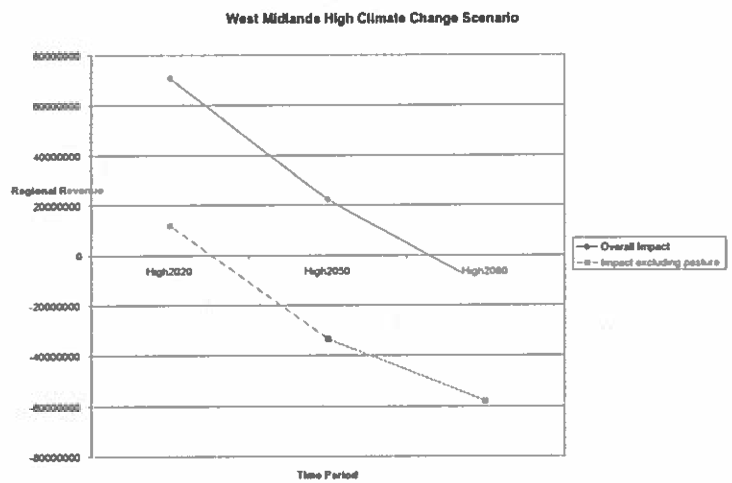

North West Low Climate Change Scenario
Regional Revenue
Time Period
Low2020
Low2050
Low2080
Overall Impact
Impact excluding pasture

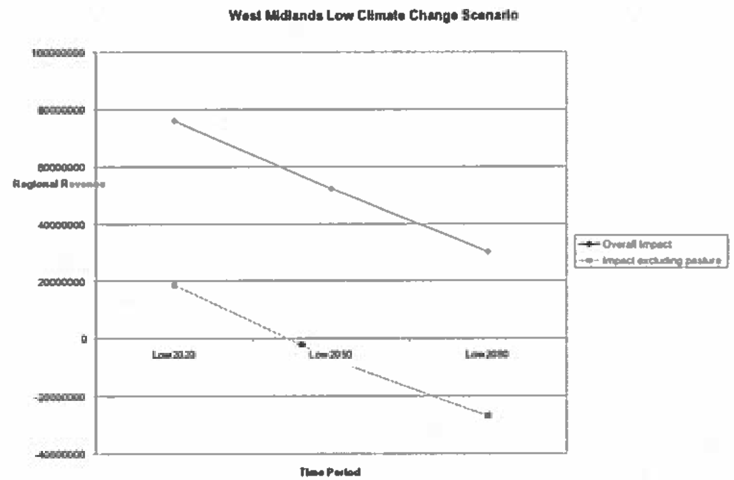

South East High Climate Change Scenario
Overall Impact
Impact excluding pasture
High2020
High2050
High2080
Time Period
80000000
60000000
20000000
0

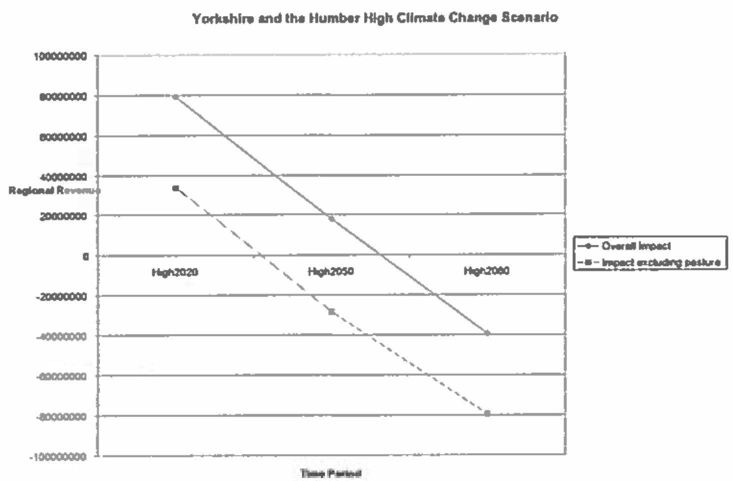

South East Low Climate Change Scenario
Regional Revenue
Overall Impact
Impact excluding pasture
Low 2020
Low 2050
Low 2080
Time Period
80000000
60000000
40000000
20000000
0
-20000000

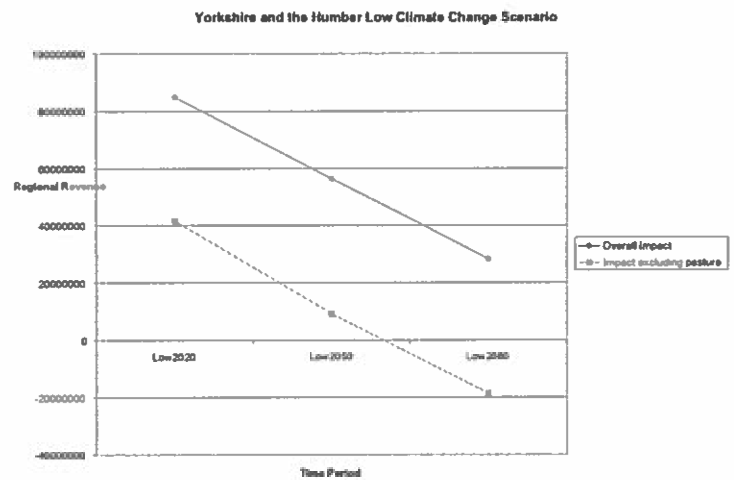

South West High Climate Change Scenario
Overall Impact
Impact excluding pasture
High2020
High2050
High2080
Time Period
200000000
150000000
50000000
0


South West Low Climate Change Scenario
Regional Revenue
Overall Impact
Impact excluding pasture
Low 2020
Low 2050
Low 2080
Time Period
180000000
160000000
140000000
120000000
100000000
80000000
60000000
40000000
20000000
0
-20000000
-40000000


West Midlands High Climate Change Scenario
Regional Revenue
Time Period
High2020
High2050
High2080
Overall Impact
Impact excluding pasture


West Midlands Low Climate Change Scenario
Regional Revenue
Time Period
Low2020
Low2050
Low2080
Overall Impact
Impact excluding pasture


Yorkshire and the Humber High Climate Change Scenario
Regional Revenue
Time Period
High2020
High2050
High2080
Overall Impact
Impact excluding pasture


Yorkshire and the Humber Low Climate Change Scenario
Regional Revenue
Time Period
Low2020
Low2050
Low2080
Overall Impact
Impact excluding pasture