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Manatū Ahu Matua

Integrated Assessment of Trade-Related Impacts of Global Climate Change and Climate Policies

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Prepared for Gerald Rys, MPI

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Executive Summary

The New Zealand Integrated Assessment Modelling System (NZIAMS) was developed between July 2010 and June 2013 by researchers at Landcare Research, AgResearch, New Zealand Agricultural Greenhouse Gas Research Centre, and Lincoln University. The project was led by Dr James Lennox, formerly of Landcare Research, who is currently a researcher at Fondazione Eni Enrico Mattei (FEEM) in Venice, Italy. Its development was funded by the Ministry for Primary Industries.

Research Aim

This research had three main aims:

- Develop a global dynamic economic model, linked with a global spatial agricultural and forestry productivity model, enabling detailed assessments of trade-related impacts on New Zealand of global climate change and policies over 5–50 years.
- Develop an integrated assessment model (IAM) framework for New Zealand to link assessments of trade-related impacts to 100-year scenarios of global climate, agricultural and forestry productivity and economic changes.
- Provide scenarios of global climate change and policies, focusing on trade-related impacts on New Zealand. Assessments of trade-related impacts over 5–50 years will be provided within the context of more general 100-year global scenarios.

Model Overview

The NZIAMS was developed with a focus on New Zealand to better inform policy makers of how policies might affect New Zealand in relation to the world (see Figure 1). The three main component models of NZIAMS are:

- The core economic model, Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium (CliMAT-DGE), describes the global economy and anthropogenic generation of greenhouse gas (GHG) emissions. It comprises a 'top-down' dynamic general equilibrium trade model as well as 'bottom-up' dynamic partial equilibrium sub-models of land allocation and primary production.
- A simple climate model, MAGICC, is adopted in NZIAMS to translate global emissions into global atmospheric GHG concentrations and mean temperatures.
- A biophysical model, the Global Yields Emulator (GYE),estimates relative changes in crop yields in different geopolitical regions and agro-ecologic zones based on the global mean climatic variables produced by MAGICC. These yield changes can then be fed into either the top-down or bottom-up components of CliMAT-DGE.

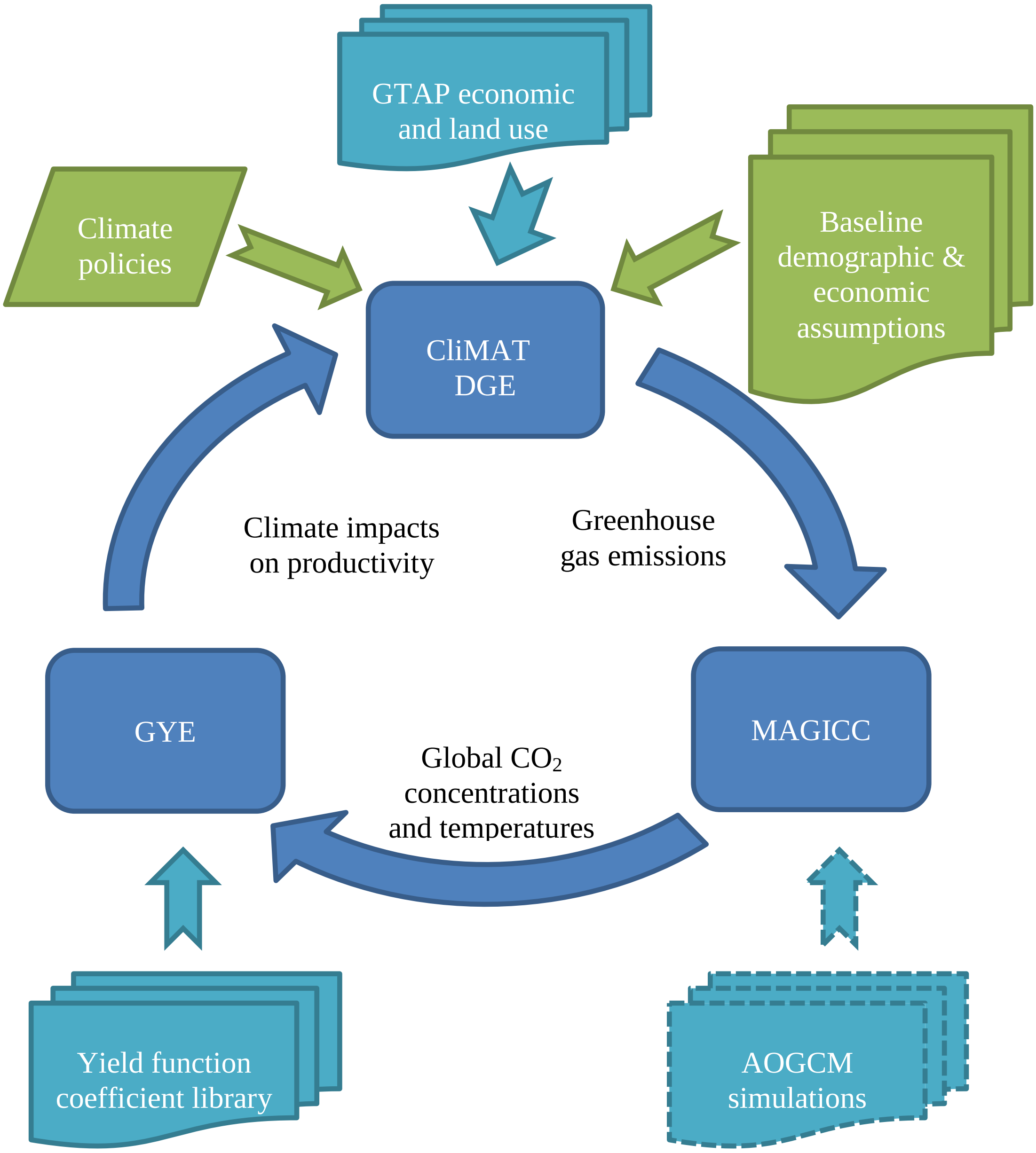

Figure 1: NZIAMS core system, comprising CliMAT-DGE economic model, MAGICC climate model, and Global Yields Emulator (GYE)

CliMAT-DGE is used to model the response of the global economy to climate policies and/or to climate impacts. This response is modelled against a baseline scenario that incorporates exogenous projections of demography, technological change and the like. Policy settings and baseline projections are represented by the green boxes in Figure 1. A large amount of data describing current and projected evolution of the economy and technologies is required to parameterise CliMAT-DGE. These data are represented by the blue box at the top of the figure.

MAGICC is a (relatively) simple model of the global atmosphere and ocean system (Wigley 2008), designed to emulate the responses of global climate variables in very complex Atmosphere Ocean General Circulation Models (AOGCMs). While an AOGCM typically takes weeks to run on a supercomputer, MAGICC runs in seconds on a desktop computer.

This study uses MAGICC version 6, which has been calibrated to emulate the responses of any of the AOGCMs and carbon cycle models used in the IPCC Fourth Assessment Report (Meinshausen et al. 2011).

The GYE emulates the responses of complex crop and forest models using a statistical pattern scaling methodology. The pattern scaling methodology has previously been used to estimate regional climate changes based on changes in carbon dioxide concentration (CO_2) and mean annual temperature. However, to our knowledge, this is the first application of the methodology to physical impacts of climate change.

Illustrative Policy Scenarios

This document provides a high level description of the architecture of the framework and the functionality of its component parts. Further technical documentation of individual components can be found in journal articles, conference papers, and technical documents cited here. Several illustrative scenarios are also presented and discussed. These scenarios are intended only to demonstrate the potential of the framework, not as a guide to policy or other decisions.

The key components of the NZIAMS were highlighted through a series of illustrative scenarios compared to the baseline. First, we modelled the impacts of climate change on the agriculture and forestry sector (base + i). Then we modelled the economic impact of a hypothetical policy that places a carbon tax on the energy and industrial sectors and then additionally agricultural GHG emissions without considering effects of climate change (cpenr and cpall, respectively). Finally, we modelled the impact of both climate impacts and the two forms of carbon tax (cpenr + i and cpall + i). The overview of these scenarios is outlined below in Table 1.

Table 1: NZIAMS Illustrative Scenarios

Abbreviation[1]	Name	Details
base	Baseline	Baseline with no climate impacts or GHG emissions reduction policy
base + i	Baseline + Climate Impacts	Baseline with land productivities moderated by climate impacts simulated with MAGICC and GYE
cpenr	Pricing Energy and Industrial GHG Emissions	Energy and industrial emissions are subject to regional carbon taxes. The tax starts at US(2004)$15/tCO2-e and increases at 5% per annum. However, the Rest of World region does not impose this common tax in the first three periods (15 years)
cpenr + i	Pricing Energy and Industrial GHG Emissions + Climate Impacts	Land productivities moderated by climate impacts simulated with MAGICC and GYE are added to the cpenr scenario
cpall	Pricing Energy, Industrial and Agricultural GHG Emissions	The same carbon taxes as modelled in the cpenr scenario are extended to cover agricultural GHG emissions
cpall + i	Pricing Energy, Industrial and Agricultural GHG Emissions + Climate Impacts	Land productivities moderated by climate impacts simulated with MAGICC and GYE are added to the cpall scenario

[1] The abbreviations are broken into:

cp = carbon price, +i= climate impacts, all = energy, industrial and agricultural GHGs, enr = energy and industrial emissions

NZIAMS uses a highly disaggregated dataset with 113 regions and 57 sectors. However, as the model has difficulty converging, it is computationally infeasible to run CliMAT- DGE with all the regions and sectors. We found that with 5 regions it is possible to have approximately 20 aggregated sectors (including energy and land sectors) and the model will converge to an optimal solution.

Our illustrative scenarios are tailored to focus on New Zealand with New Zealand included as a separate region. The primary production sectors are aggregated to focus on the land and food sectors as these are the most important for the New Zealand economy. The energy sectors include major GHG emitters (for studying GHG impacts on climate) as well as carbon free electricity which makes up a significant part of New Zealand's energy share. The model aggregations used in this report for the illustrative scenarios are shown in Table 2.

Table 2: Regions and economic sectors (primary production, secondary energy, manufacturing/value added) used for illustrative scenarios

Name	NZIAM abbreviation	Notes
Regions		
New Zealand	NZL	
Australia	AUS	
North America	NAM	USA, Canada, Mexico
Rest of OECD	OECD	Rest of OECD, including Singapore, Chile, Turkey, and Korea
Rest of World	ROW	All other countries
Primary Production Sectors		
Bovine cattle, sheep and goats, horses	CTL	
Forestry	FST	
Grains including rice	GRA	
Oil seeds and sugar cane	OSC	
Other crops	CRO	
Plant based fibres	PFB	
Raw milk	RMK	
Secondary Energy Sectors		
Carbon-free electricity	ECF	
Coal	COA	
Fossil electricity	EFS	
Gas	GAS	
Oil	OIL	
Petroleum, coal products	P_C	
Manufacturing/Value Added Sectors		
Energy-intensive manufacturing	EMT	
Food products	FOO	
Harvested wood products	HWP	
Non-energy-intensive manufacturing	NSV	

Summary of Results

For the baseline (base), a key trend is the strong growth in economic and sectoral output from the rest of the world, relative to the other regions modelled. Associated with this is strong growth in baseline GHG emissions from this region. It should be noted though, that all other regions modelled also experience a growth in baseline GHG emissions. The baseline GHG emissions from our model closely follows the projected emissions representative concentration pathway (RCP) 8.5 (Riahi et al. 2011; van Vuuren et al. 2011).

For the version of the model run for this study, climate impacts alone (base+i) have a very modest effect on outputs and prices within the 50-year period of analysis considered (2004–2054). Global GDP is slightly higher; 0.2% higher in year 50 compared with the baseline. New Zealand GDP is expected to increase by about 0.7% over the baseline estimate in year 50, the highest of all modelled regions. This is mainly due to the increased productivity expected from the long term climatic changes. However, this analysis does not take into account the negative impacts of climate change such as extreme events like storms that may devastate a growing season thereby affecting GDP.

The carbon pricing scenarios (cpenr and cpall) have a more significant effect on output, prices and emissions relative to the baseline. The carbon price scenarios are expected to reduce global GHG emissions by between 47 and 53% relative to the baseline in year 50, which follows a similar trajectory to RCP 4.5 (Thompson et al. 2011; van Vuuren et al. 2011). Not unexpectedly, a carbon tax on the energy sectors (cpenr) is estimated to lead to a reduction of global GDP of 3.4% in year 50. The main impact is a significant reduction in electricity output, and a shift from fossil-based to carbon-free electricity. Modelling suggests this will lead to a large reduction in emissions from the secondary energy sector, relative to the baseline. New Zealand is unique among the regions considered in our modelling, in that it already has a large share of energy output that is from carbon-free electricity. This moderates the scope for New Zealand to reduce GHG emissions from the secondary energy sector, compared with other regions.

Applying a carbon tax to all sectors (cpall) results in a stronger negative effect on global GDP; 3.9% lower than the baseline in year 50 (2054). The main impact is on primary product output, and hence on value-added agricultural output, land-use change, and emissions from this sector. Value-added agricultural sector output is lower, due to a combination of lower demand (due to negative income effects) and the higher cost of inputs from the primary production sectors. The most significant impact of a carbon tax is an estimated reduction in cattle, sheep and goat output from the rest of the world, leading to an increase in output of these products in New Zealand, Australia and the rest of the OECD. For the model assumptions used here,[2] this is predicted to result in relatively higher prices for cattle, sheep and goats, and raw milk, a relatively lower output of raw milk, and a substitution in land use in New Zealand from raw milk production to cattle, sheep, and goat production, relative to the baseline.

Table 3 shows estimates of the GDP, GHG emissions, and output for year 50 for all scenarios by sectors. New Zealand makes a small emissions contribution to the global GDP, GHG

[2] The original GTAP data used in the model have higher GHG emissions associated with producing raw milk than cattle, sheep and goat production in New Zealand. This is another reason for the shift in land use away from raw milk in New Zealand.

emissions and output. However, for many scenarios the sectoral GHG reductions and outputs of New Zealand are comparable to those at a global scale in percentage terms (Table 4).

There are, however, some differences. A decrease in the secondary energy sector GHG emissions for New Zealand by about 90% only implies a 5–6% reduction in output, whereas a 94% reduction in the rest of the world implies a 50–56% reduction in output. This is because the New Zealand secondary energy sector makes up a very small share of the total energy generated in New Zealand.

The decrease in GHG emissions in the value added agriculture sector is large compared with the relative change in output in the sector. This comes from a combination of increase in prices, changes in land productivity, substitution between high emitting energies to alternative low emitting energies in producing the value added agriculture. Additionally, the changes in the types of food produced, i.e. instead of using arable products there could be an increase in fish as inputs into producing food which are less GHG intensive.

Benefits

NZIAMS was developed to assess the medium- and long-term environmental (climate change) effects of policies and their economic costs and benefits to New Zealand. The modularity of NZIAMS provides a degree of flexibility to link with other biophysical or partial equilibrium economic models not currently included in NZIAMS relatively easily. It also allows the exploration of the relative importance of the choice of climate or crop models for estimates. This is a key innovation over standard IAMs, which usually have a particular climate and/or crop model hard-wired into them. Because it is global in nature but specifies New Zealand as a stand-alone region, the model/framework can be used to estimate the impact changes in global commodity prices and productivity on the country's economy.

The modelling framework allows researchers to assess a range of policies and scenarios. Examples of policies that can be explored using NZIAMS include: introduction of emissions or offsets trading for agriculture and/or forestry in different countries (Lee et al. 2007); adjusting consumer preferences through marketing aims such as carbon labelling (Saunders et al. 2009a); liberalisation of agricultural trade (Verburg et al. 2009); and imposition of border carbon adjustments (Ballingal et al. 2009).

Table 3: Estimated GDP, Output and GHG emissions for year 50 (2054)[3]

Scenario		All Sectors		Secondary Energy		Energy Intensive Manufacturing		Non Energy Intensive manufacturing		Value Added Agriculture		Primary Production	
		GDP (bil $)	GHG (GtCO2e)	Output (bil $)	GHG (GtCO2e)	Output (bil $)	GHG (GtCO2e)	Output (bil $)	GHG (GtCO2e)	Output (bil $)	GHG (GtCO2e)	Output (bil $)	GHG (GtCO2e)
Global	base	102,092	63	6,841	25	30,109	13	148,566	7	15,221	0.8	4,183	11.2
	base +i	102,275	63	6,844	25	30,154	13	148,756	7	15,318	0.8	4,246	11.3
	cpenr	98,661	32	5,273	1	27,920	9	143,445	6	14,895	0.4	4,131	10.6
	cpenr +i	98,851	32	5,280	1	27,975	9	143,649	6	14,997	0.4	4,195	10.7
	cpall	98,089	28	5,232	1	27,597	9	142,821	6	14,450	0.4	3,813	6.6
	cpall +i	98,256	28	5,238	1	27,645	9	143,002	6	14,539	0.4	3,869	6.7
NZL	base	250	0.14	11.0	0.008	58	0.03	364	0.01	63	0.001	27	0.084
	base +i	251	0.14	10.9	0.005	58	0.03	365	0.01	65	0.001	28	0.088
	cpenr	247	0.12	10.5	0.001	57	0.02	360	0.007	63	0	27	0.081
	cpenr +i	249	0.12	10.5	0.001	57	0.02	362	0.007	65	0	27	0.084
	cpall	244	0.11	10.4	0.001	56	0.02	359	0.007	52	0	26	0.079
	cpall +i	245	0.12	10.4	0.001	56	0.02	360	0.007	54	0	26	0.081

[3] Non-energy intensive manufacturing output is larger than the total GDP. The gross ouputs of mulitple sectors involves double counting, causing NSV to be larger than the total GDP. GDP is calculated as GDP = Consumption (includes Government here) + Investment + Exports – Imports = Sum of all sectors' Value Added.

Table 4: % change in Key Estimates Relative to Baseline (no policy or impacts)

Scenario		All Sectors		Secondary Energy		Energy Intensive Manufacturing		Non Energy Intensive manufacturing		Value Added Agriculture		Primary Production	
		GDP	GHG	Output	GHG	Output	GHG	Output	GHG	Output	GHG	Output	GHG
Global	base +i	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	2%	1%
	cpenr	-3%	-50%	-23%	-94%	-7%	-31%	-3%	-19%	-2%	-49%	-1%	-5%
	cpenr +i	-3%	-50%	-23%	-94%	-7%	-30%	-3%	-19%	-1%	-49%	0%	-4%
	cpall	-4%	-56%	-24%	-94%	-8%	-32%	-4%	-20%	-5%	-51%	-9%	-41%
	cpall +i	-4%	-56%	-23%	-94%	-8%	-31%	-4%	-19%	-4%	-50%	-8%	-40%
NZL	base +i	1%	0%	-1%	-35%	0%	-3%	0%	-1%	3%	-2%	4%	4%
	cpenr	-1%	-15%	-5%	-90%	-3%	-30%	-1%	-24%	-1%	-68%	-3%	-3%
	cpenr +i	0%	-13%	-5%	-90%	-3%	-30%	-1%	-23%	2%	-67%	0%	0%
	cpall	-2%	-17%	-6%	-90%	-4%	-32%	-1%	-24%	-17%	-73%	-6%	-6%
	cpall +i	-2%	-15%	-5%	-90%	-4%	-32%	-1%	-24%	-15%	-72%	-3%	-3%

1 Introduction

The New Zealand Integrated Assessment Modelling System (NZIAMS) was developed between July 2010 and June 2013 by researchers at Landcare Research, AgResearch, New Zealand Agricultural Greenhouse Gas Research Centre and Lincoln University, led by Dr James Lennox. Its development was funded by the Ministry for Primary Industries.

The research was organised around three main research aims (RA):

- Develop a global dynamic economic model, linked with a global spatial biophysical model, enabling detailed assessments of trade-related impacts on New Zealand of global climate change and policies over 5–50 years.
- Develop an integrated assessment model (IAM) framework for New Zealand to link assessments of trade-related impacts to 100-year scenarios of global climate, biological and economic changes.
- Provide assessments of global climate change and policies, focusing on trade-related impacts on New Zealand. Assessments of trade-related impacts over 5–50 years will be provided within the context of more general 100-year global scenarios.

Global IAMs account for complex interactions between global economic, atmospheric, ocean, and terrestrial systems with an ever-increasing degree of sophistication (van Vuuren et al. 2007; Riahi et al. 2007, 2012; Smith & Wigley 2012). However, their resolution (spatial, temporal, and economic) is generally too coarse to enable detailed assessments of trade-related impacts of climate change and policies on New Zealand as there are often theoretical, methodological, and practical impediments to adapting a full-scale IAM to enable such detailed assessments (Pitcher 2009). In most cases, global IAMs do not include New Zealand as a stand-alone region in the model, but rather aggregate it into a larger region representing Oceania or Australia.

Integrated assessment modelling is a tool increasingly used for environmental policy analysis. It links systems models together allowing analysis of complex interactions between multiple systems such as climate, biophysical, and economics. Scenarios run with these models aim to answer questions that can be helpful for policy makers to get a better understanding of the possible effects of their decisions on a multitude of systems.

There are three main component models of NZIAMS:

- *Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium (CliMAT-DGE)* models the global economy and anthropogenic generation of greenhouse gas (GHG) emissions. It comprises a ‘top-down’ dynamic general equilibrium trade model as well as ‘bottom-up’ dynamic partial equilibrium sub-models of land allocation and primary production.
- *MAGICC* is a simple climate model that is adopted in NZIAMS to translate global emissions into global atmospheric GHG concentrations and mean temperatures.
- *Global Yields Emulator (GYE)* is a statistical model that predicts relative changes in crop and forest yields in different geopolitical regions and agro-ecologic zones based on the changes in global mean atmospheric GHG concentration and mean temperatures produced by MAGICC. These yield changes can then be fed into either the top-down or bottom-up components of CliMAT-DGE.

This document provides a high level description of the framework's architecture and the functionality of its component models. Further technical documentation of individual models can be found in journal articles, conference papers and manuals cited herein and available upon request from the authors.

Several illustrative scenarios are also presented and discussed. Our illustrative scenarios are tailored to focus on New Zealand first by including New Zealand as a separate region. The primary production sectors are aggregated to focus on the land and food sectors as these are the most important for the New Zealand economy. The energy sectors include major GHG emitters (for studying GHG impacts on climate) as well as carbon-free electricity that makes up a significant part of New Zealand's energy share. These scenarios are intended only to demonstrate the potential of the framework, not as a guide to policy or other decisions. The scenarios are outlined in Table 5.

Table 5: NZIAM Scenario Overview

Abbreviation	Name	Details
base	Baseline	Baseline with no climate impacts or GHG emissions reduction policy
base + i	Baseline + Climate Impacts	Baseline with land productivities moderated by climate impacts simulated with MAGICC and GYE
cpenr	Pricing Energy and Industrial GHG Emissions	Energy and industrial emissions are subject to regional carbon taxes. The tax starts at US(2004)$15/tCO2-e and increases at 5% per annum. However, the ROW region does not impose this common tax in the first three periods (15 years)
cpenr + i	Pricing Energy and Industrial GHG Emissions + Climate Impacts	Land productivities moderated by climate impacts simulated with MAGICC and GYE are added to the cpenr scenario
cpall	Pricing Energy, Industrial and Agricultural GHG Emissions	The same carbon taxes as modelled in the cpenr scenario are extended to cover agricultural GHG emissions
cpall + i	Pricing Energy, Industrial and Agricultural GHG Emissions + Climate Impacts	Land productivities moderated by climate impacts simulated with MAGICC and GYE are added to the cpall scenario

The document is organised as follows. First, we discuss the methodology behind NZIAMS. Second, we list the data required to parameterise the model results. Third, we highlight key outputs from the model baseline. Fourth, we estimate the impacts of climate change on the global agriculture and forestry sector. Fifth, we assess the impact of a price of GHG emissions on the global economy and emissions trajectory. Then, we look at the possible implications of a scenario that includes both a price on GHG emissions and climate change. Finally, we discuss possible extensions and future research.

2 New Zealand Integrated Assessment Model System (NZIAMS)

Global integrated assessment models (IAMs) account for complex interactions between global economic, atmospheric, ocean, and terrestrial systems with an ever-increasing degree of sophistication (van Vuuren et al. 2007; Smith & Wigley 2012). The NZIAMS is tailored specifically to New Zealand representing New Zealand as a separate region and focussing on agriculture and forestry which are a large part of the New Zealand economy. It links biophysical and economic models together to achieve this with the possibility of downscaling agriculture and forestry sectors in linked partial equilibrium (PE) models to better understand the impacts and interactions in these sectors.

2.1 Model Overview

The NZIAMS was developed with a focus on New Zealand to better inform policy makers. There are three main component models of NZIAMS and linkages between them are shown in Figure 3. The 3 main components of the model are:

- *Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium (CliMAT-DGE)*: models the global economy and anthropogenic generation of greenhouse gas (GHG) emissions. It comprises a ‘top-down’ dynamic general equilibrium trade model as well as ‘bottom-up’ dynamic partial equilibrium sub-models of land allocation and primary production.
- *MAGICC*: translates global emissions into global atmospheric GHG concentrations and mean annual temperatures.
- *Global Yields Emulator (GYE)*: estimates relative changes in crop yields in different geopolitical regions and agro-ecologic zones based on the global atmospheric GHG concentrations and mean temperatures produced by MAGICC. These yield changes can then be fed into either the top-down or bottom-up components of CliMAT-DGE.

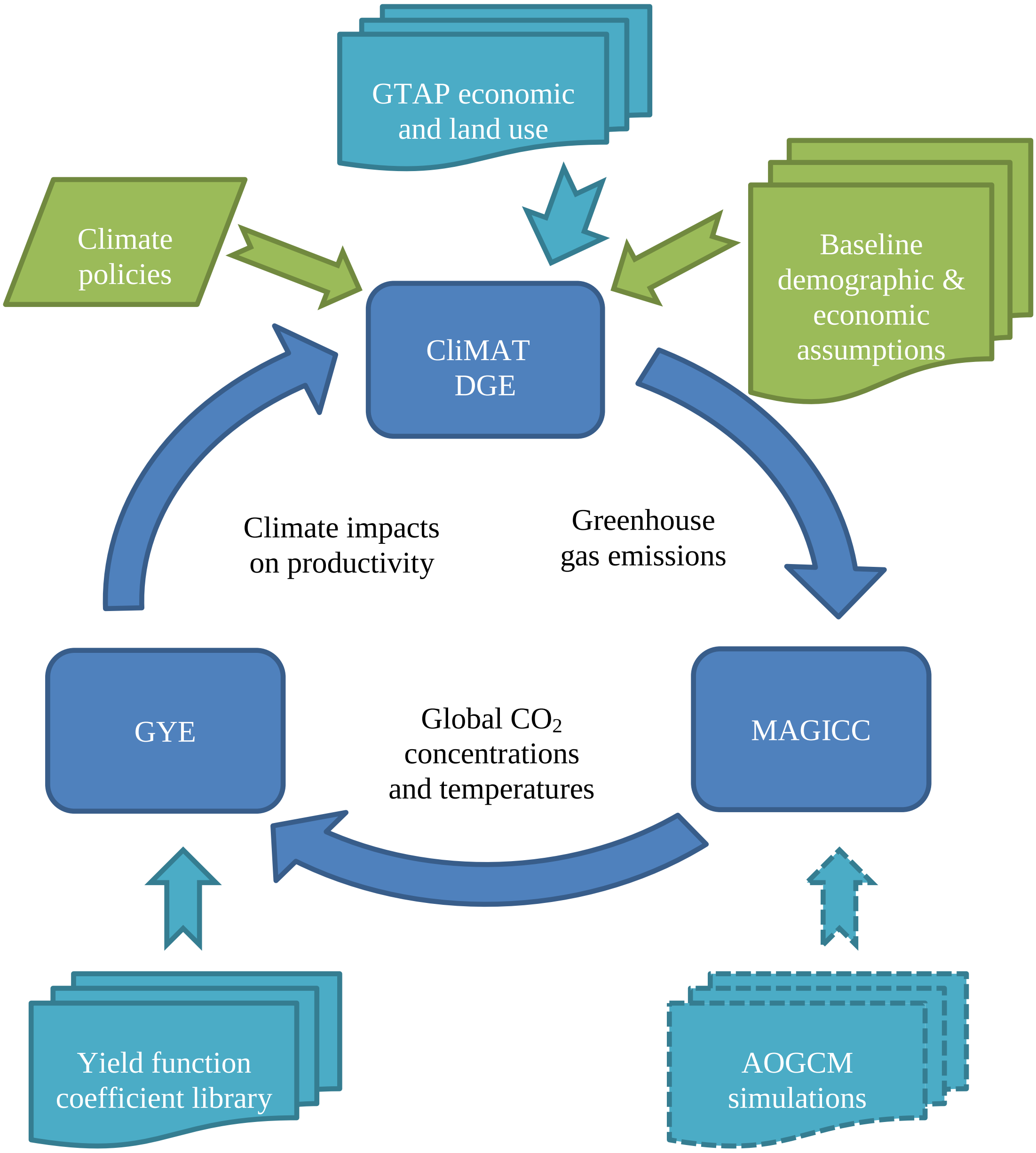

Figure 3: NZIAMS core system, comprising CliMAT-DGE economic model, MAGICC climate model, and Global Yields Emulator (GYE).

CliMAT-DGE is used to model the response of the global economy to climate policies and/or to climate impacts. This response is modelled against a baseline scenario, which incorporates projections of demography, technological change, etc. Policy settings and baseline projections are represented by the green boxes in Figure 3. A large amount of data describing current and projected evolution of the economy and technologies is required to parameterise CliMAT-DGE. These data are represented by the blue box at the top of the figure.

MAGICC is a (relatively) simple model of the global atmosphere and ocean system (Wigley 2008), designed to emulate the responses of global climate variables in very complex Atmosphere Ocean General Circulation Models (AOGCMs). While an AOGCM typically takes weeks to run on a supercomputer, MAGICC runs in seconds on a desktop computer. This study uses MAGICC version 6, which has been calibrated to emulate the responses of any of the AOGCMs and carbon cycle models used in the IPCC Fourth Assessment Report (Meinshausen et al. 2011).

The GYE emulates the responses of complex crop models using a statistical pattern scaling methodology. The pattern scaling methodology has previously been used to estimate regional climate changes based on changes in global variables. However, to our knowledge, this is the first application of the methodology to physical impacts of climate change. For this project, the GYE has been parameterised to emulate the responses to change in CO_2 concentration and temperature[4] for detailed crop models for wheat, maize, soya and rice within the decision support system for agrotechnology transfer (DSSAT) framework (Jones et al. 2003; Hoogenboom et al. 2012) and for forestry from the MC1 dynamic vegetation model (Bachelet 2001). However, the GYE is a flexible tool that could use impact patterns produced by other crop yield models. The basic output of the GYE is yield changes on a 0.5 degree global grid. These outputs can also be aggregated spatially and temporally within GYE to provide inputs suitable for use in CliMAT-DGE.

The NZIAMS not only links these three main components but also provides feedback loops allowing the model to optimise across these components, thereby accounting for the impacts of the climatic and biophysical changes. It is therefore useful in analysing questions that policy makers would be interested in asking, like:

- What effect will a particular policy measure have on alleviating climate change?
- How will regions, industries/sectors be affected?
- What kind of impacts will the changing climate have on production?

The NZIAMS also includes a downscaled partial equilibrium (PE) sub-model, which provides further detail into the agriculture and forestry sectors and can be linked to the NZIAMS. It explores each region in more detail with regional disaggregation into agro-ecological- zones (AEZs). (See chapter 2.2.3 for more detail).

2.2 CliMAT-DGE

CliMAT–DGE is a multiregional and multi-sectoral dynamic general equilibrium model with a relatively long time horizon of approximately 100 years. Climat-DGE's framework is based on the Massachusett Institute of Technology's (MIT's) Emission Prediction and Policy Analysis (EPPA) Model (Babiker et al. 2008), but with a strong focus on New Zealand. This type of model is suited to studying the efficient (re)allocation of resources within the economy and over time in response to resource or productivity shocks or policies.

For this project, we focused on developing a model that could estimate the impacts of climate change on productivity in agriculture and forestry and hence the wider economy. It was also developed to analyse the effects of climate policies on the economy and global emissions. We were concerned not only with climate impacts and the effects of policies within individual countries (or larger regions), but also their transmission between countries and regions via trade flows.

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[4] It is important to note that the GYE only models patterns based on CO_2 concentration and temperature. It does not account for other climate variables (such as rainfall, storms, radiation, etc.) or other imputs like nutrients.

CliMAT-DGE is a forward-looking, dynamic general equilibrium model. The term 'general equilibrium' refers to the equilibration of supply and demand for all goods and factors of production (land and other natural resources, labour and capital) by adjustment of relative prices in domestic and international markets.

A simple illustration of how the flow of income in the economy is represented in the CGE model is shown in Figure 4.[5] The main component of the circular flow is that the consumer sector supplies factor inputs such as capital and labour to the producer sectors, which in turn produces goods and services that are demanded by consumers. Corresponding to this flow is a reverse flow of payments, whereby households receive income for the factors they supply and then use that income to purchase the goods and services they consume. Note that there is no government sector included in this figure. This is because the government is modelled in CliMAT-DGE as a passive entity that simply collects taxes from producers and transfers the full value of these proceeds to the households. Our global CGE model also accounts for trade flows for goods between regions/countries.

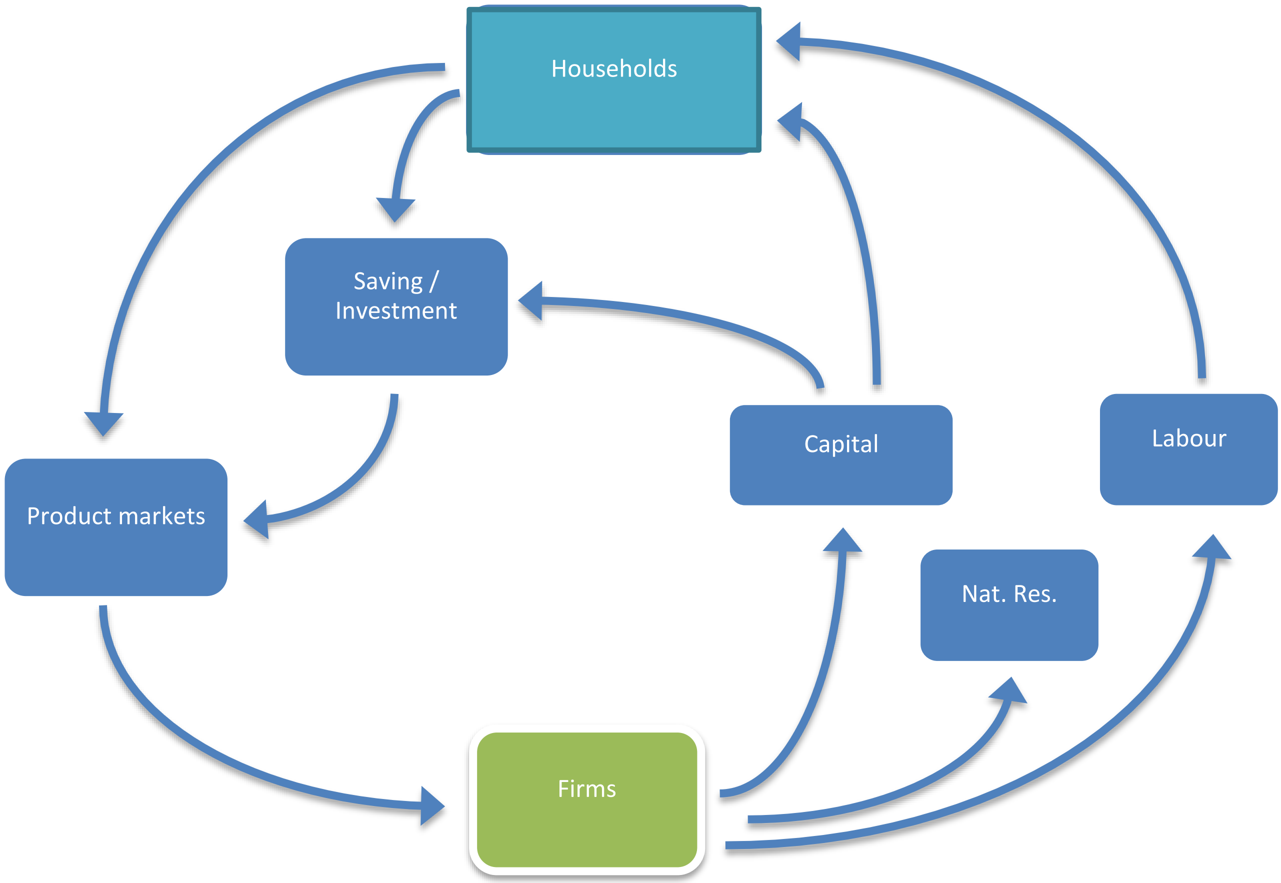

Figure 4: The Flow of Regional Income in CliMAT-DGE.

[5] NB: if the direction of the arrows were reversed, it would represent the flow of supply in the economy. For example, housholds supply labour as an input of production for firms (along with capital and natural resources), which in turn supply products for households to consume.

In a forward-looking model, optimisation of the model over time means that decisions made today about production, consumption and investment are based on future expectations that are realised in the CGE model simulation. The economic actors in the model are characterized as having “perfect” foresight or expectations. As a result, they know exactly what will happen in the future in all periods of the model’s time horizon. As a consequence, households are able to smooth their consumption over time and the savings rate varies endogenously. It is assumed that consumers maximise their utility while producers maximise their profits while retaining full knowledge of all present and future prices. The forward-looking feature of the CGE model makes it feasible to address economic and policy issues such as banking and borrowing of GHG allowances, international capital flows, and optimal emissions abatement paths among others. The implication is that we generally expect a forward-looking version to simulate lower cost of a GHG emissions reduction policy than we may get with an alternative structure such as recursive-dynamic (i.e. myopic) because agents have the additional flexibility to adjust saving and consumption over time. The forward-looking approach in economic modelling is considered to be advantageous because in reality agents’ expectations about the future affect current behaviour (Babiker et al. 2008).

Factor and product markets are assumed to be perfectly competitive, meaning that firms and workers and capital owners take prices as given. Supply of land, natural resources and labour are assumed to be fixed in each period, while capital stocks accumulate through new investment and are reduced by depreciation as they are used over time. Everything produced is consumed and no resources are wasted which is a necessary condition for CGE model due to the equilibration nature of it. These assumptions are typical of multi-region computable general equilibrium models (Adams et al. 2003; Babiker et al. 2008.

2.2.1 Definition of regions, sectors and time horizon

CliMAT–DGE was designed with the flexibility to represent different aggregations of countries or geopolitical regions, economic sectors, horizon lengths, and assumptions of the economy such as economic growth, technological change, and taxes and subsidies on production and consumption goods. The current version of the model is specified based on the following:

- Two or more regions can be defined covering any combinations of the 127 individual countries and aggregate regions in the GTAP 7.1 database (Narayanan & Walmsley 2008).
- Coal, oil, gas, petroleum refining, renewable electricity and fossil electricity sectors are always defined as separate sectors, as this is required by the model structure. Note that renewable and fossil electricity generation sectors have been disaggregated from the single GTAP sector: ‘electricity’. This was done by allocating all fossil fuel inputs to the fossil electricity sector and distributing the remaining outputs in their original proportions to achieve market shares derived from IEA generation data. More details are provided in Appendix 1.
- One or more land-use sectors can be defined covering any combinations of the 12 GTAP 7.1 agricultural and forestry sectors that use land (‘other animal products’ does not use land).
- One or more other sectors can be defined covering any combinations of the remaining 40 GTAP 7.1 sectors.

There is no limit on the number of regions or sectors the user can define but there are practical computational limitations on the overall model dimension. As a rough guide, it is difficult and often impossible to solve the full model with more than eight regions and/or a total of eight non-agricultural and non-energy sectors. To enable agricultural sectors to be modelled in more detail, CliMAT-DGE allows these sectors to be split into bottom-up regional sub-models, which can be coupled with CliMAT- DGE. This methodology is described in section 2.2.3.

CliMAT-DGE is intended to provide results over a horizon of between thirty and fifty years. However, model simulations employ a longer horizon (80–150 yr) to minimise the impact of the model's terminal conditions[6] on the results of interest. The longer the simulation horizon, the less the terminal conditions should affect the results of interest, but the more difficult the model becomes to solve numerically. For this report we have used a simulation horizon of 80 years. However, if the model includes unusually low depreciation rates, other very slow dynamics (e.g. a more realistic representation of forestry[7]), or a low discount rate, a longer time horizon may be preferred.

2.2.2 Model Structure

Following Mathiesen (1985) and Lau et al. (2002), the model is formulated as a mixed complementarity problem (MCP). The MCP formulation primarily consists of three sets of conditions: zero profit, market clearance, and income–expenditure balance. The zero profit condition implies that, in equilibrium, economic profits should be equal to zero for all sectors that produce a positive quantity of output. If profits are negative for any sector, then there should be no production at all. The market clearing condition means that there is a positive price for any good with supply less or equal than demand. If the good has an excess supply, then its price should be zero. The income–expenditure balance condition restricts total expenditure for each agent to be equal to the total value of the agent's endowments. These market equilibrium conditions are in turn defined from microeconomic theory using the duality concept in consumption and production theory (Babiker et al. 2008).

Each region has a single representative household. Government and private consumption are not distinguished. We assume households have perfect foresight and maximise the discounted sum of their instantaneous utilities, subject to a lifetime budget constraint. Firms are assumed to be identical within each production sector and to operate with constant returns to scale in perfectly competitive markets. Regions are linked by bilateral trade flows, modelled under the Armington assumption that represents the imperfect substitution between domestic and imported products from different regions.[8] International transport margins are associated with

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[6] Terminal conditions must be imposed on the model to make it finite and obtain a feasible and optimal solution. The computational model is a finite horizon approximation of an infinite horizon problem. The terminal conditions imposed force equality between the final growth rates of investment and consumption in each region. Conditions are imposed on the final periods of the simulation to approximate the level of investment that would occur in future periods if there were an infinite time horizon. This condition holds on the balanced growth path to which the model should converge in the (very) long run.

[7] A realistic representation of plantation forestry would account for the lifetime of a tree, from planting to harvest, which in New Zealand is typically about 30 years for *Pinus radiata*.

[8] The Armington assumption basically implies that a domestically produced good is treated as a different (i.e. inferior) commodity from an imported good produced by the same industry. For example, imported energy-intensive goods are not modelled as perfect substitutes for domestically produced energy-intensive goods.

bilateral trade flows. Taxes and subsidies on output, factor inputs, intermediate and final consumption of goods are modelled, as are taxes and subsidies on bilateral trade flows, thereby eliminating the need for a separate government sector.

Consumers in the model are assumed to maximise utility within and between periods, subject to an intertemporal budget constraint. This permits the optimal determination of the time-paths of both saving and investment in each region. Within each period, preferences of a representative consumer are described by a nested constant elasticity of substitution (CES) sub-utility function. Intertemporal substitution in consumption is described using a conventional logarithmic utility function.

Firms' technologies are described by nested CES, Cobb-Douglas and Leontief production functions (See Appendix 2). The general nesting structures contain sub-nests for factor inputs (labour and capital), energy inputs (primary and secondary fuels and electricity), and non-energy intermediates (e.g. services). Different nesting structures are used for agricultural and forestry sectors, each of the coal, oil, gas, oil refining, and electricity sectors, and manufacturing and service sectors. Sectors use intermediate inputs, capital and labour. Agricultural and forestry sectors use land, while the primary energy sectors use sector-specific and depletable resources. Capital, once installed, is sector specific and depreciates at a constant rate.

Sector-specific modifications for the model are as follows:

- Agricultural and forestry sectors use land as an additional factor input. The total supply of land in each region is exogenously specified and is usually fixed. Elasticities dictate the ability for land use change within each region to occur.
- Coal, oil, and gas sectors use sector-specific fossil fuel resources as an additional factor input. These factors are fixed in each region and are calibrated so that fossil fuel supply follows an exogenously specified path in the baseline scenario. As the resource is substitutable with other inputs, supply still responds to changes in prices in counter-factual scenarios.
- Carbon-free electricity sector uses a sector-specific resource as an additional factor input. This resource relates to the availability and quality of sites for these forms of electricity generation.
- The energy nestings of all energy sectors are modified according to the particular characteristics of these sectors. For example, in petroleum refining, crude oil is primarily a feedstock and therefore has very limited substitution possibilities with other energy inputs.

All factor and product markets are assumed to be perfectly competitive; therefore producers make no 'pure' economic profits. However, rents accrue to fixed factors of production: labour, land and sector-specific energy resources. Firms pay indirect taxes or receive subsidies on their production inputs and outputs. Households pay indirect taxes or receive subsidies on their final consumption. Direct taxes (e.g. personal and corporate income taxes) are not explicitly represented in the model. All tax and subsidy rates are estimated from the benchmark input data and are held constant by default. However, the user may change them as part of a baseline or counter-factual scenario if desired.

Goods and services can be traded internationally. Substitution between imported and domestic products and between imports from different origins is described by two-level CES functions. This follows the Armington assumption that a domestically produced good is treated as a different commodity from an imported good produced by the same industry and is not perfectly substitutable. Tariffs and international transport margins are applied to the imported good.

It is assumed that the representative household lives forever. However, a computational model must have a finite number of time steps. To transform the infinite horizon problem of the representative household into a finite horizon problem, we impose a set of terminal conditions. The terminal conditions chosen are that the growth rates of investment and of consumption (in each region) should be equal (Lau et al. 2002). This gives us a way to determine the demand for final period investment that is consistent with the long run equilibrium properties of the infinite horizon model.[9]

Most sectors (and consumers) produce greenhouse gas emissions from fuel (energy) use. Many sectors also produce 'industrial' greenhouse gas emissions while agricultural sectors produce emissions from livestock, fertiliser, etc. Carbon-free electricity, biofuel refining and bioelectricity production produce no direct emissions. Non-CO2 GHG emissions are quantified in CO_2-equivalent units. The equivalence factors for non-CO2 gases, namely CH_4, N_2O and fluorinated gases, are based on IPCC (2007) 100-year global warming potentials, and can be changed as desired.

Each region has an allowance of GHG emissions that can be exogenously set to simulate a regional cap-and-trade scheme. Alternatively, it can be endogenously determined while the GHG price can be exogenously specified. In either case, regional emissions will equal the allowance if there is a non-zero GHG price.

Regional GHG markets can be linked by imports and/or exports of allowances. The user can specify which regions may import and/or export allowances, which are traded in a single international market. The user can also specify whether and in which periods banking and/or borrowing of allowances is permitted in each regional market. International trading will equalise GHG prices between trading regions. With banking and borrowing, prices will rise at the discount rate.

2.2.3 Primary Production Sub-Models

Primary production sub-models allow for more detailed representations of land use, land-use change, and production technologies and dynamics in the agricultural and forestry sectors. The original intension was to excise these sectors and their associated land resources from the GE model. A top-down GE and multiple regional bottom-up partial equilibrium (PE) sub-models could then be solved iteratively, as shown in Figure 5. In theory, the overall system should converge to a full dynamic general equilibrium solution. This approach is referred to as 'hard-linking'.

The version of the model used for this report currently has instability problems when the hard-link is included, as the model fails to converge to a feasible solution. As a result, we have temporarily employed a 'soft-linking' approach to illustrate the important aspects of the PE sub-model components of NZIAMS.

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[9] In this type of model, all quantities (output, investment, etc.) must grow at the same exogenously determined 'balanced growth rate' in the very long run.

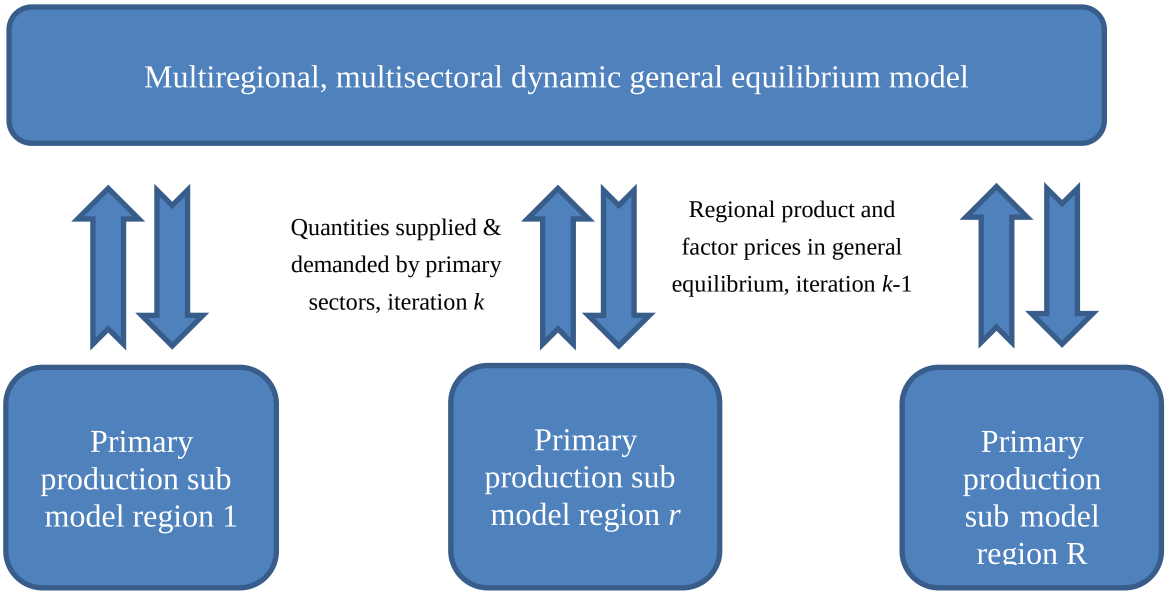

Figure 5: CliMAT-DGE hard linked sub-models.

In the soft-linking approach (Figure 6), the full CGE model (i.e. including top-down representations of land resources and agricultural and forestry production) is first solved. Both prices and quantities (of regional agricultural outputs) are then passed to the regional PE sub-models. These 'downscale' the results to distinguish changes in different agro-ecologic zones (AEZs).

It is also possible to employ more realistic dynamic formulations in the PE downscaling. Soft-linking is much simpler and avoids the potential numerical problems associated with hard-linking. However, soft-linking has the disadvantage that inconsistencies may arise between the top-down results and (aggregated) bottom-up results. The further the specification of the bottom-up model diverges from the corresponding specifications in the top-down model, the larger these inconsistencies may be.

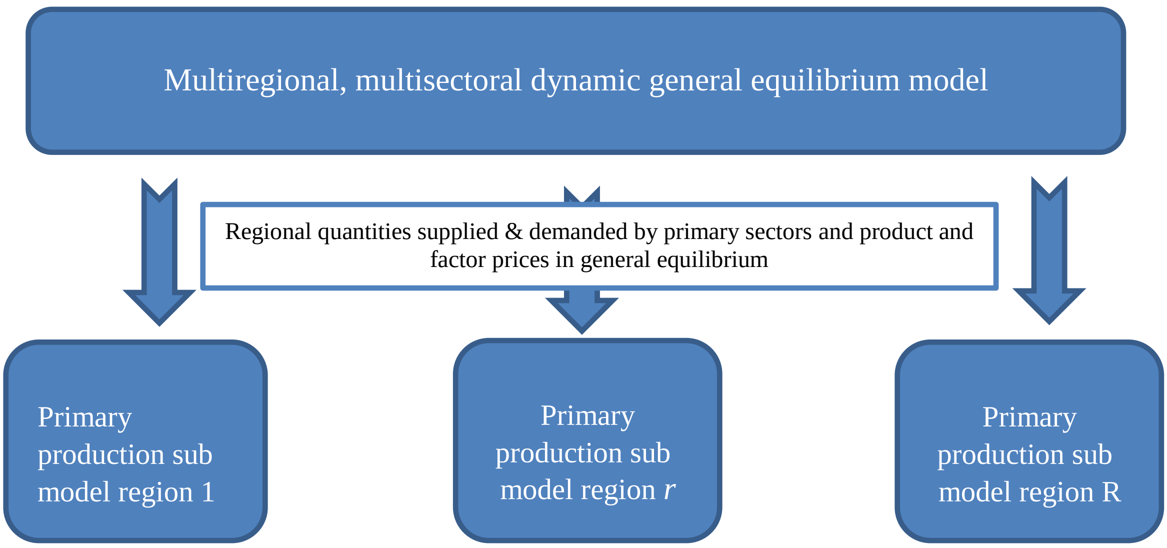

Figure 6: CliMAT-DGE soft-linked sub-models.

In each primary production sub-model, we can represent up to twelve agricultural and one forestry sector[10] for each region.[11] Production can be further differentiated in each of these sectors by up to 18 AEZs. The AEZ classification is based on climate, terrain and soil types, which allows us to differentiate the land resource and crop suitability within a geopolitical region according to length of growing season and by tropical, temperate, or boreal climates. Figure 7 shows a map of where the AEZs are located across the globe, based on data from Fischer et al. (2002). It is apparent is that not all 18 AEZs are present within a single country. New Zealand only has six AEZs: 6, 10, 12, 15, 16, and 17.

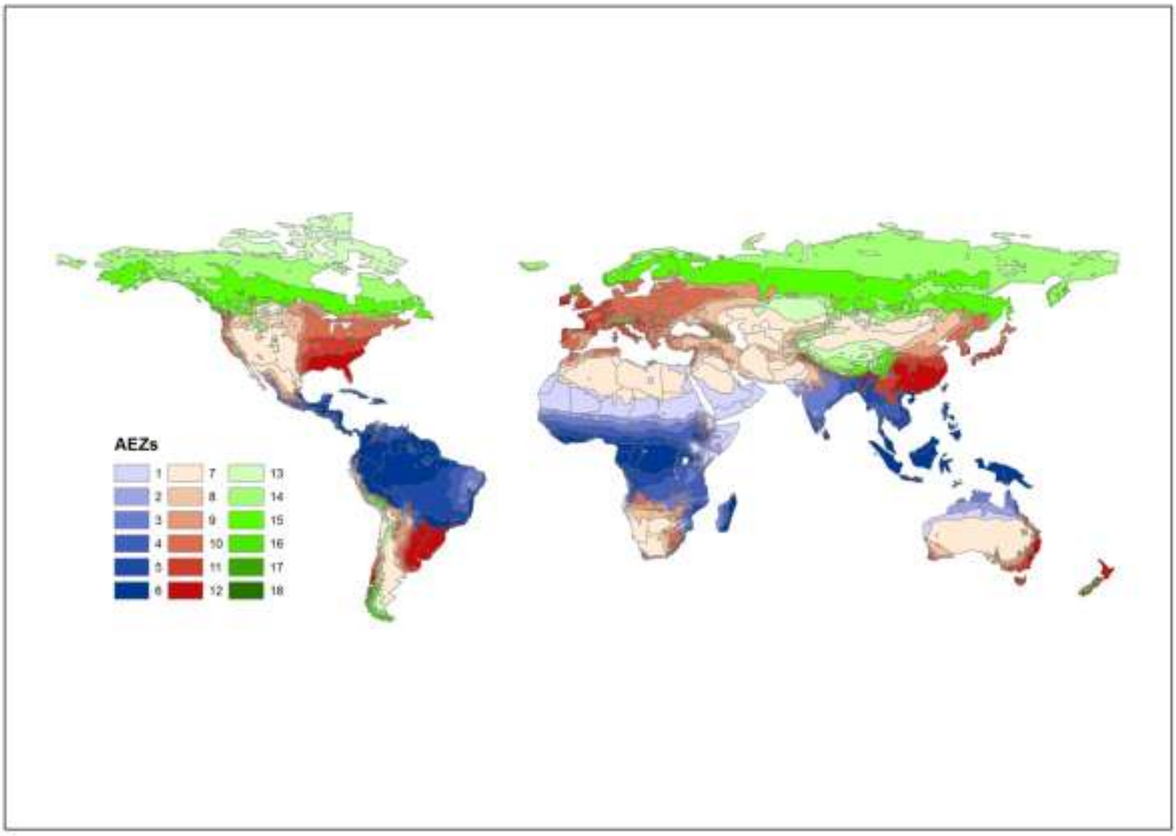

Figure 7: Global Agro Ecological Zones.

Theoretically, climate change impacts on agricultural and forest productivity can also be estimated in CliMAT-DGE at the AEZ level. For each sector in each AEZ of each model region, a climate impact function is used to relate the global climate variables output from MAGICC to productivity impacts initially generated off-line by running the GYE. More details on this methodology are discussed in Sections 2.3 and 2.4.

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[10] Currently, we only have the capacity to model a single, aggregate forestry sector. To model plantation and deforestation separately requires further research would have to be conducted

[11] With our current configuration, the sectors represented in the PE model have to mirror those in the GE model in the soft-link. As this is improved it will be possible to have disaggregated sectors that allow a more indepth understanding of the sectors. This is because the primary data that is ‘fed’ back to the CGE model will be economic output and GHG emissions from land-based sectors

2.2.4 Benchmark Dataset

CliMAT-DGE is calibrated to the GTAP v7.1 global economic database, including datasets for land use (Narayanan & Walmsley 2008). The GTAP land-use data disaggregates only land rents by AEZ. Data for the forest sector were disaggregated using information from a database that was originally created to parameterise the Global Timber Model (GTM), but modified for GTAP (Sohngen et al. 2009).

The disaggregated global dataset is extremely large. A moderate level of aggregation is necessary to run the soft-linked partial equilibrium primary production models, while a relatively high level of aggregation is required to run the general equilibrium model. We found that the computational limit is approached when we have 5 regions and roughly 21 aggregated sectors (including 6 separate energy and 7 primary production/land sectors) specified in the baseline.

Aggregation of sectors in the general equilibrium model is straight-forward. The user must provide many-to-one mappings that show which original sectors and which original countries/regions belong to which aggregated sectors and which aggregated regions respectively (see Appendix 3 for our current mappings used to create the illustrative scenarios). Each time these mappings are changed, the aggregation procedure must be rerun. This is fully automated[12] and takes only minutes.

It is possible to run the model without any aggregation of agricultural sectors included in GTAP v7.1.[13] However, if desired (e.g. to increase computational speed), aggregations may be implemented in the same way as for other sectors. Similarly, AEZs can be aggregated to any smaller number of agro-ecological zones if desired.

Perhaps the most difficult part of the aggregation process is combining different forest types identified in the GTM database to one representative forest per region and AEZ for use in the partial equilibrium model. Characterising the aggregate forest requires parameterising the timber yield curve and specifying a benchmark rotation length. To identify these parameters, we equate the level, slope and curvature of the aggregate yield curve with the level, slope and curvature of an area-based weighted sum of the individual yield curves. This aggregation procedure must be run whenever the regional aggregation is changed, but only takes a few minutes to complete. In the GE model there are no AEZs so it is relatively easy to aggregate the economic data to aggregate regions.

2.2.5 Modelling Package

CliMAT-DGE is programmed in GAMS. It utilises the packages mathematical programming system for general equilibrium analysis (MPSGE) framework (Rutherford, 1999) and is solved using the PATH solver (Ferris & Munson 1998) with a 5-year time-step. It is calibrated to the GTAP version 7.1 database (Narayanan & Walmsley 2008). More details on the calibrated baseline are discussed below.

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[12] Rarely, user intervention may be required if the particular sectoral and regional configuration creates scaling or other numerical problems.

[13] We have disaggregated the forestry sector data into three distinct categories: managed plantiations, naturally regenerating secondary forests, and primary deforestation. However, the current version of NZIAMS does not converge to an optimal solution unless the sector is aggregated to a single activity, ‘production forestry’.

2.3 MAGICC- A Model for the Assessment of Greenhouse Gas Induced Climate Change

MAGICC is a (relatively) simple climate model that has been used in successive IPCC assessment reports and various versions are used widely in IAMs (Wigley & Raper, 1992, 2001; Wigley 2008; Meinshausen et al. 2011). It simulates changes in global and hemispheric mean temperature changes as a result of changes in radiative forcing due to changes in atmospheric greenhouse gas and aerosol concentrations, using a set of coupled gas cycle, carbon and ocean heat transfer equations. While MAGICC is often referred to as a 'simple climate model', it might better be considered a model of 'reduced complexity'. It is simple enough to run in seconds on a personal computer, but involves hundreds of equations and thousands of lines of code. MAGICC is far more sophisticated than models consisting of only a few equations that are sometimes used in small-scale integrated assessment models (e.g. Nordhaus' DICE model). The latest version of MAGICC, version 6, has been demonstrated to be able to closely emulate global mean temperature changes projected by far more complex AOGCMs (Meinshausen et al. 2011), and also to be able to simulate feedbacks between climate change and the global carbon cycle (Joos et al. 2013).

As a model of reduced complexity, MAGICC necessarily has to parameterise some complex physical processes into simpler equations, but as far as possible those equations are still based on and consistent with the underlying bio-physical processes. More importantly, MAGICC version 6 has been calibrated to the full suite of AOGCMs and carbon cycle models that were used in the IPCC Fourth Assessment Report (Friedlingstein et al. 2006; Meehl et al. 2007), thereby allowing the user to simulate global mean changes from individual climate and carbon cycle models (Meinshausen et al. 2011). This flexibility, which is built into the NZIAMS, enables the testing of the relative importance of differences between climate models for policy questions. An example would be whether differences between climate models have a greater or lesser influence on future crop prices than alternative crop models or alternative policy choices.

MAGICC takes as inputs historic and future annual global emissions of GHGs. It produces as key outputs (normally on an annual time step):

- Global mean atmospheric concentrations of GHGs
- Global mean temperature over land in the northern hemisphere
- Global mean temperature over sea in the northern hemisphere
- Global mean temperature over land in the southern hemisphere
- Global mean temperature over sea in the southern hemisphere

It is important to note that MAGICC emulates underlying trend values of these variables. It does not reproduce the natural variability of the global mean temperatures that are observed historically and simulated by complex AOGCMs.

The user can select any one of over a dozen AOGCMs to emulate in MAGICC version 6. However, when MAGICC is used in NZIAMS together with the GYE, it is imperative that the same AOGCM is emulated by MAGICC and by GYE (as described below). For this report, we updated the MAGICC calibration to emulate the results from only one AOGCM, the Hadley Centre Earth System Model (HadGEM2-ES) as used in the 5th Coupled Climate Model Intercomparison Project (CMIP5)[14] (Jones et al. 2011), which was also used to drive the Global Yields Emulator (see chapter 2.4).

Figure 8 shows, as an example, the change in global mean temperature simulated by the HadGEM2-ES, and as simulated by MAGICC version 6, calibrated to this AOGCM, for two prescribed GHG scenarios over the 21st century (RCP2.6 and RCP8.5; see van Vuuren et al. 2011). RCP 2.6 represents a scenario with rapidly declining global GHG emissions (including net negative CO2 emissions by the end of the 21st century, consistent with the goal to limit the increase in global average temperature to less than 2°C relative to preindustrial levels); while RCP 8.5 represents a scenario of unabated growth in population and more limited endogenous technological change, resulting in a continued increase in global GHG emissions throughout the 21st century. Those two scenarios do not necessarily represent the extreme ends of possible future emissions and the actual future could still lie outside those scenarios. However, the very wide range they cover makes them useful as low and high emissions benchmark scenarios in IAM and impacts/adaptation studies (Moss et al. 2010; Reisinger et al. 2010; van Vuuren et al. 2012). While MAGICC is obviously unable to reproduce the natural variability exhibited by the complex AOGCM, the secular trend is reproduced very well under those two contrasting emissions and concentration scenarios.

Additional calibrations of MAGICC version 6 to other AOGCMs from the CMIP5 intercomparison will enable the emulation of other complex AOGCMs and the changes in crop yields simulated under those patterns of future climate change.

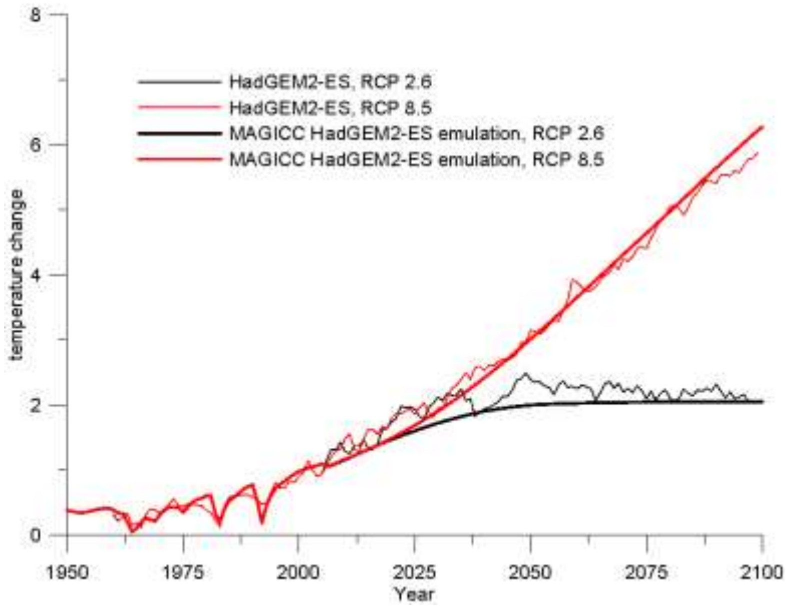

Figure 8: Simulated global average temperature change for two alternative GHG and aerosol concentration pathways (RCP 2.6, black; and RCP 8.5, red), using the complex AOGCM HadGEM2-ES (thin lines) and MAGICC using a calibrated parameter set to emulate HadGEM2-ES results (thick lines).

[14] http://cmip-pcmdi.llnl.gov/cmip5/

2.4 Global Yields Emulator

The Global Yields Emulator (GYE) is a command-line software tool developed for this project in collaboration with BodekerScientific (Bodeker and Kremser, 2013) for the emulation of crop yield responses to global climate change. In NZIAMS, we use the GYE to project changes in annual crop yields in different geopolitical regions and agro-ecologic zones[15] based on changes in the climate variables (temperature and CO_2 concentration) simulated by MAGICC, based on the emissions generated by CliMAT-DGE.

2.4.1 Crop yield simulations

The basis for GYE are changes in crop yields for each cell of a global 0.5×0.5° grid, calculated with the Decision Support System for Agrotechnology Transfer (DSSAT) model (Jones et al. 2003; Hoogenboom et al. 2012.[16] As input, the DSSAT runs used the local climate[17] at each grid cell, for each year from 1950 to 2100, simulated by the HadGEM2-ES AOGCM forced with two alternative GHG scenarios (RCP 2.6 and RCP 8.5).

Figure 9 shows an example output from the DSSAT model. The example simulated average yields for the periods 1980–1999 and 2080–2099 for non-irrigated wheat yield at a global 0.5×0.5° grid using the HadGEM2-ES climate change simulations under the RCP 8.5 scenario. Yields and areas of potential crops are simulated to contract mainly in sub-Saharan Africa and parts of Latin America, but would expand particularly in central and northern Europe and northern North America, consistent with theoretical expectations and results reported in the scientific literature (IPCC 2007).

[15] GYE can also be used to project changes in crop yields on a regular latitude/longitude grid.

[16] These yield datasets were provided by Joshua Elliot of the University of Chicago, who has performed a large number of global gridded DSSAT runs using the CMIP5 (daily) data as inputs. These data were provided in confidence for use in this project, but will be made publicly available when related publications are complete, probably by mid-2013.

[17] T_{max}, T_{min}, precipitation, relative humidity, and solar radiation

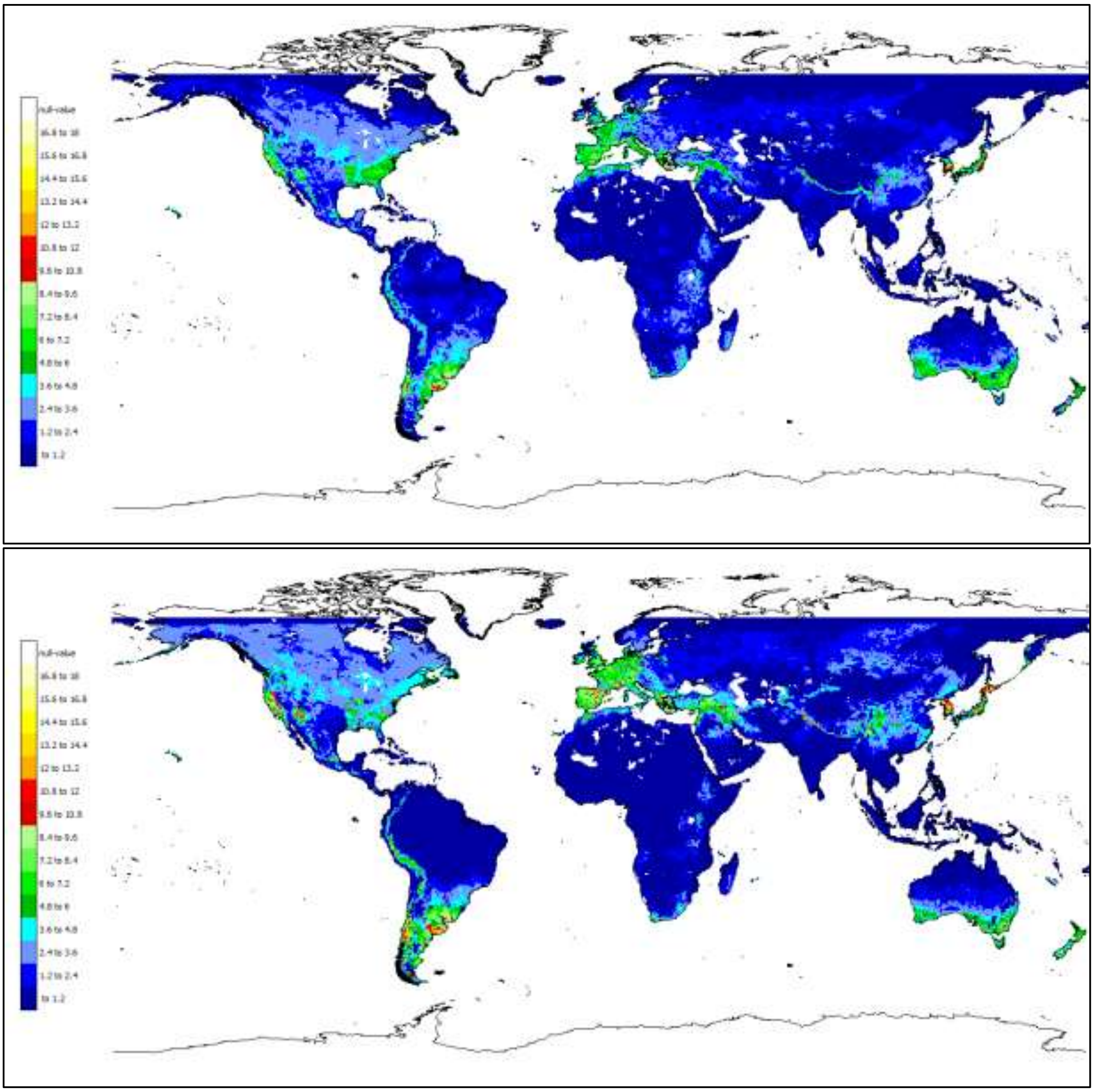

Figure 9: DSSAT-simulated 20-year average wheat yield, for 1980–1999 (top) and 2080–2099 (bottom), for projections with the HadGEM2-ES model and RCP8.5 scenario.

The DSSAT dataset requires significant supercomputing resources to produce results for each grid cell, year, alternative GHG scenarios, and alternative driving AOGCMs. As a result, on-line computation of crop yields within an NZIAMS run using DSSAT (or any other similar crop yield model) is computationally prohibitive. The challenge for the GYE thus was to efficiently simulate changes in future crop yields at each grid cell (or more aggregated regions) using the existing library of DSSAT simulations as input.

To perform this simulation, we employ a simple pattern scaling algorithm: to a first approximation, the projected change in future local climate is a function of the projected change in global mean temperature (for a given AOGCM). This pattern scaling approach is well studied and serves as the basis for many regional climate projections (Mitchell et al. 1999; Huntingford & Cox 2000; Mitchell 2003; Giorgi 2005; Ruosteenoja et al. 2007). In turn, the change in local crop yield is a function of the change in local climate. The pattern scaling approach implies that the change in crop yield at each grid cell can be approximated through a regression function based on the correlation derived from the detailed DSSAT-simulated crop yields and the global mean climate variables, and using the change in global mean temperature and CO_2 concentration from MAGICC as a predictive variable.

Note that the correlation between the change in crop yield at each grid point and the change in global climate (as expressed in global average temperature and CO_2) is specific to an individual AOGCM and crop model. For some grid cells, one AOGCM might project an increase in precipitation while another might project a decrease, with consequent different impacts on crop yields. But for any given AOGCM and crop model, given the robust correlation between the amount of local and global climate change, the change in crop yield at each grid cell can be simulated (to a first approximation) by the change in global mean temperature and CO_2 as simulated by the same AOGCM that was used to drive the detailed DSSAT simulations.

Figure 10 demonstrates the results of this pattern scaling approach, for two arbitrary regions showing different impacts on crop yields. Region A shows a significant negative impact on wheat yields with global climate change, while region B shows a positive response. The individual points are individual annual DSSAT simulations of crop yields (exhibiting significant natural variability due to the interannual variability in the underlying AOGCM climate simulations), while the thick solid lines are the simulated average crop yields, using MAGICC outputs for the same GHG emissions and the correlation coefficients derived from modelled DSSAT yields and AOGCM simulated global mean temperature and CO_2. The secular trend in yields is reproduced robustly for both of contrasting regions.

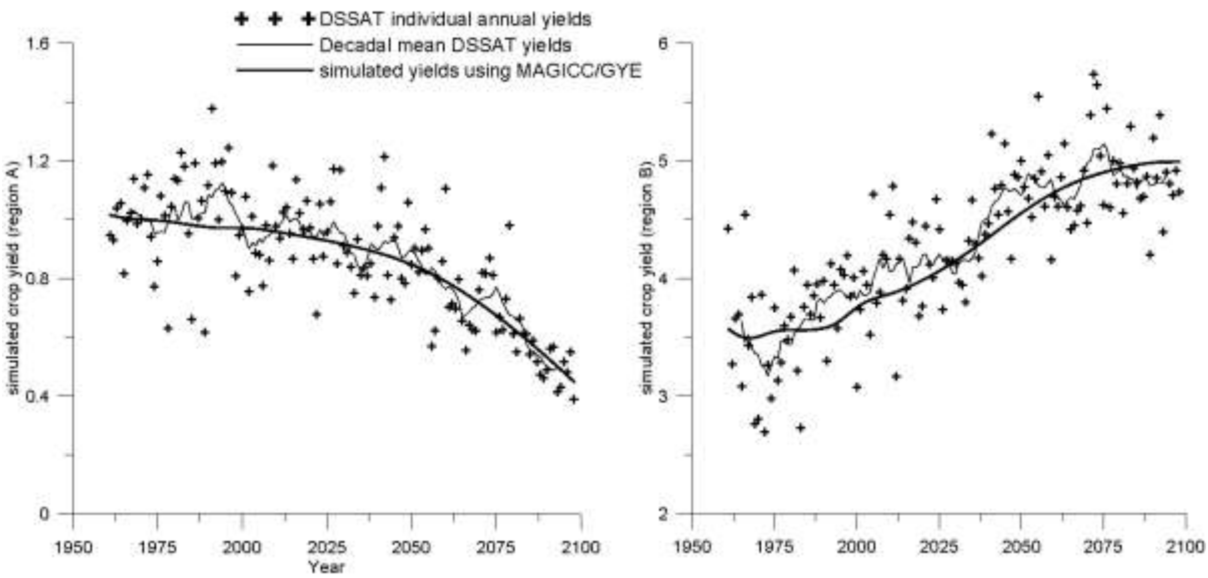

Figure 10: DSSAT-simulated annual wheat yields (crosses are individual annual yields, and the thin line is the decadal running mean), and simulated yields using GYE (think line), for two arbitrary regions showing different responses to climate change. The underlying AOGCM is HadGEM2-ES, and the emissions scenario is RCP 8.5.

2.4.2 Plantation forest yield simulations

To simulate climate impacts on forestry, we used data from the MC1 model, a dynamic global vegetation model (Gonzalez et al. 2010). MC1 is simulates vegetation types, ecosystem fluxes of carbon, nitrogen, and water, as well as wildfire occurrence and impacts. The model reads climate data at a monthly time step and calls interacting modules that simulate biogeography, biogeochemistry, and fire disturbance. The model was used to calculate future vegetation carbon based on AOGCMs at a various degrees of resolution. For this study, we used the Hadley CM3 climate model, as no forest simulations using the HadGEM2-ES are as yet available. The Hadley CM3 models a very similar response characteristic to the HadGEM2-ES model used for crop yield simulations. The MC1 model also simulated changes in forest yields at a 0.5 degree resolution (Bachelet 2011) to be consistent with the crop yields generated by DSSAT.

Data were available only as the mean forest yield for two time slices (1961–1990 and 2070–2099) and for three emissions scenarios (SRES B1, A1B, and A2). This essentially gives four data points from which to derive correlations between changes in global mean temperature and CO_2 and changes in forest yield, namely the yield and climate during the baseline period (1961–1990), and the yields and climates during the 2070–2099 period for the temperature and CO_2 under the three scenarios B1, A1B, and A2. This correlation was used to produce correlation coefficients for each grid cell (% yield change per degree C global temperature change and per ppm change in CO_2 concentration), which can then be used to simulate forest yield changes for each grid cell using again the MAGICC derived changes in global mean temperature and CO_2 for any emissions pathway produced by CliMAT-DGE.

2.4.3 Use of GYE within the NZIAMS

To use the GYE, one first needs to generate the basis functions[18] based on regressions between the AOGCM simulated global mean temperature and CO_2 changes and crop/forest yield data at each grid cell as described in the preceding sections. The fitted regression coefficients of the basis functions are stored in data files and need to be generated only once, before the actual NZIAMS is run.

Once this has been generated, the GYE can be used in simulation mode within the NZIAMS (See Figure 11). The stored coefficients (derived for simulations under both the RCP 2.6 and RCP 8.5 scenarios) allow the very efficient calculation of estimated changes in yields for any emissions pathway generated by CliMAT-DGE, using the change in global mean temperature and CO_2 simulated by MAGICC for those emissions. The correlation coefficients and forward simulations can be calculated either at 0.5×0.5° grid mode, or for more aggregated regions defined by country and AEZ.

To deal with potential non-linearities, GYE forward simulations of crop yields use a statistical weighting of correlation coefficients derived from both RCP2.6 and RCP 8.5 DSSAT simulations. That is, if the emissions produced by CliMAT-DGE are closer to a RCP 2.6 pathway, then more weight is given to the correlations derived from the DSSAT RCP 2.6 simulations, while if the CliMAT-DGE emissions are closer to a RCP 8.5 pathway, then more weight is given to the correlations derived from the DSSAT RCP 8.5 simulations. In practice

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[18] The basis functions are a mathematical concept. Every regression coefficient can be represented as a linear combination of the basis functions.

for most regions, there was little difference between GYE simulations based on weighted correlation coefficients and based on single (either RCP 2.6 only or RCP 8.5 only) coefficients. However, in some regions, using a weighted set of correlation coefficients improved agreement between GYE and DSSAT simulated yields. A weighted approach was therefore employed uniformly because there is little computational cost once the complete set of correlation coefficients has been derived.

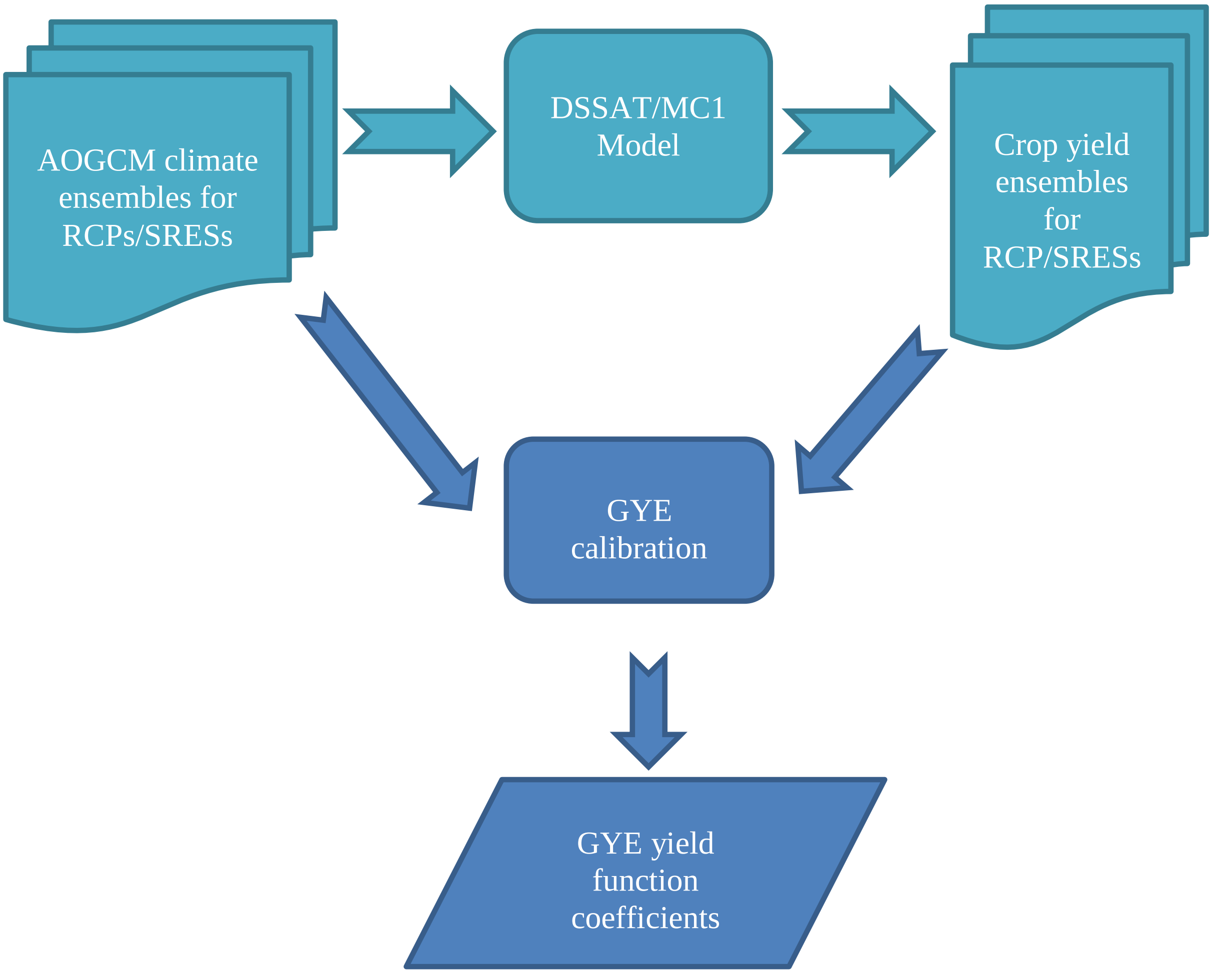

Figure 11: The Global Yields Emulator (GYE).

3 Model Baseline

CliMAT-DGE is initially calibrated to a baseline or reference case for which all policy analysis is referenced against or compared to. In CGE modelling it is imperative to have a baseline to which the scenarios can be compared as the outputs from the model are not simply projections but relative changes from a baseline scenario, which is what is estimated to happen if the economy continued to evolve along a business-as–usual (BAU) assumption (i.e. without any shocks to the model like climate impacts or a carbon price).

The first step for baseline calibration is to initialise CliMAT-DGE with values corresponding to a 'balanced growth path' (BGP). On a BGP, all outputs in all regions grow at the same, constant rate. The default growth rate is 1.8% p.a., but any non-negative value may be chosen. The BGP serves two purposes. First, the model cannot be solved successfully without providing a 'good' starting point. As the values of all variables on the BGP are known, it provides such a starting point. Second, if the user cannot solve the model to replicate the known BGP solution, this indicates an error in either the model structure or data. Any such error should be resolved by the user before attempting to run any other scenario.

Having successfully replicated the BGP, the next step is to construct and solve a baseline scenario. This reflects the fact that economic growth, for example, is in reality unbalanced. Some regions grow faster than others and growth rates change over time. In our model, the baseline scenario incorporates realistic projections of key macroeconomic (e.g. labour productivity) and other (e.g. energy efficiency) variables. The baseline has been developed from a number of sources. A summary of the key sources and assumptions for the baseline are listed in Table 6.

Table 6: Key Baseline Assumptions

Category	Assumption	Source/Notes
Labour productivity	Varies for each region	Exogenous – CEPII
Active population	Varies for each region	Exogenous – CEPII
Land and resource productivity	Varies for each sector and region	Exogenous – Same as labour productivity (CEPII)
Energy productivity (linked to energy emissions)	Varies for each region	Exogenous – Based on labour productivity (CEPII)
Fossil fuel resources	Varies for each region	Exogenous – based on trajectory of IEA WEO projections of fossil fuel supplies
Fossil and carbon-free electricity supply shares	Fixed for each region	Exogenous – own assumptions

The economic baseline is primarily constructed around a growth scenario developed by the Centre d'Etudes Prospectives et d'Informations Internationales (CEPII); The World Economy in 2050: a Tentative Picture (Fouré et al. 2010). That scenario in turn built on economic forecasts of the International Monetary Fund, labour force projections of the International Labour Organisation and demographic projections of the United Nations. Energy supply and efficiency projections are based primarily on several 2009 through 2012 editions of the

World Energy Outlook, produced by the International Energy Agency. Some of the projections used for the baseline are included in Appendix 4.

The baseline scenario is currently defined as involving neither climate policies nor climate impacts for all regions of the globe, although this could be changed if desired. .

3.1 Model Aggregation

Even though GTAP v7.1 is a highly disaggregated dataset, it is computationally difficult to run CliMAT- DGE with all the regions and sectors over a long time horizon as the model has difficulty converging. We found that with 5 regions and an 80-year time horizon (2004–2084) it is feasible to include roughly 20 aggregated sectors (including energy and primary production sectors). The aggregations used in the illustrative scenarios in this report are shown in Table 7. More details on this aggregation are included in Appendix 3.

Our illustrative scenarios are tailored to focus on New Zealand, first, by including New Zealand as a separate region in the global economy. Second, the primary production sectors are aggregated to focus on the agricultural and forestry sectors as these are the most important for the New Zealand economy. Third, the energy sectors include major GHG emitters (for studying global and New Zealand GHG impacts on climate) as well as carbon-free electricity which makes up a significant part of New Zealand's energy share.

Table 7: Regions and economic sectors (primary production, secondary energy, manufacturing/value added) used in the illustrative scenarios

Name	NZIAM abbreviation	Notes
Regions		
New Zealand	NZL	
Australia	AUS	
North America	NAM	USA, Canada, Mexico
Rest of OECD	OECD	Rest of OECD, including Singapore, Chile, Turkey, and Korea
Rest of World	ROW	All other countries
Primary Production Sectors		
Bovine cattle, sheep and goats, horses	CTL	
Forestry	FST	
Grains including rice	GRA	
Oil seeds and sugar cane	OSC	
Other crops	CRO	
Plant based fibres	PFB	
Raw milk	RMK	
Secondary Energy Sectors		
Carbon-free electricity	ECF	
Coal	COA	
Fossil electricity	EFS	
Gas	GAS	
Oil	OIL	
Petroleum, coal products	P_C	
Manufacturing/Value Added Sectors		
Energy-intensive manufacturing	EMT	
Food products	FOO	
Harvested wood products	HWP	
Non-energy-intensive manufacturing	NSV	

3.2 Calibrated Baseline Estimates

Key estimates for the NZIAMS baseline are highlighted in this section for year 0 (2004) through year 50 (2054). These estimates are what the model measures changes from in the five policy scenarios. Baseline emissions roughly mimic the trajectory in RCP 8.5 (van Vuuren et al. 2011). All dollar amounts are in 2004 USD. Key baseline estimates for Australia and New Zealand are also in Appendix 5.

3.2.1 Gross Domestic Output Baseline Estimates

Baseline estimates of regional GDP are shown in Figure 12. New Zealand and Australia estimates are small relative to the other much larger regions. All regional GDP increases, with the rest of the world increasing most rapidly, and global GDP increasing to about $100,000 billion by year 50.

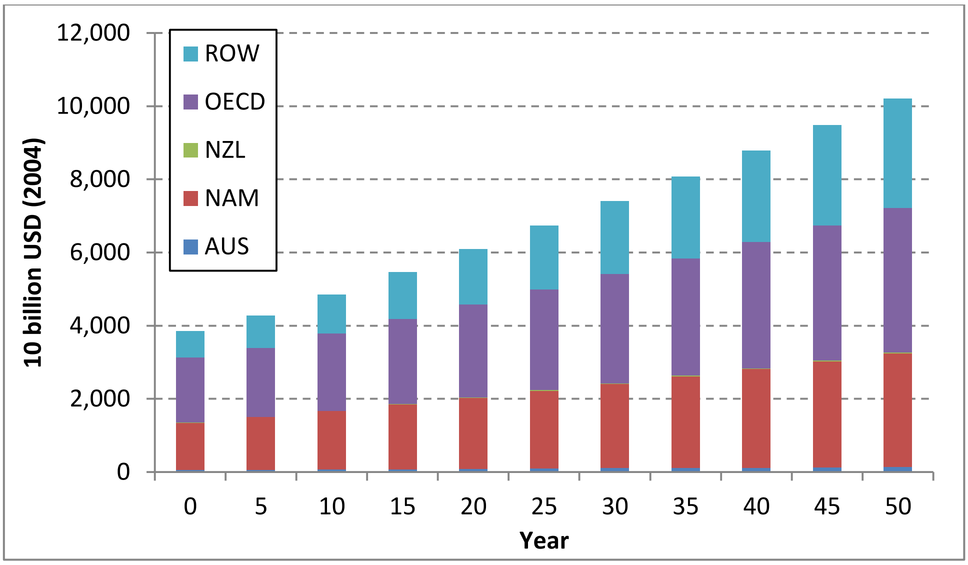

Figure 12: Baseline GDP by region.

Baseline GHG emissions by region are shown in Figure 13. New Zealand and Australia estimates are small relative to the other much larger regions. All regional GHG emissions increase, with the rest of the world increasing most rapidly, and global GHG emissions increasing to about 63 Gt CO2-e by year 50.

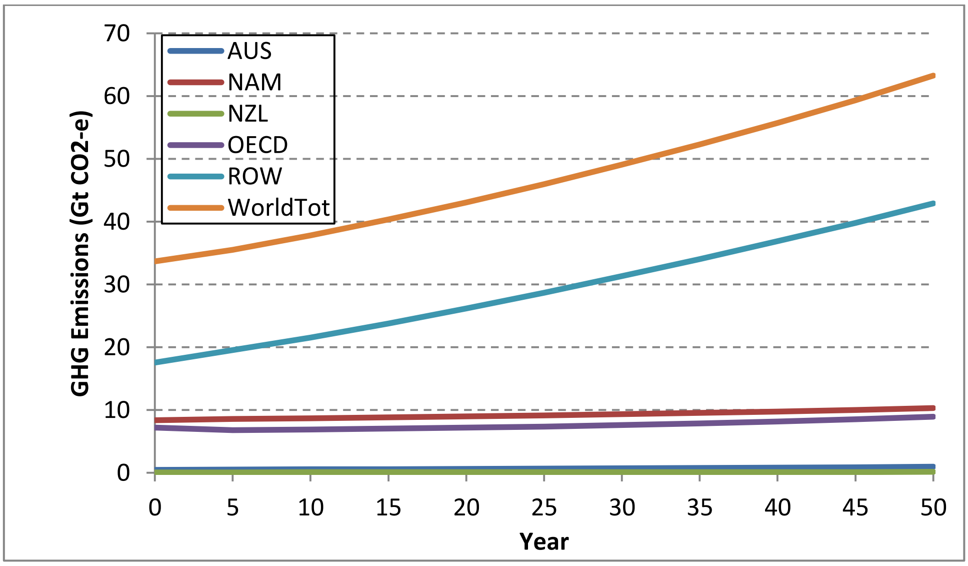

Figure 13: Baseline GHG emissions by region.

3.2.2 Secondary Energy Sector Baseline Estimates

The secondary energy sector refers to energy-specific sectors (e.g. electricity and petroleum refining) that use primary energy (e.g. coal, oil, and gas) as inputs for production. For example, the fossil electricity sector (EFS) uses a combination of coal, gas, and oil to produce electricity. The OIL sector here refers to the extraction and refining of oil. This means GHG emissions for this sector are those associated with the processes of extraction and refining oil, not with the use of oil.

Figure 14 shows the regional totals of the value of output in the secondary energy sector in 10s of billions of 2004 USD. The rest of the world experiences the most rapid growth in the value of secondary energy sector output. This corresponds to the more rapid economic growth expected in this region. Global output grows from just over $4,000 billion to just under $7,000 billion in year 50.

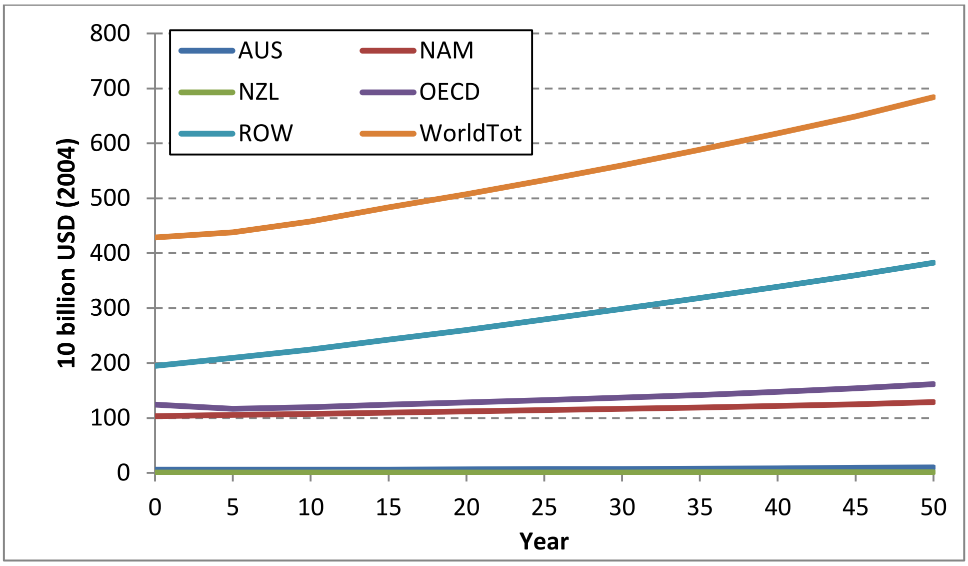

Figure 14: Baseline regional output in the secondary energy sector.

Figure 15 shows the sectoral value of secondary energy sector output under the baseline by region. In New Zealand, the carbon-free electricity output increases strongly compared with all other energy sectors, which remain fairly constant. This increase is valued at $5 billion. All energy types increase in the rest of the world as this region is still developing. Oil (OIL) and coal (COA) increase the least in all sectors except the rest of the world and Australia (AUS). where coal output value rises.

There is a general pattern of greater growth in the output of carbon-free electricity (ECF), with fossil electricity (EFS) growing less steeply across all regions. This reflects a general trend toward lower emissions energy sectors in the World Energy Outlook energy projections. Australia is the only regional exeption, showing output in the fossil electricty sector growing more rapidly than the carbon-free electricity.

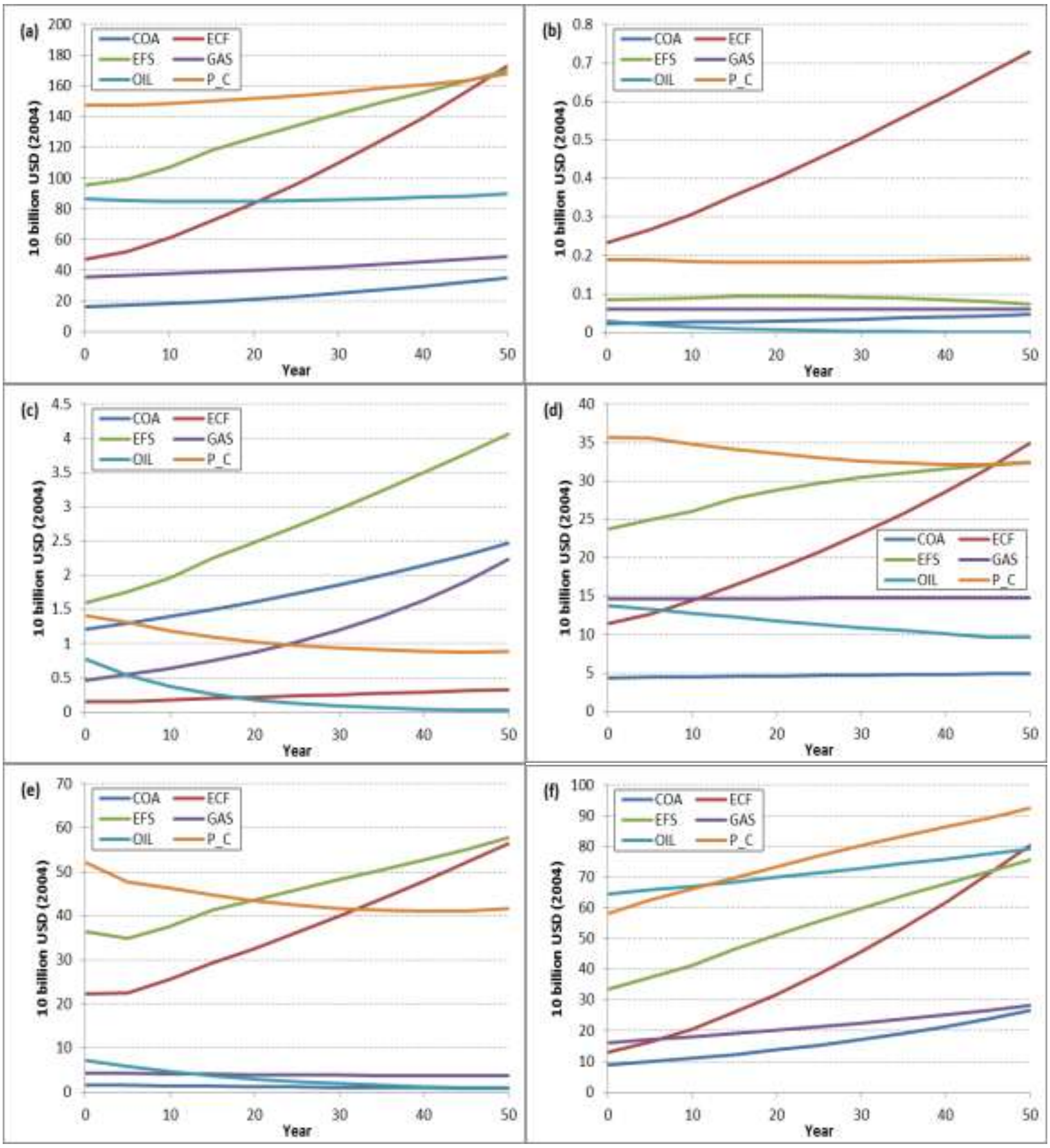

Figure 15: Baseline sectoral output in secondary energy sector by region; (a) Global (b) New Zealand, (c) Australia, (d) North America, (e) rest of the OECD, and (f) rest of the world.

Baseline GHG emissions per region in the secondary energy sector are illustrated in Figure 16. This indicates the emissions from the rest of the world will increase while the other regions will remain fairly level. Global emissions are also expected to rise in parallel with growth in emissions from the rest of the world due to the large share of global emissions from of the rest of the world.

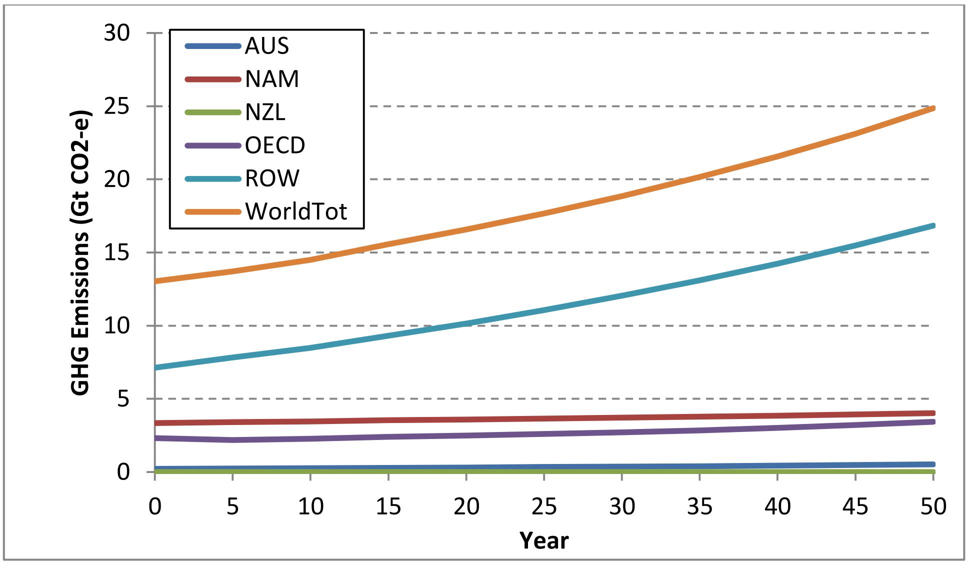

Figure 16: Baseline GHG emissions in secondary energy sector by region.

3.2.3 Manufacturing/Value-added Sector Baseline Estimates

Energy Intensive Manufacturing

The output value of energy intensive manufacturing is expected to increase globally to just over $30,000 billion in year 50 with the largest share from the the rest of the world (see Figure 17). The output value from the rest of the world surpasses the output from the rest of OECD in year 20.

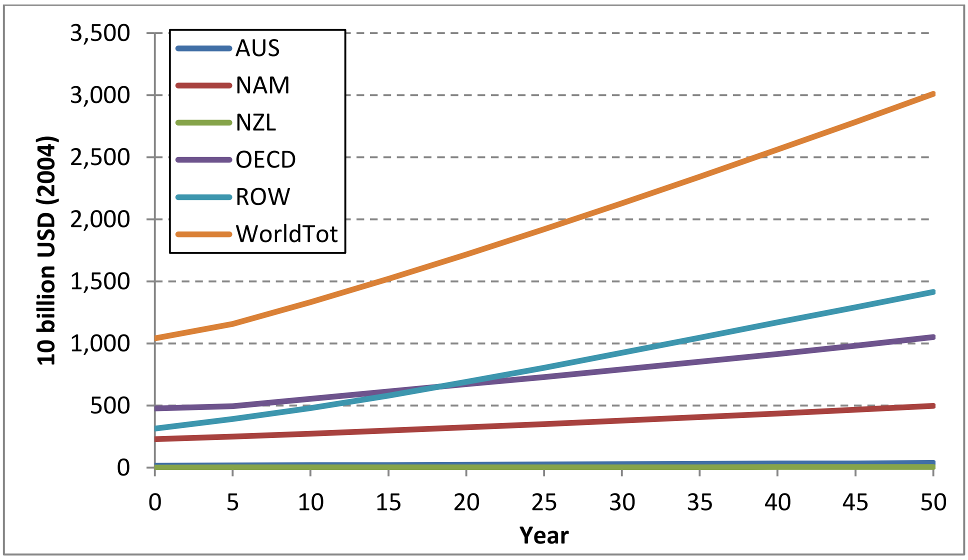

Figure 17: Baseline output in energy intensive manufacturing by region.

Baseline emissions from energy intensive manufacturing in the rest of the world are the biggest contributor to global emissions from this sector. There are higher emissions from the rest of the world relative to the rest of the OECD, but the regions have comparable values for output. This implies that the emissions from energy-intensive manufacturing are higher in the rest of the world than the rest of the OECD. This is illustrated in Figure 18.

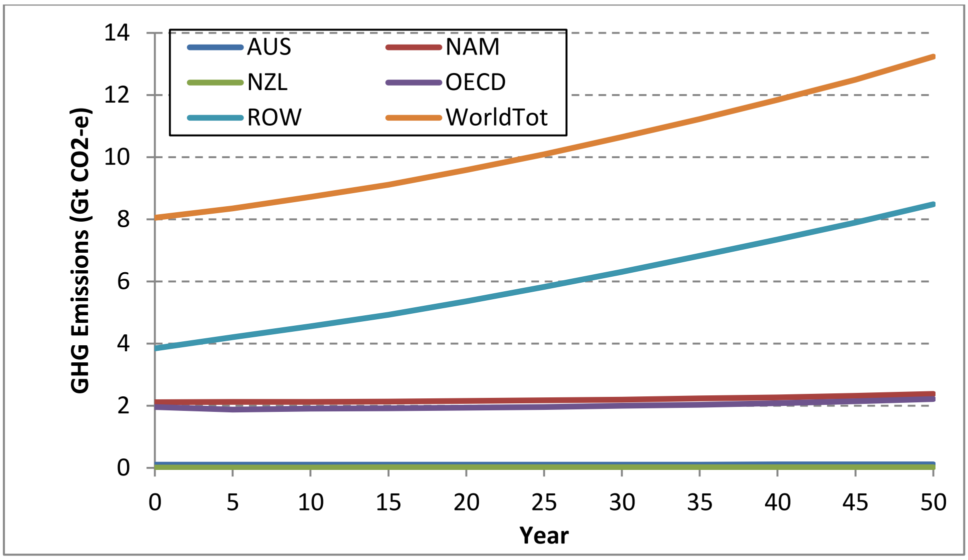

Figure 18: Baseline GHG emissions in energy intensive manufacturing by region.

Non-energy Intensive Manufacturing and Services

Value of output for the non-energy intensive manufacturing and services increases globally to $140,000 billion by the year 50. The rest of the OECD, North America, and then the rest of the world contribute most to this (Figure 19).

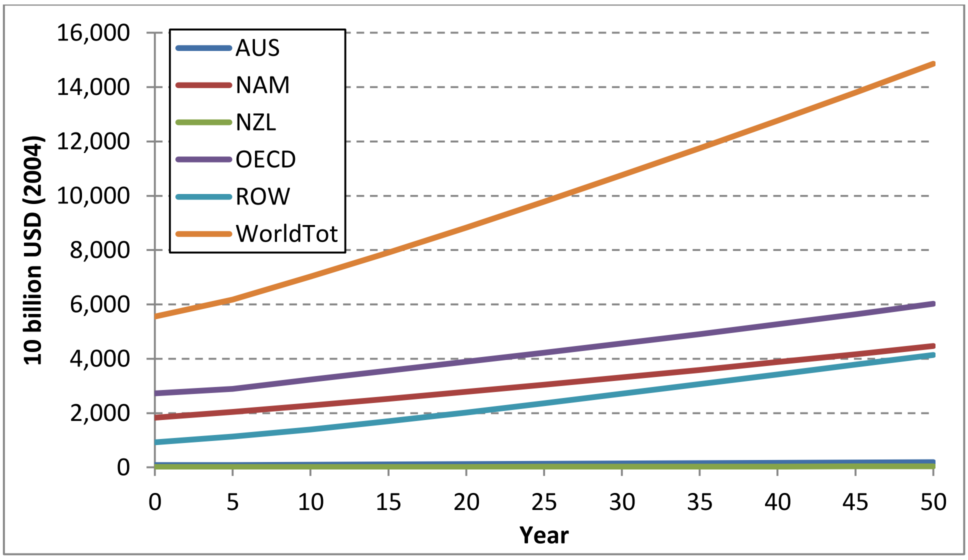

Figure 19: Baseline output in non-energy intensive manufacturing and services by region.

GHG emissions from the non-energy intensive manufacturing and services also increase, as shown in Figure 20. The rest of the world makes the largest contribution to the GHG emissions and is almost parallel to the global emissions, implying the other regions make a modest difference to the GHG emissions in the non-energy instensive manufacturing and services sector. Although there are higher emissions from the rest of the world relative to the rest of the OECD, the rest of the world has a low value of output. This implies the emissions from non-energy intensive manufacturing and services are higher in the rest of the world than the rest of the OECD.

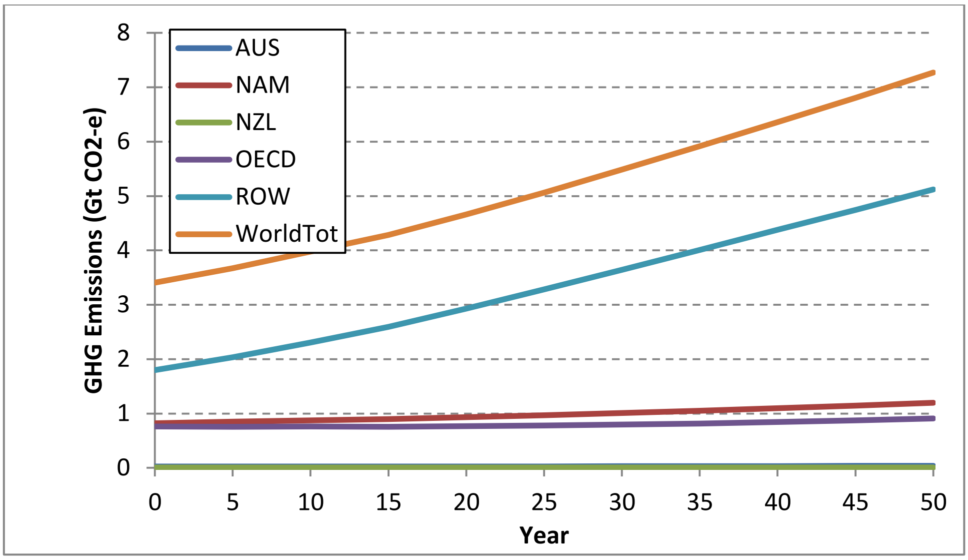

Figure 20: Baseline GHG emissions in non-energy intensive manufacturing and services by region.

Value-added Agriculture

Value-added agriculture includes both food products and harvested wood products.

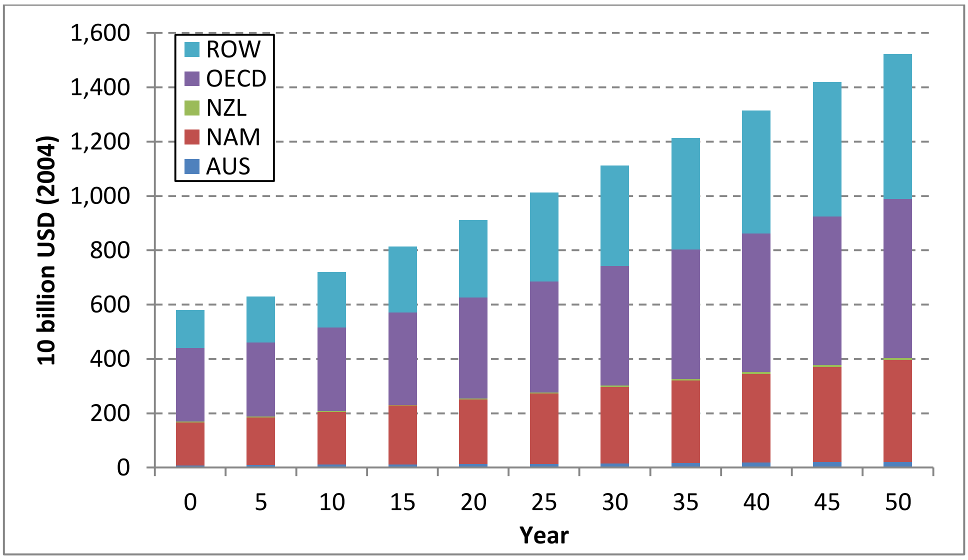

Figure 21: Baseline output value in the value added agriculture sctor by region.

Figure 21 shows output from the value-added agricultural sector under the baseline, by region. The value of output for the value-added agriculture sector increases globally to $15,000 billion by the year 50. The rest of the OECD and the rest of the world experience the strongest growth in the value of output from the value-added agriculture sector.

Figure 22 shows the baseline GHG emissions in the value added agriculture sector, by region. The largest contribution is from the rest of the world, which also grows most significantly by year 50. Interestingly, GHG emissions from the rest of the OECD are largely unchanged out to year 50, even though the value of output increases strongly. This implies the emissions intensity of value-added agriculture output in the rest of the OECD declines in the baseline.

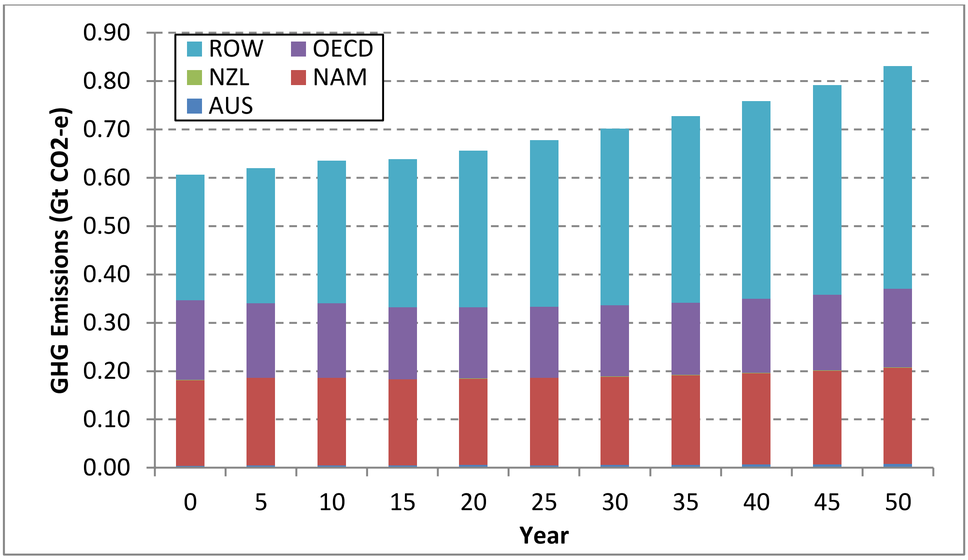

Figure 22: Baseline GHG emissions in value added agriculture sector by region.

3.2.4 Primary Production Sector Baseline Estimates

The baseline estimates for the primary products sector for output value, by region are shown in Figure 23 and

Figure 24. The value of New Zealand output associated with plant-based fibres (PFB), oil seeds (OSC), and grains (GRA) is small. In New Zealand the value of cattle (CTL), crops (CRO), and raw milk (RMK) output grows to between $7 and $9 billion in year 50. There is generally a rapid increase in the value of output from crops (CRO) in all regions.

Baseline land use shares by region are shown in Figure 25. The most significant land use in New Zealand is from forestry (FST) with other important land uses being cattle, sheep and goats (CTL), raw milk (RMK), and crops (CRO). New Zealand is unique among the regions modelled in having a significant share of land use in the production of raw milk (RMK). In all the other regions crops (CRO) is the most significant land use, expect for Australia, which has a similar share in cattle, sheep and goats (CTL), crops and grains (GRA).

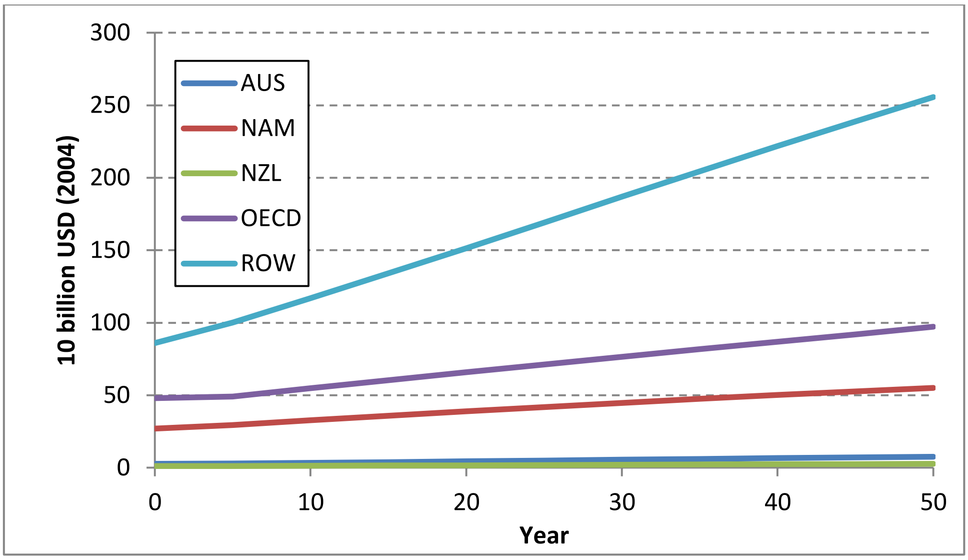

Figure 23: Baseline output in the primary production sector by region.

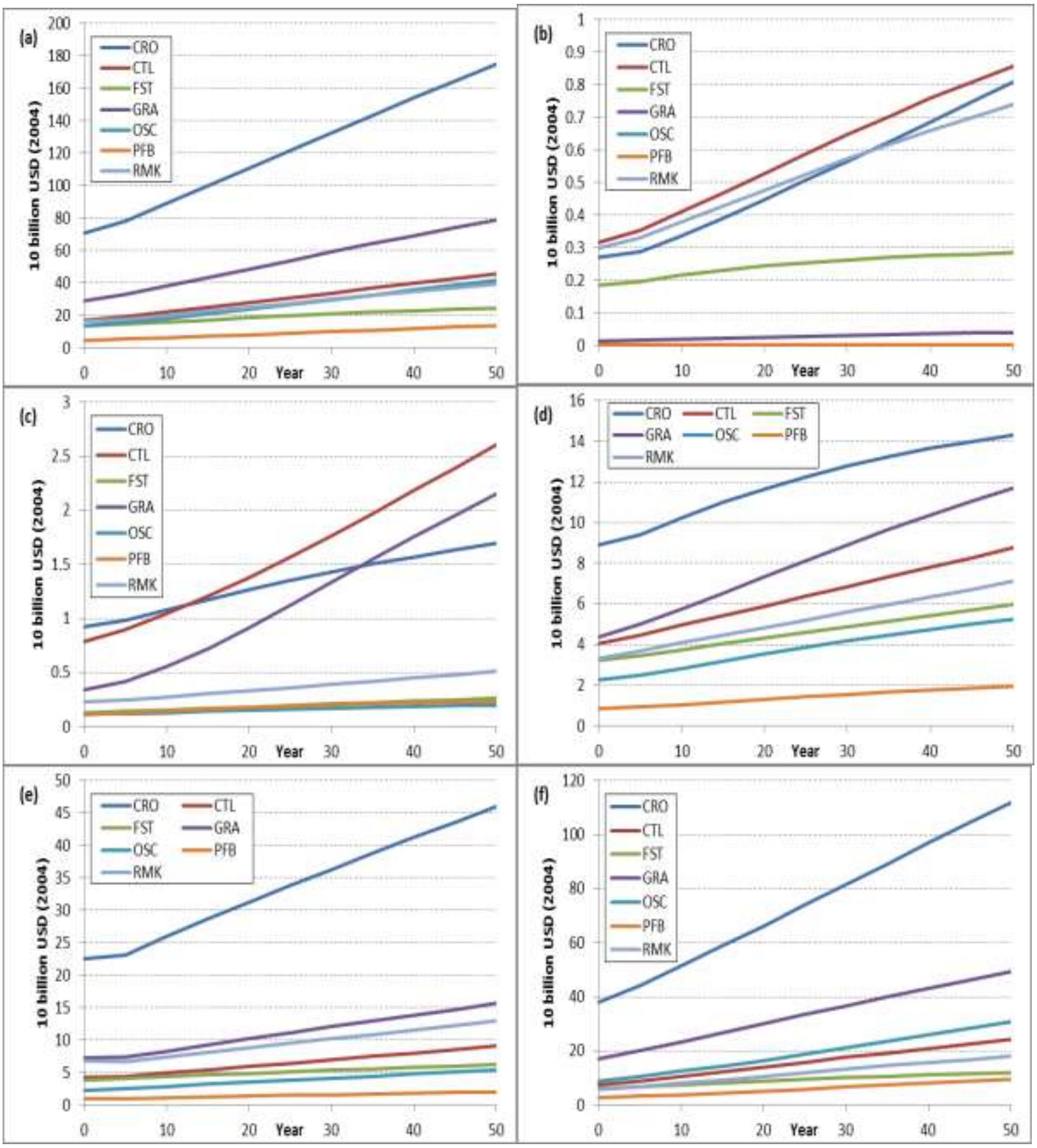

Figure 24: Baseline sectoral output in primary production sector by region; (a) Global (b) New Zealand, (c) Australia, (d) North America, (e) rest of the OECD, and (f) rest of the world.

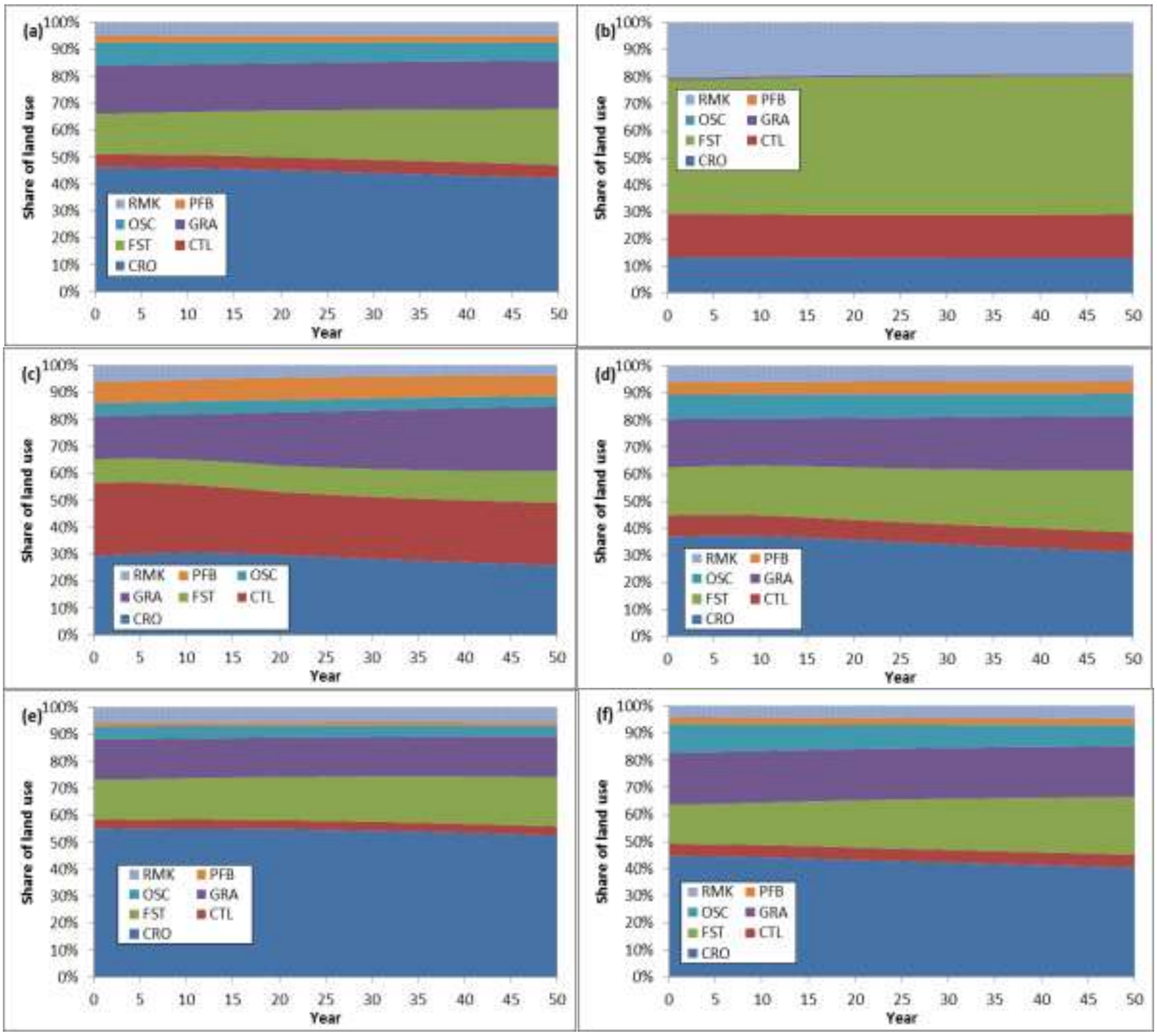

Figure 25: Baseline land use shares by region; (a) Global (b) New Zealand, (c) Australia, (d) North America, (e) rest of the OECD, and (f) rest of the world.

Figure 26 shows the GHG emissions from the primary production sector in the baseline, by region. GHG emissions from the rest of the world grow steeply compared with all other regions; reaching 9 Gt CO_2-e per year by year 50. All the other regions remain either well below 1 Gt CO_2-e (New Zealand and Australia) or very close to this (North America and the rest of the OECD) by year 50.

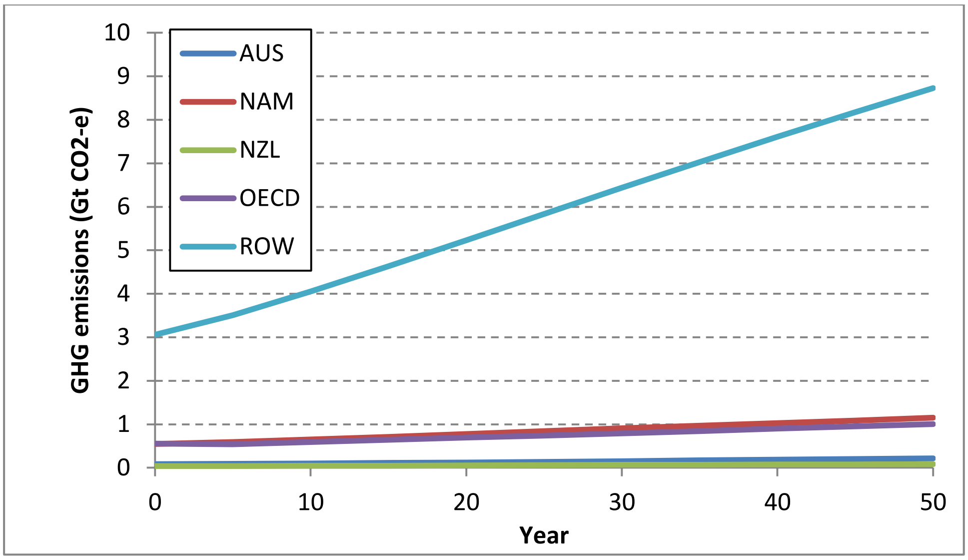

Figure 26: Baseline GHG emissions in the primary production sector by region.

4 Illustrative Scenarios with Climate Policies and Impacts

Policy scenarios are simulated by changing the value of one or more parameters from their baseline values. Most notably, climate mitigation policy scenarios can be defined in terms of regional emissions caps or regional emissions taxes. In the case of regional caps, emissions trading between regions and/or banking and borrowing between periods may also be allowed. Other policy parameters that can be changed include exogenous, time-dependent tax rates applied on inputs, outputs or international trade.

Scenarios may include or exclude climate impacts. As noted above, the current baseline excludes climate impacts. Therefore, one scenario is defined as simply ‘baseline + impacts’. Any type of policy scenario may also be run with or without accounting for climate impacts.

4.1 Modelling Policy Scenarios

The code used to define scenarios in the model allows for the flexible definition of new and/or any alteration of existing scenarios. It also allows the user to run any specified subset of the defined scenarios. As with the baseline, it is often impossible to solve a given scenario in one shot because the shocks (now, relative to baseline values) are too large. Therefore, a procedure of incrementally approaching the solution is used.

If climate impacts are to be simulated, for each step of each scenario, CliMAT-DGE is first solved to generate an estimate of the emissions, given the last computed estimate of climate impacts. The scenario script then runs MAGICC using these emissions as inputs. It then runs the GYE using MAGICC outputs (e.g. global mean temperature) as inputs. Finally, CliMAT-DGE is rerun with the updated climate impacts (see Figure 27). Given that each scenario is solved incrementally and that climate impacts are modelled only for primary production, the feedback effects are sufficiently weak that this procedure will suffice. If a broader spectrum of impacts were modelled, further iterations between the economic, climate and impacts models might be required.

In addition to scenarios, the template allows for the definition of multiple sets of behavioural parameters, known as sensitivity cases. For example, different elasticity values can be used in different sensitivity cases. This will help determine how much the elasticities are affecting the model results and will allow estimation of variability in model results. Certain elements of the model structure may also be switched on or off in sensitivity cases, e.g. sector-specific versus generic capital stocks. In principle, sensitivity cases could also use different baseline specifications, although this has not been implemented to date. However, note that changing behavioural or structural parameters will in itself alter the baseline to some extent.

CGE simulation results are saved in a single GAMS output file. Once the simulations are complete, some or all of the results can be written to an Excel spreadsheet. Pivot tables are constructed from the raw output, allowing for sorting and selection. Further analysis of the results may be conducted based on pivot data as desired. As the volume of results can potentially be many hundreds or thousands of MB, it may be preferable not to write results for every intermediate step of each scenario. While the large size of the GAMS output file should not pose any major problem, very large Excel files are unmanageable. The size of the Excel file is kept manageable by writing only a small subset of results required for analysis to the file.

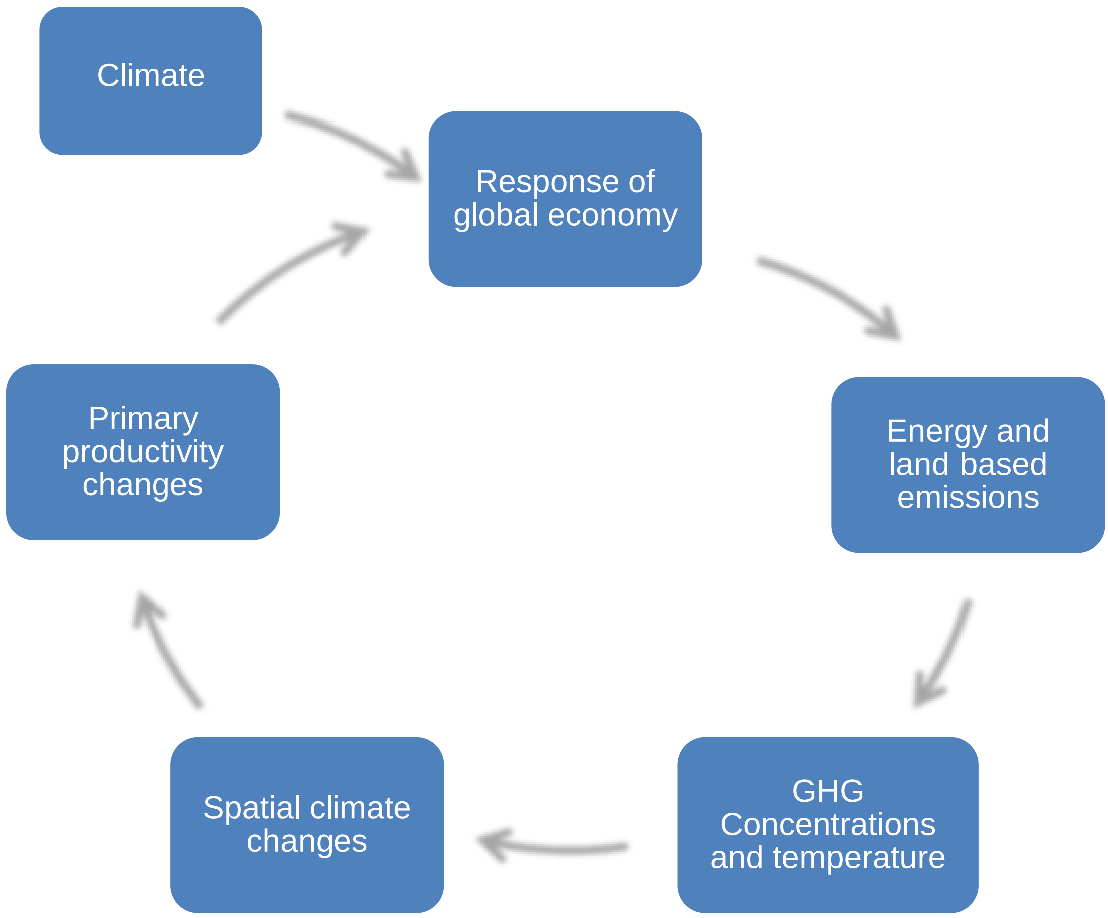

Figure 27: NZIAMS loop with climate impacts.

Once a set of scenarios has been solved as above, the downscaling script may be run. The basic procedure is analogous to that for the CGE scenario script. First, the baseline must be solved. Then, a series of scenarios are solved in incremental steps to facilitate a numerical solution. For the baseline, the number of steps can be independently specified; for scenarios, only incremental steps saved in the CGE scenario GAMS output file are available.

Downscaling can be performed with various PE model configurations, which are set in the PE model files. Land-use change may be modelled either using CET functions (as are used in the GE model and this report) or using quadratic adjustment cost functions.

4.2 Illustrative Scenarios

NZIAMS was primarily developed to model the response of the global economy to climate policies and/or to climate impacts. The key components of the modelling system are highlighted through a series of illustrative scenarios. The scenarios presented here are not intended to serve as a guide to policy or other decisions.

First, we modelled the impacts of climate change on the agriculture and forestry sector. Second, we assessed the economic impact of a hypothetical policy that places a carbon tax on the energy, industrial, and agricultural GHG emissions. Third, we analysed the impact of modelling both climate impacts and carbon tax. The details of the scenarios can be found in Table 8.

The carbon tax scenarios start at $15 in the initial period and increase at 5% per annum. The carbon tax is applied on either energy or industrial emissions (cpenr), or on all sources of emissions (cpall). The rest of the world region does not impose the tax in the first 3 periods, i.e. for the first 15 years. This is in keeping with Kyoto protocol regarding the entry date of developing countries into the carbon market.

Table 8: Scenarios with their descriptions

Scenario Name	Scenario Description	Details
base	Baseline	Baseline with no climate impacts or GHG emissions reduction policy
base + i	Baseline + Climate Impacts	Baseline with land productivities moderated by climate impacts simulated with MAGICC and GYE
cpenr	Pricing Energy and Industrial GHG Emissions	Energy and industrial emissions are subject to regional carbon taxes. The tax starts at US(2004)$15/tCO2-e and increases at 5% per annum. However, the ROW region does not impose this common tax in the first three periods (15 years)
cpenr + i	Pricing Energy and Industrial GHG Emissions + Climate Impacts	Land productivities moderated by climate impacts simulated with MAGICC and GYE are added to the cpenr scenario
cpall	Pricing Energy, Industrial and Agricultural GHG Emissions	The same carbon taxes as modelled in the cpenr scenario are extended to cover agricultural GHG emissions
cpall + i	Pricing Energy, Industrial and Agricultural GHG Emissions + Climate Impacts	Land productivities moderated by climate impacts simulated with MAGICC and GYE are added to the cpall scenario

4.3 Policy Scenario Estimates

4.3.1 Gross Domestic Product Scenario Estimates

Policy scenario estimates of global GDP relative to the baseline are shown in Figure 28. Global GDP is slightly higher (0.2% higher in year 50) in the (base+i) scenario with climate impacts on land productivity. This is due to an increase in land productivity, enabling greater output of agricultural and forestry products. These climate impacts moderate the decline in GDP relative to the baseline for the two carbon pricing scenarios (cpenr+i and cpall+i). A carbon tax applied to all energy sector GHG emissions (cpenr) has a negative effect on global GDP (3.4% in year 50). Extending the carbon tax to include all sectors (cpall) results in a stronger negative effect on global GDP (3.9% lower in year 50) relative to the baseline.

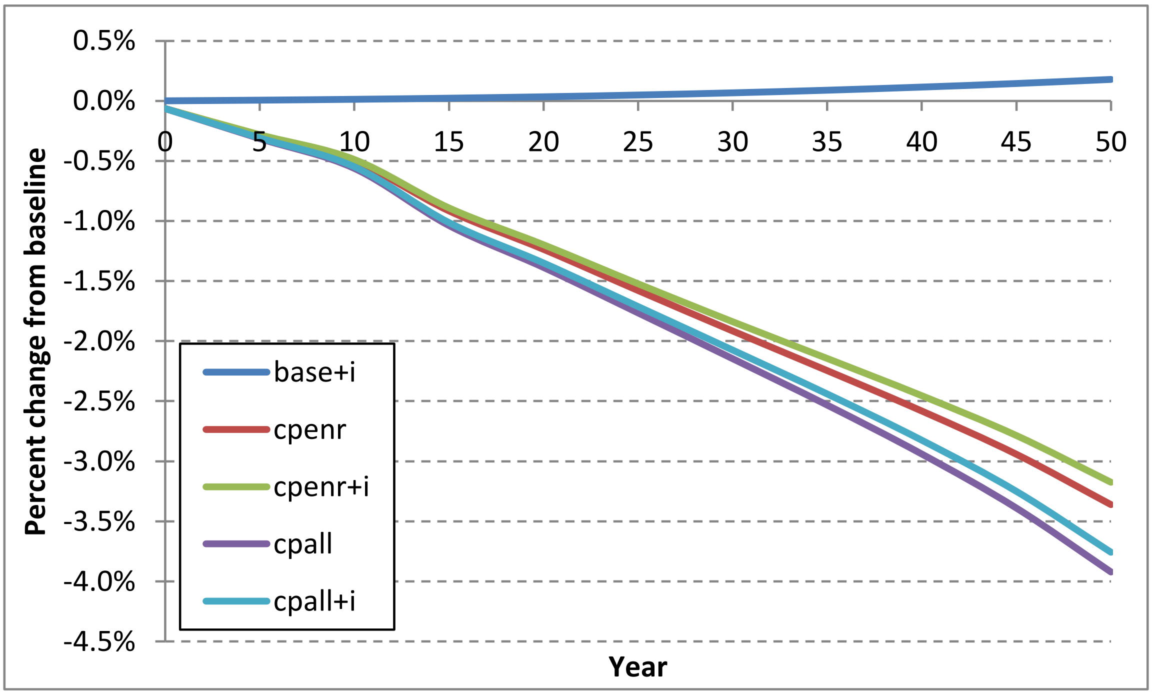

Figure 28: Policy scenario estimates of global GDP relative to the baseline (%).

Climate impacts on land productivity have a modest positive effect on global GDP by year 50 (Figure 29), with regional variation in effects due to regional variation in climate impacts and the size of the primary production sectors in the overall economy. There is a sizable regional variation in the impact of the carbon pricing scenarios on GDP relative to the baseline, with a large impact on the rest of the world and Australia and a modest impact on the rest of the OECD (Figure 29). This regional variation in impact is due to differences in emissions intensity of sectors and the size of the high emissions sectors, such as fossil energy, in the regional economies.

Relative to the baseline, the New Zealand economy is 0.7% larger in year 50 when climate impacts on land productivity are modelled. This partially offsets the negative effect of the carbon pricing scenarios on GDP, which when all sectors have a carbon tax applied (cpall) is 2.3% lower in year 50, relative to the baseline. Given the importance of primary production in the New Zealand economy, the carbon-pricing scenario with all sectors included has a much larger economic impact than the carbon pricing of the entire energy sector alone.

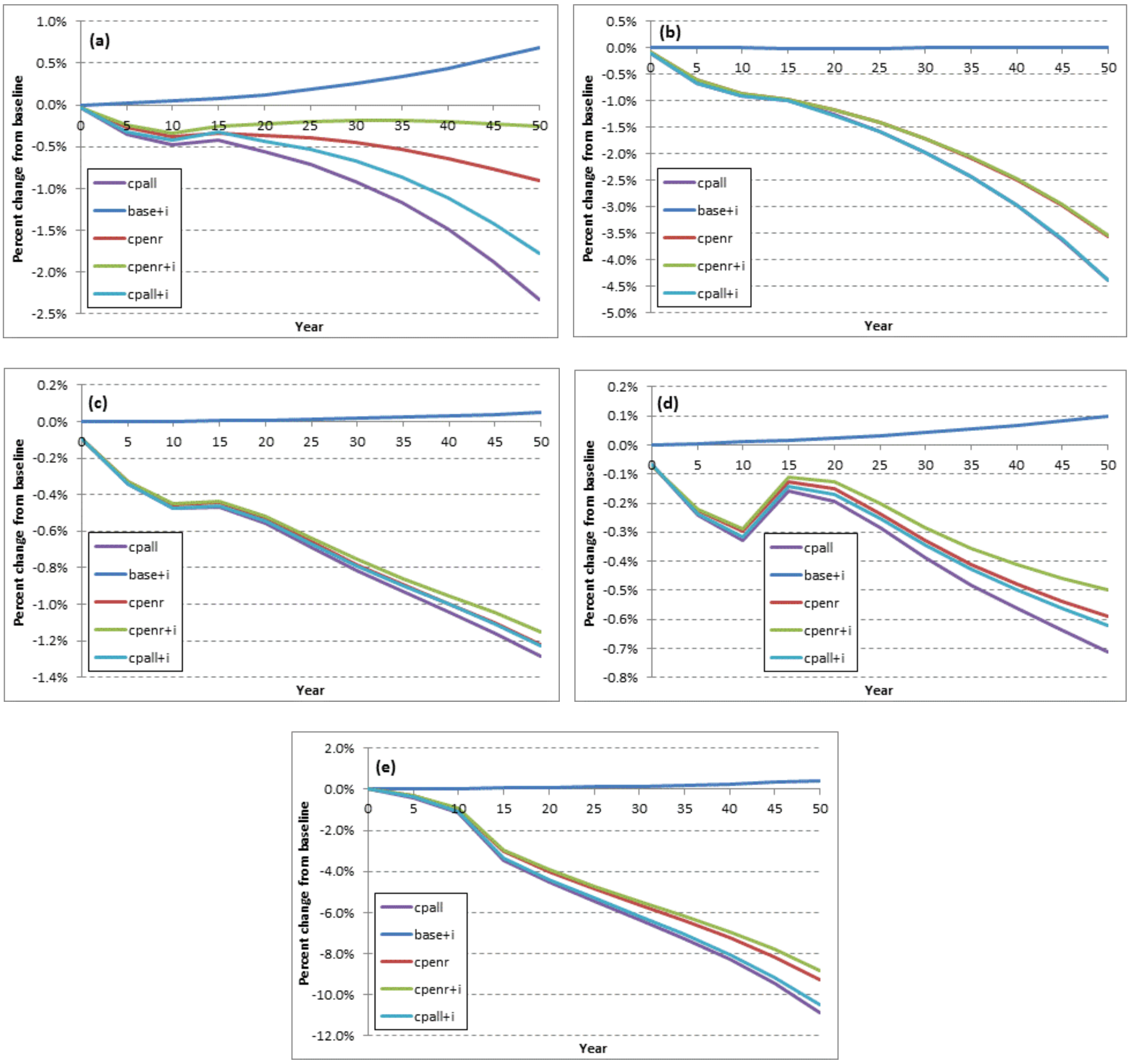

Figure 29: Policy scenario estimates of regional GDP relative to the baseline; (a) New Zealand, (b) Australia, (c) North America, (d) rest of OECD, and (e) rest of the world.

4.3.2 Total GHG Emissions Estimates

Climate impacts (base+i) on regional and global GHG emissions are negligible, being less than 0.1% by year 50 (Figure 30). Global GHG emissions are estimated to be significantly lower when carbon pricing is applied to all sectors; 56.4% lower relative to the baseline in year 50. Most of this reduction in global GHG emissions due to carbon pricing appears to be associated with a carbon tax in the energy sectors, with global emissions 49.8% lower relative to the baseline in year 50 under the CPNER scenario. More details on sector-specific emissions reductions under the various scenarios are provided below.

Figure 31 shows regional total GHG emissions relative to the baseline for each of the policy scenarios. New Zealand's relative emissions are reduced less under the policy scenarios than the other regions. This is due to low emission reductions in the secondary energy sector (see section 4.3.3). For North America and the rest of the OECD there is very little difference in emission reductions between the two carbon pricing scenarios. This suggests that reduction in emissions from pricing carbon in the energy sector is the main contributor to overall reductions.

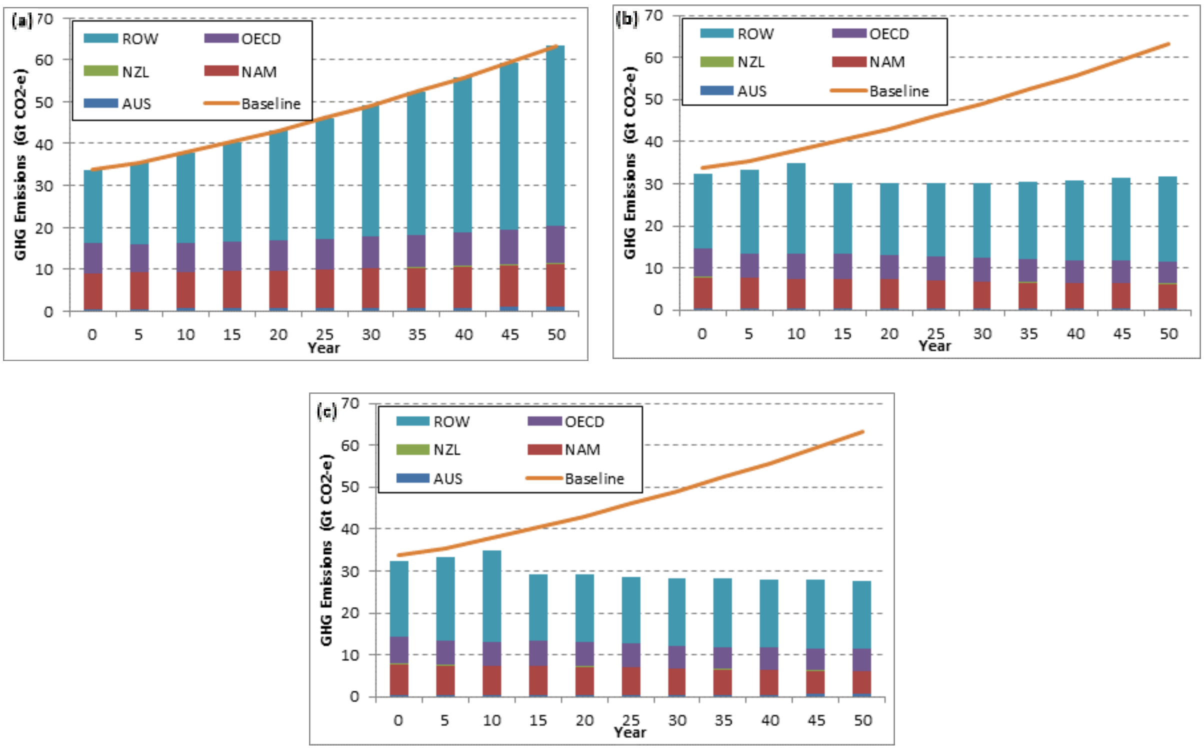

Figure 30: Policy scenario estimates of global GHG emissions for the (a) base+i, (b) cpenr and (c) cpall scenarios, by region. The line shows baseline global GHG emissions.

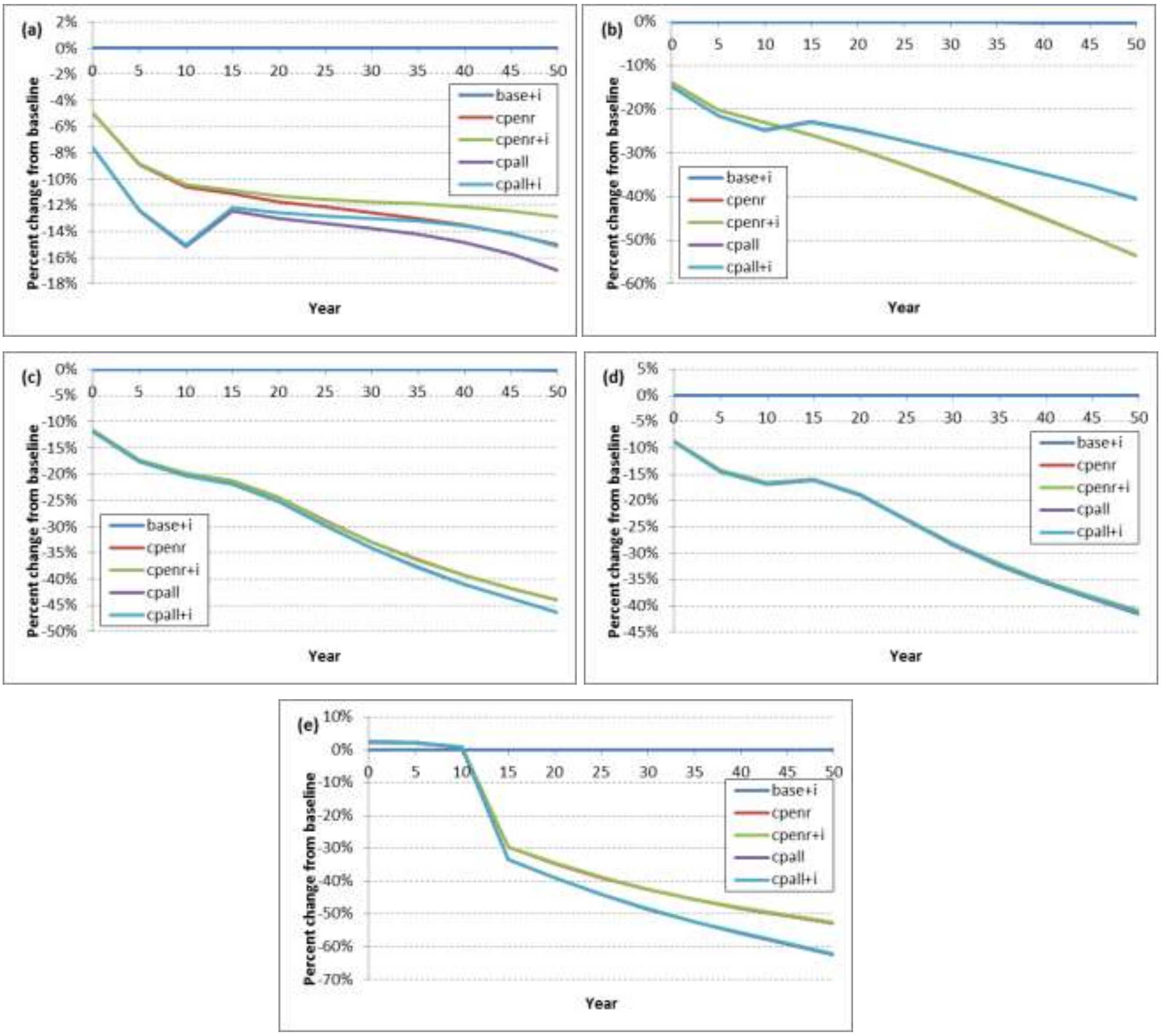

Figure 31: Policy scenario estimates of regional GHG emissions relative to the baseline; (a) New Zealand, (b) Australia, (c) North America, (d) rest of OECD, and (e) rest of the world.

4.3.3 Secondary Energy Sector Scenario Estimates

The secondary energy sector here refers to sectors that use primary energy (coal, oil, gas and petroleum) in production. For example, the fossil electricity sector (EFS) uses a combination of coal, gas and oil to produce electricity. The OIL sector refers to the extraction and refining of oil. This means that GHG emissions for this sector are those associated with the processes of extraction and refining oil, not with the use of oil.

Output

Global estimate of the secondary energy sector output relative to the baseline is shown in Figure 32. Global energy sector output is estimated to be lower under the carbon policy scenarios (cpall and cpenr), relative to the baseline. Under the carbon pricing scenarios there is no practical difference in the estimated reduction in secondary energy sector output between carbon pricing applied to the primary and secondary energy sectors alone (cpenr), and all sectors together (cpall); secondary energy sector output is 24% lower by year 50 for WorldTot relative to the baseline.

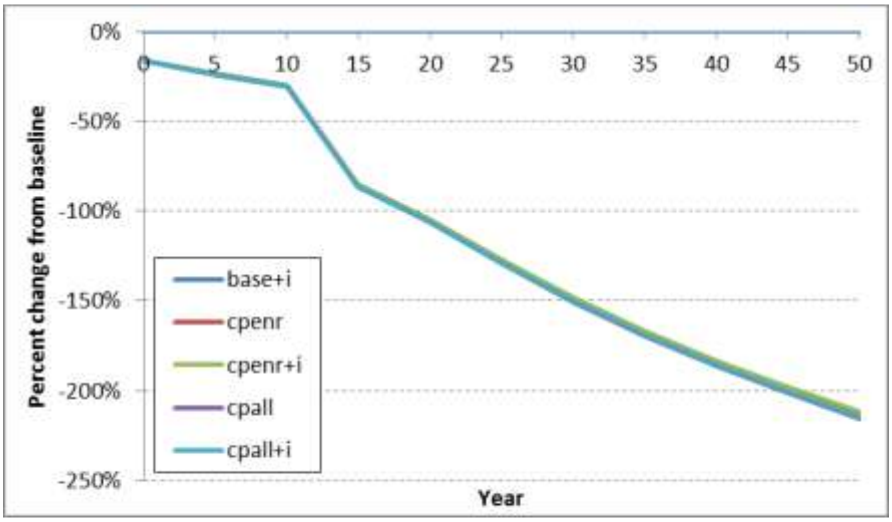

Figure 32: Global estimate of the secondary energy sector output relative to the baseline (%).

Regional secondary energy sector output under the scenario of carbon pricing applied to all sectors (cpall), relative to the baseline is shown in Figure 33. Secondary energy sector output for Australia in year 50 is 56% lower, relative to the baseline. This is due to the much higher price for electricity (ELY), relative to the baseline (Figure 35b), in Australia. This reflects the large share of fossil electricity (EFS) in Australian electricity output (Figure c), which has a high carbon output that has a price applied to it. Because electricity costs so much more with the carbon price, the secondary energy sector output for Australia is expected to decrease.

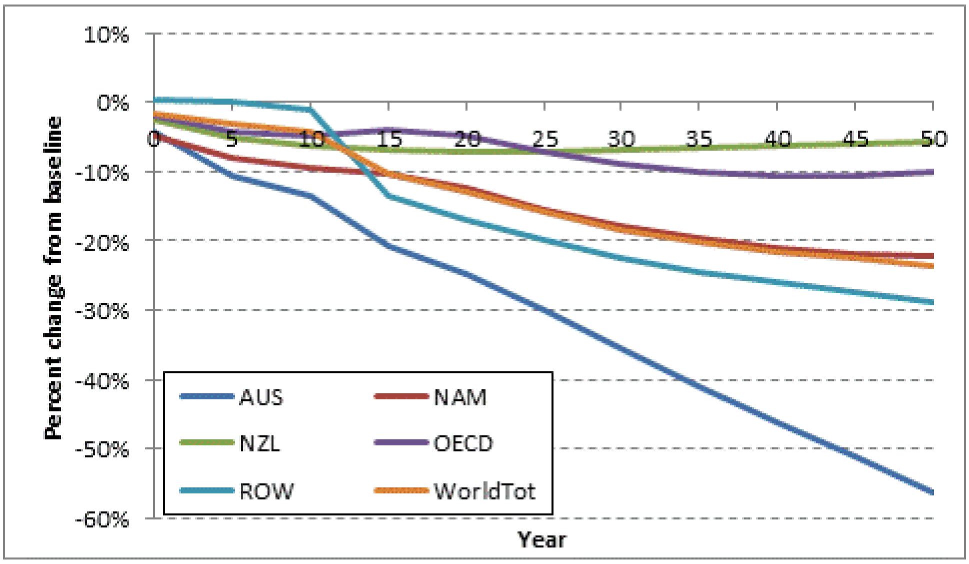

Figure 33: Policy scenario estimate of the regional secondary energy sector output under the cpall scenario, relative to the baseline (%).

Figure 34 shows the sectoral shares of the value of secondary energy sector output under the baseline (base) and carbon pricing applied to all sectors (cpall) scenarios. The latter scenario had the largest overall impact on the secondary energy sectors, and so represents the extreme policy scenario.

There is a general pattern of greater growth in the share of carbon-free electricity (ECF), with a decline in the share of fossil electricity (EFS) across all regions. This reflects a shift to lower emissions energy sectors. Regional variation in this shift is influenced by the baseline shares of secondary energy sector output across the regions. For example, New Zealand already has a large share of secondary energy sector output from carbon-free electricity (ECF); in the baseline this share is predicted to grow. This limits the opportunity for further growth in the share of carbon-free electricity under the carbon pricing scenario. Australia is at the other extreme, with a very small share of secondary energy sector output from carbon-free electricity (ECF), and predicted growth in the share of fossil electricity (EFS) in the baseline. Under the carbon pricing scenario, Australia's share of carbon-free electricity grows, with a decline in the share fossil electricity (EFS). The share of coal (COA) in secondary energy sector output is also lower under the carbon pricing scenario. This probably reflects a moderate shift away from high emissions intensity coal as an input to fossil electricity to lower emissions intensity fossil fuels.

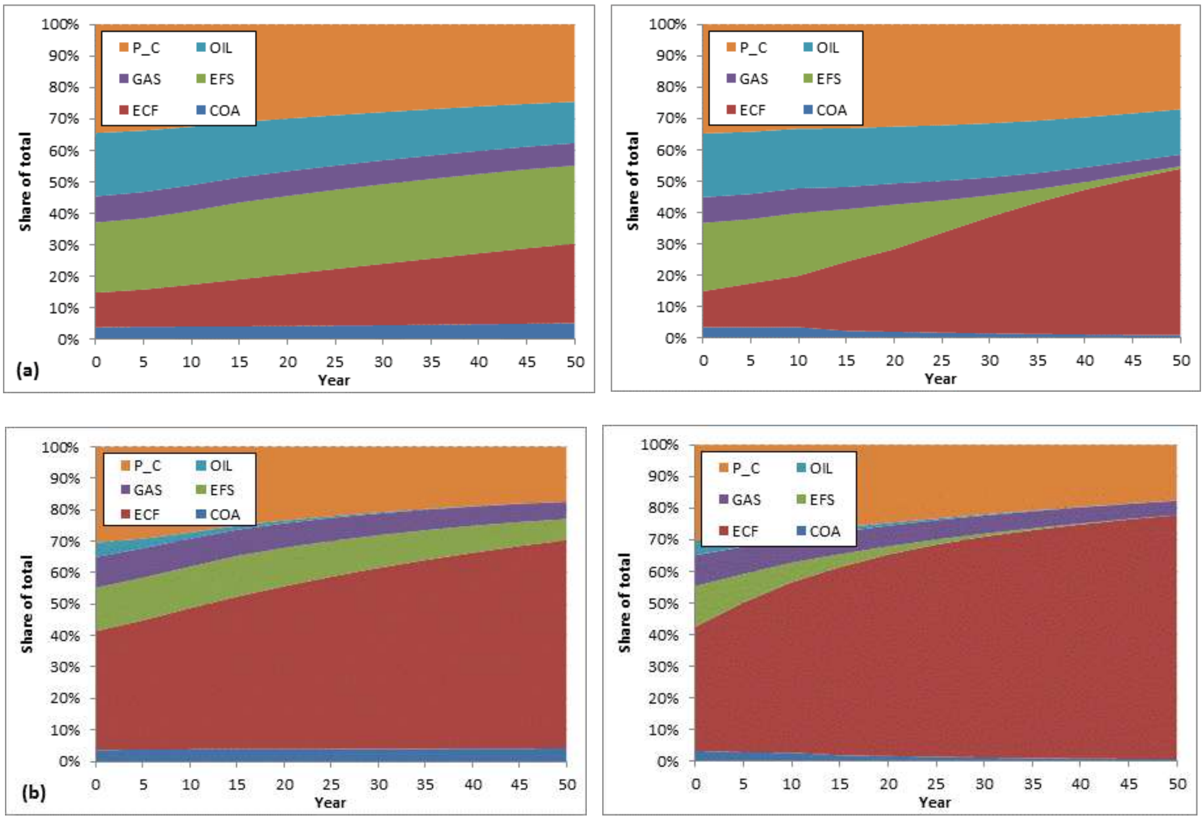

Figure 34: Policy scenario estimates of sectoral shares of secondary energy output under the base (left) and cpall (right) scenarios, by region; (a) global, (b) New Zealand (con't next page)

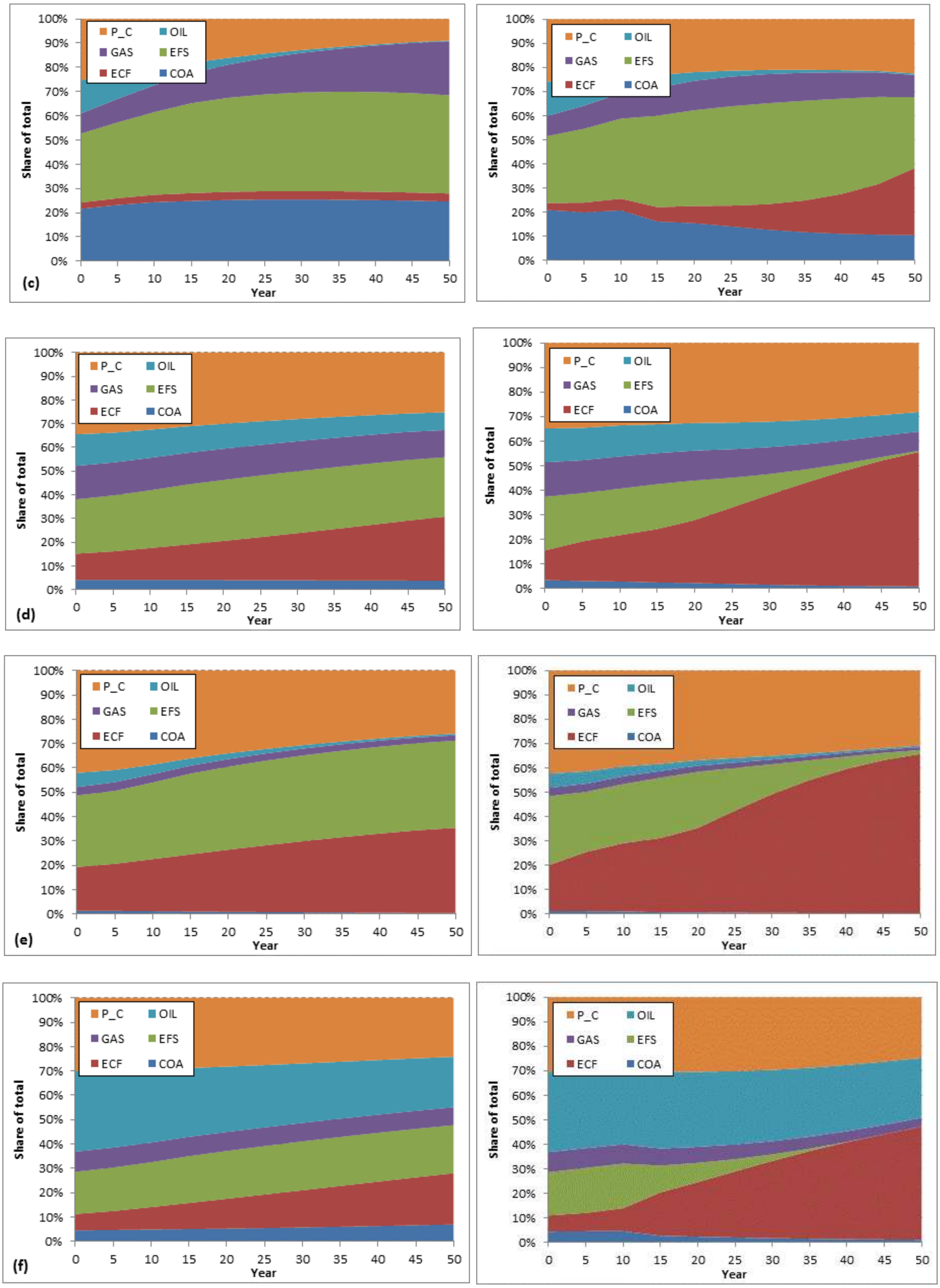

Figure 34 (con't): (c) Australia, (d) North America, (e) rest of the OECD, and (f) rest of the world.

Prices

Higher prices for electricity (ELY), relative to the baseline, under a carbon tax applied to all sectors (cpall) are due to the shift to carbon-free electricity (ECF) production across all regions, and because fossil-electricity (EFS) has a high emissions intensity (Figure 35). The latter means that the carbon tax results in an increase in the price of electricity.

The regional variation in the change in prices relative to the baseline reflects the share of carbon-free electricity in the baseline mix of energy sectors. For example, Australia experiences higher electricity (ELY) prices than other regions due to the small share of carbon-free electricity in energy sector output (Figure). New Zealand, on the other hand, has only a moderately higher electricity (ELY) price relative to the baseline, reflecting the much larger share of baseline electricity output from carbon-free sources (Figure).

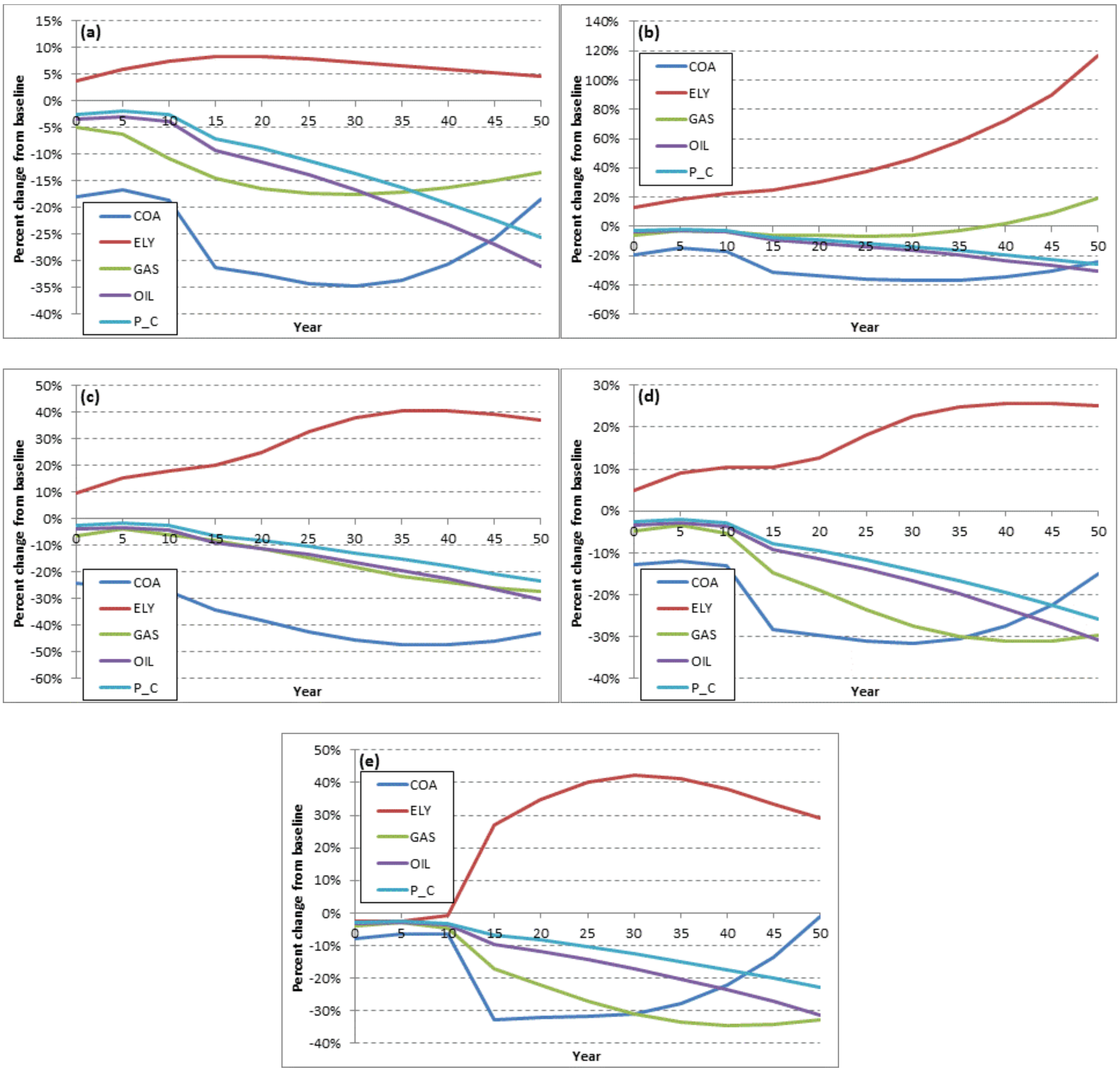

Figure 35: Policy scenario estimates of secondary energy sector market prices under the cpall scenario relative to the base scenario, by region; (a) New Zealand, (b) Australia, (c) North America, (d) rest of the OECD, and (e) rest of the world.

GHG Emissions

Figure 36 shows the global GHG emissions from the secondary energy sectors, relative to the baseline, for the five scenarios. It is important to note here that the representation of the secondary energy sector means emissions from the coal, oil, gas, and petroleum sectors are those associated with the extraction and refining of these products, not with their use. This is why emissions from these secondary energy sectors are small relative to emissions from fossil electricity (Figure 38).

GHG emissions from the secondary energy sectors are 92% lower relative to the baseline under all of the carbon pricing scenarios. The lower relative emissions are due to a combination of factors. First, lower secondary energy sector output, which is due to the negative income effect (Figure 28) and the lower demand for energy sector inputs from other sectors. This demand is a result of reduced output in these sectors in response to carbon pricing. Second, emissions are lower due to the shift away from fossil-based electricity to carbon-free electricity, and a modest switch to lower emissions intensity fossil fuels (e.g. from coal to gas) in fossil-based electricity (Figure).

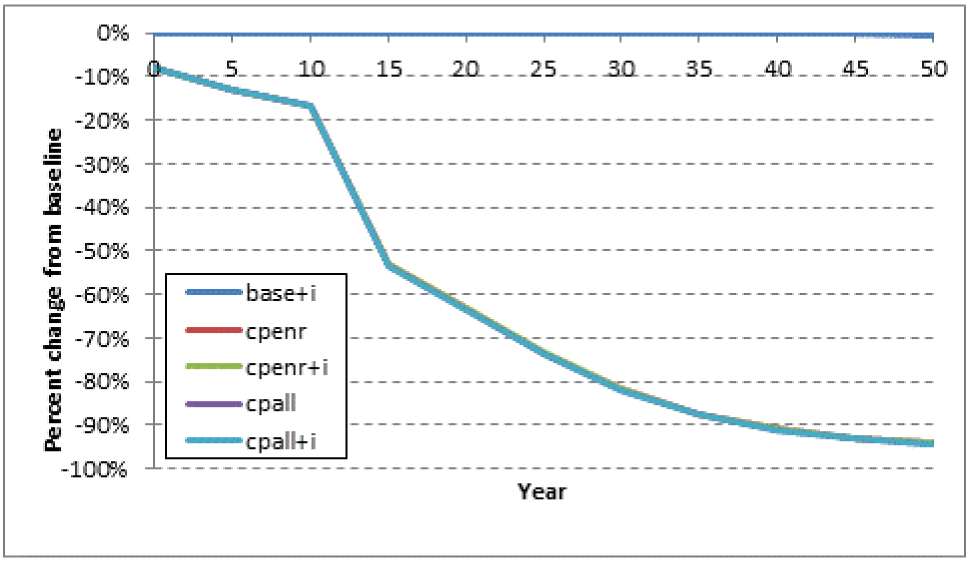

Figure 36: Estimates of the percent change in global GHG emissions from the secondary energy sector relative to the baseline (%), by policy scenario.

Figure 37 shows the reduction in GHG emissions from the secondary energy sector, relative to the baseline, by region. By year 50, all regions have approximately 90% lower GHG emissions from the secondary energy sectors, relative to the baseline. The trend in emissions reduction over time follows the trends in growth in the share of carbon-free electricity (ECF) as part of secondary energy sector output. For example, New Zealand is predicted to quickly increase the share of carbon-free electricity (Figure b), which allows that country to quickly reduce GHG emissions from the secondary energy sector.

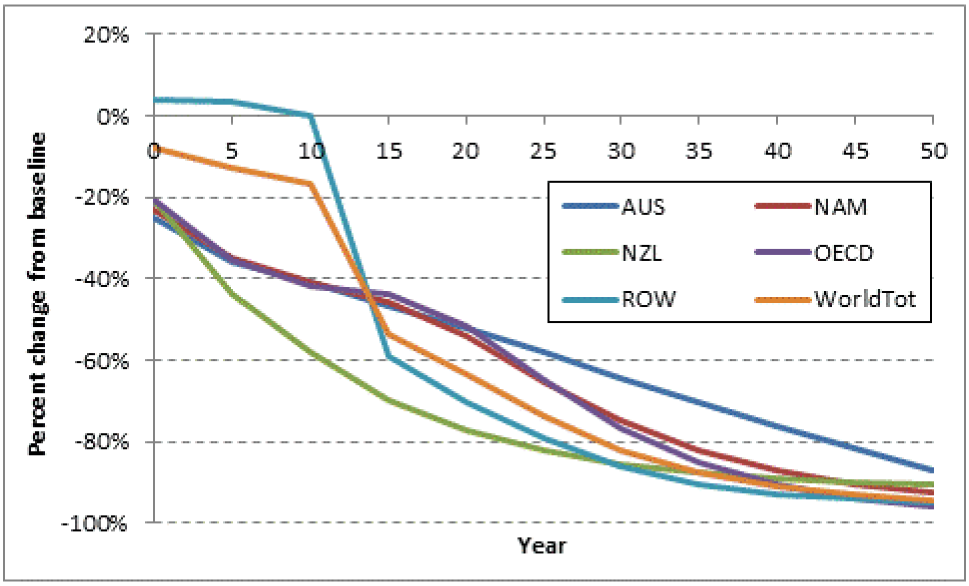

Figure 37: Estimates of the percent change in GHG emissions from the secondary energy sectors relative to the baseline (%) for the cpall scenario, by region.

For the assumed initial carbon price ($15t CO_2-e) and growth in carbon price (5% per year) under the carbon tax on all sectors, GHG emissions from the secondary energy sector are significantly lower (Figure 38). Given a large share of emissions from this sector are from fossil-based electricity, the switch to carbon free-electricity is the major contributor to the reduction in net GHG emissions relative to the secondary energy sectors baseline. This is also an artefact of how the energy sector is represented in the reporting, with secondary energy sector emissions associated with oil, gas, petroleum, and coal being from extraction and refining activities in these sectors.

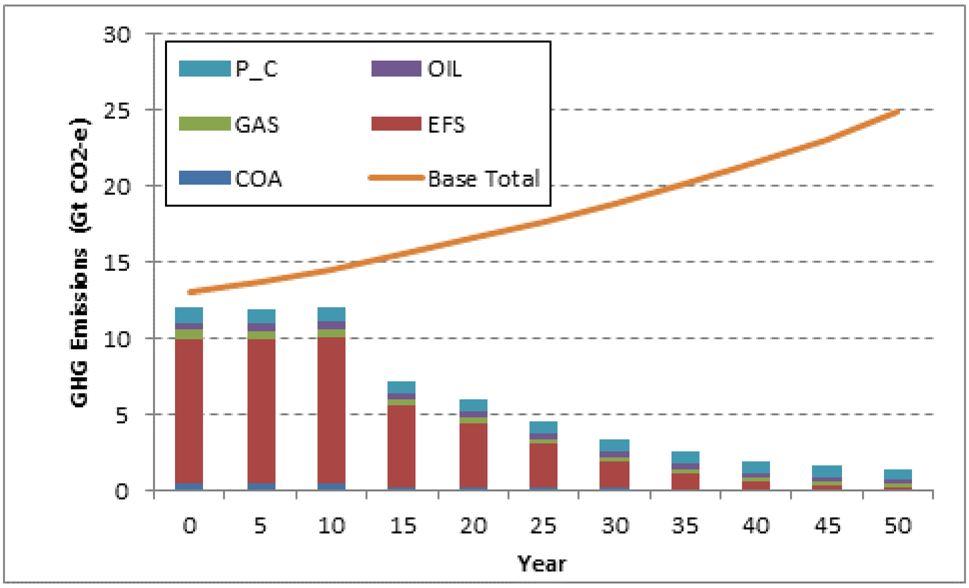

Figure 38: Estimates of GHG emissions from the secondary energy sectors relative to the baseline for the cpall scenario, by sector.

4.3.4 Manufacturing/Value-Added Sector Scenario Estimates

Energy-Intensive Manufacturing

Output

Figure 39 shows the regional output from the energy-intensive manufacturing sector (EMT) for each of the scenarios, relative to the baseline. The global output from the energy intensive sector is 7–8% lower, relative to the baseline, under the carbon pricing scenarios (cpall and cpenr),across all regions, except for the rest of the OECD, which has a slightly higher output relative to the baseline. This may be due to the emissions intensity of energy-intensive manufacturing in the rest of the OECD already being lower than in other regions.

Output from the New Zealand energy-intensive manufacturing sector is slightly lower (0.8% in year 50) under the climate impact scenario (base+i) relative to the baseline. This is possibly due to labour and capital shifting out of the energy-intensive sector to primary production and value added agriculture sectors due to the strong increase in New Zealand output from these sectors under the climate impact scenario (Figure 39b).

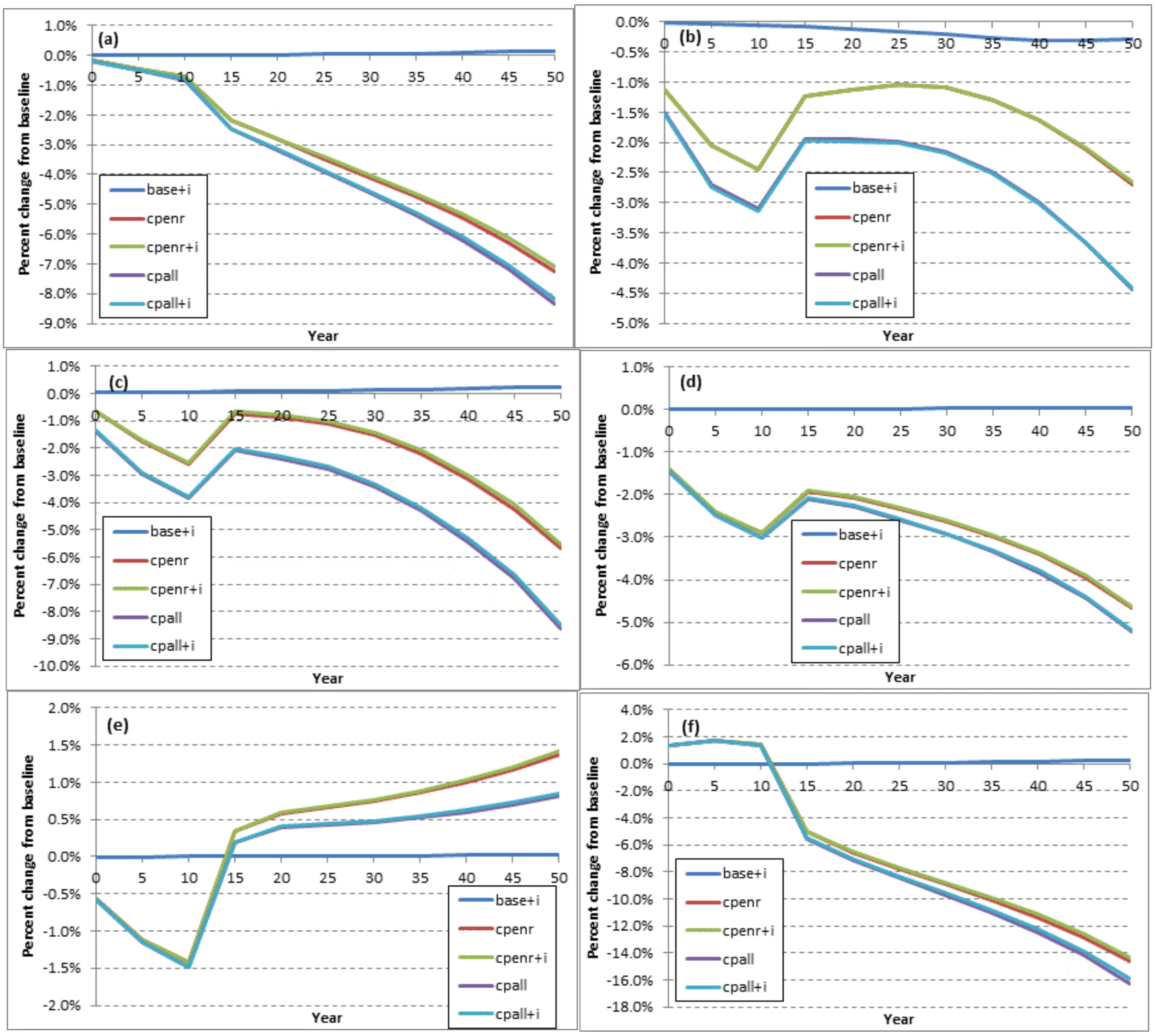

Figure 39: Policy scenario estimates of regional output from the energy intensive manufacturing sector relative to the baseline; (a) global, (b) New Zealand, (c) Australia, (d) North America, (e) rest of OECD, and (f) rest of the world.

Prices

Market prices for the energy-intensive manufacturing sector in all regions are higher (3.5 – 9.0% in year 50) under the carbon policy scenarios, relative to the baseline (Figure 40). This is due to the increased cost of energy inputs to energy-intensive manufacturing under the carbon pricing scenarios. The rest of the OECD shows a similar trend but at lower increase, which is consistent with the OECD having lower emissions intensity, and hence lower input costs.

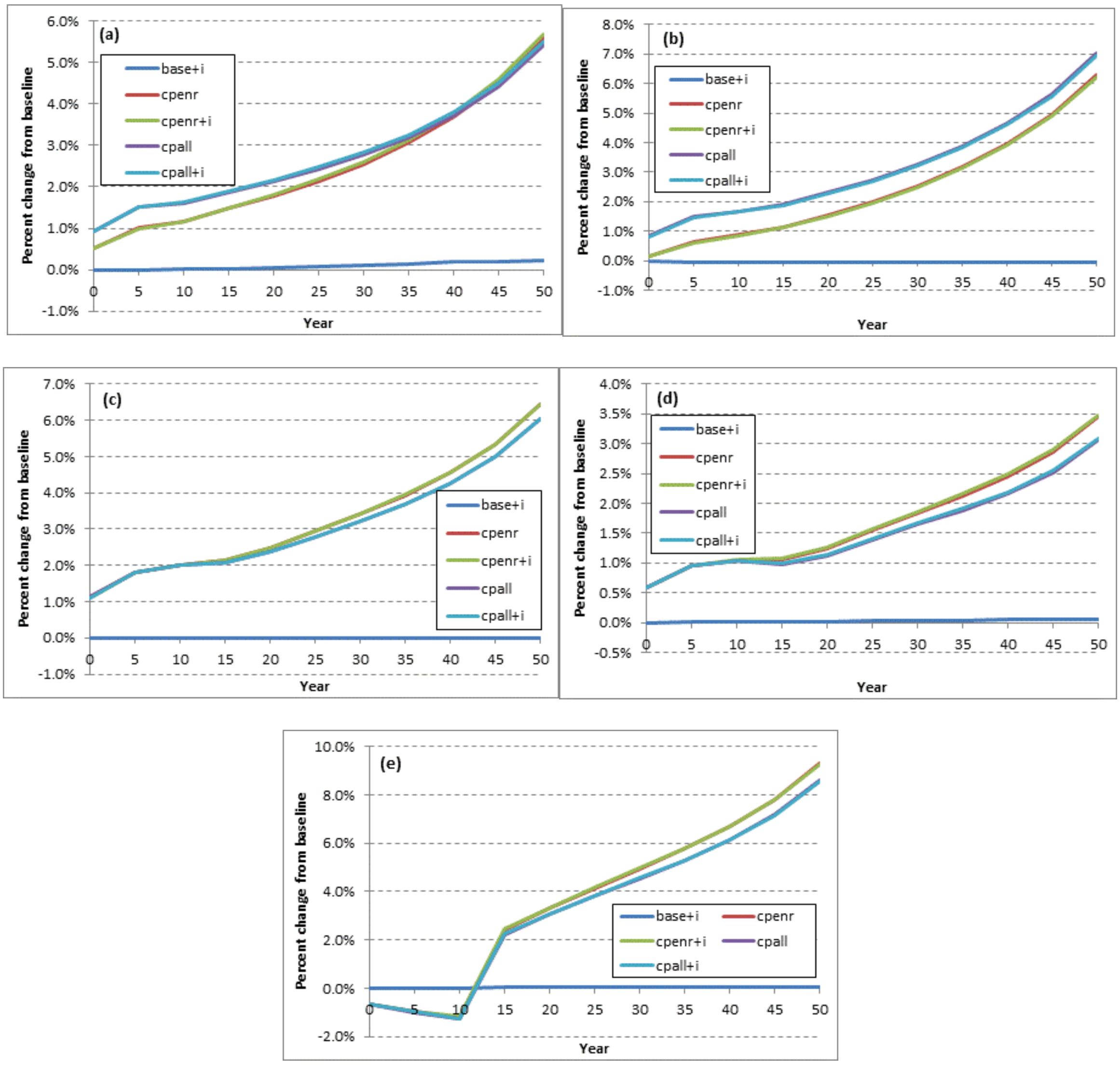

Figure 40: Policy scenario estimates of energy intensive manufacturing sector market prices relative to the baseline, by region; (a) New Zealand, (b) Australia, (c) North America, (d) rest of the OECD, and (e) rest of the world.

GHG Emissions

Global GHG emissions from energy-intensive manufacturing are lower under the carbon pricing scenarios, relative to the baseline (Figure 41). This is due to lower output from this sector, as well as to a shift away from high emissions energy inputs such as fossil electricity to lower emissions energy inputs, such as carbon free electricity. This is evident in Figure 42, which shows slightly lower emissions (5% in year 50) in the rest of the OECD under a carbon tax applied to all sectors (cpall), relative to the baseline, even though output from the energy intensive sector in the rest of the OECD was higher (Figure 39).

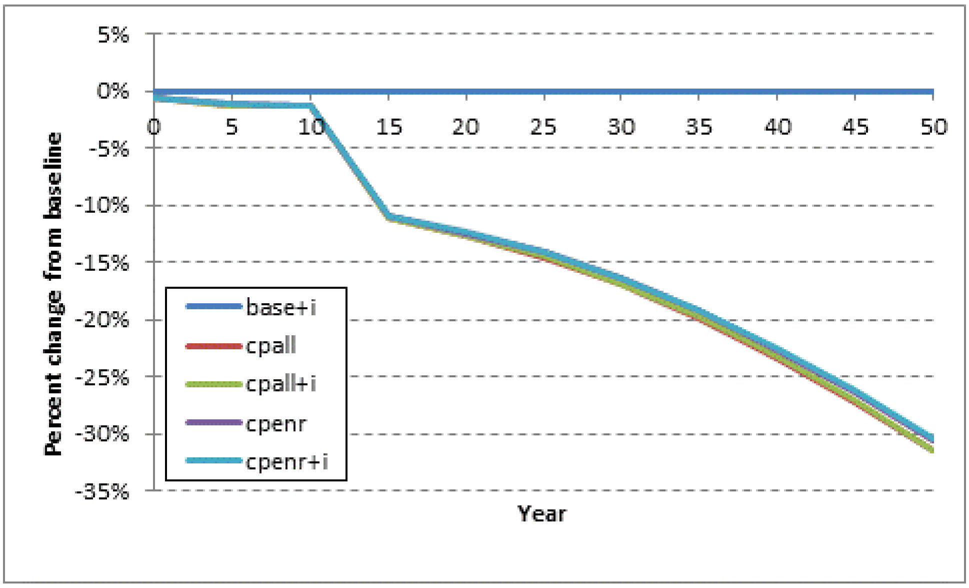

Figure 41: Estimates of the percent change in global GHG emissions from the energy intensive manufacturing sector relative to the baseline (%), by policy scenario.

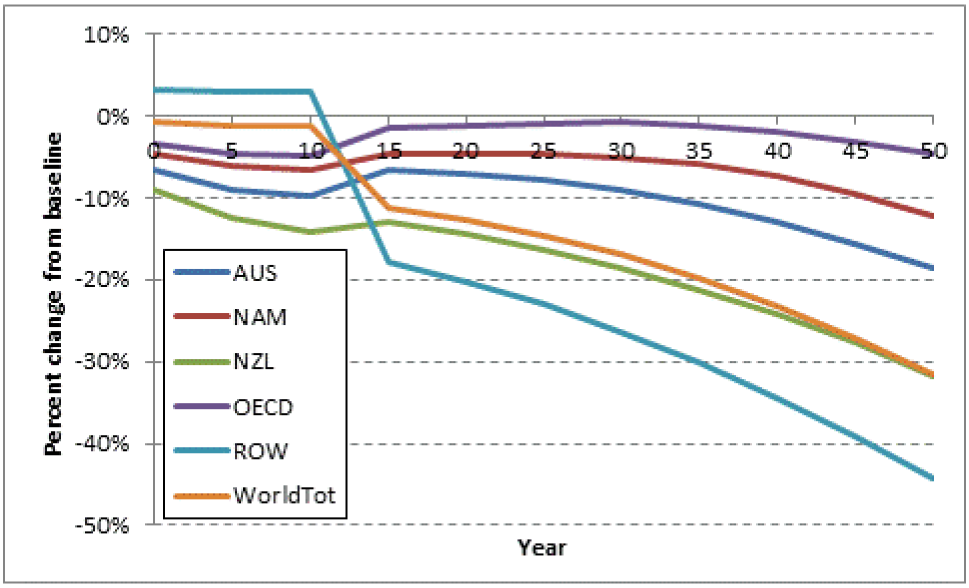

Figure 42: Estimates of the percent change in GHG emissions from the energy intensive manufacturing sector relative to the baseline (%) for the cpall scenario, by region.

GHG emissions from the rest of the world were 44% lower under a carbon tax applied to all sectors, relative to the baseline. The reduction in emissions from the rest of the world is the main source of the global reduction in emissions from the energy intensive sector. While New Zealand has a significant reduction in emissions from the energy intensive sector (30% in year 50) under a carbon tax on all sectors, relative to the baseline, New Zealand's contribution to the global reduction in emissions is negligible (Figure 43).

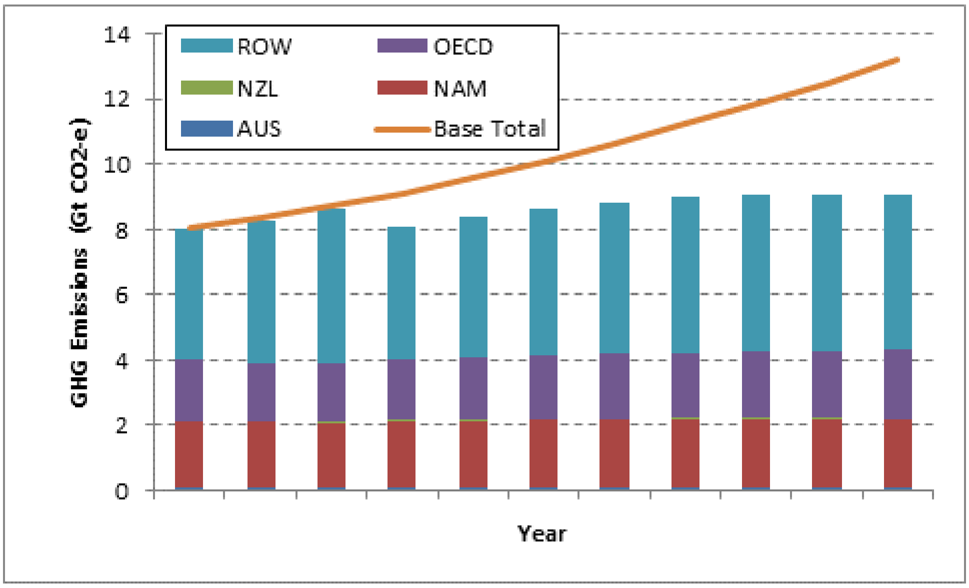

Figure 43: Estimates of GHG emissions from the energy intensive manufacturing sector relative to the baseline for the cpall scenario, by region.

Non-energy Intensive Manufacturing and Services

Output

Figure 44 shows the generally modest effects of the carbon pricing scenarios and climate impacts on output from non-energy intensive manufacturing and services (NSV). The exception is the rest of the world, which has 11% lower output, relative to the baseline, in year 50. The low emissions intensity of the non-energy intensive sector means that the lower output under carbon pricing is predominantly due to negative income effects (Figure 28). The rest of the world experiences a larger reduction in GDP, relative to the baseline, than the other regions. Income effects are also likely to explain the higher non-energy intensive sector output for New Zealand under the impact of climate change on land productivity (Figure 44b).

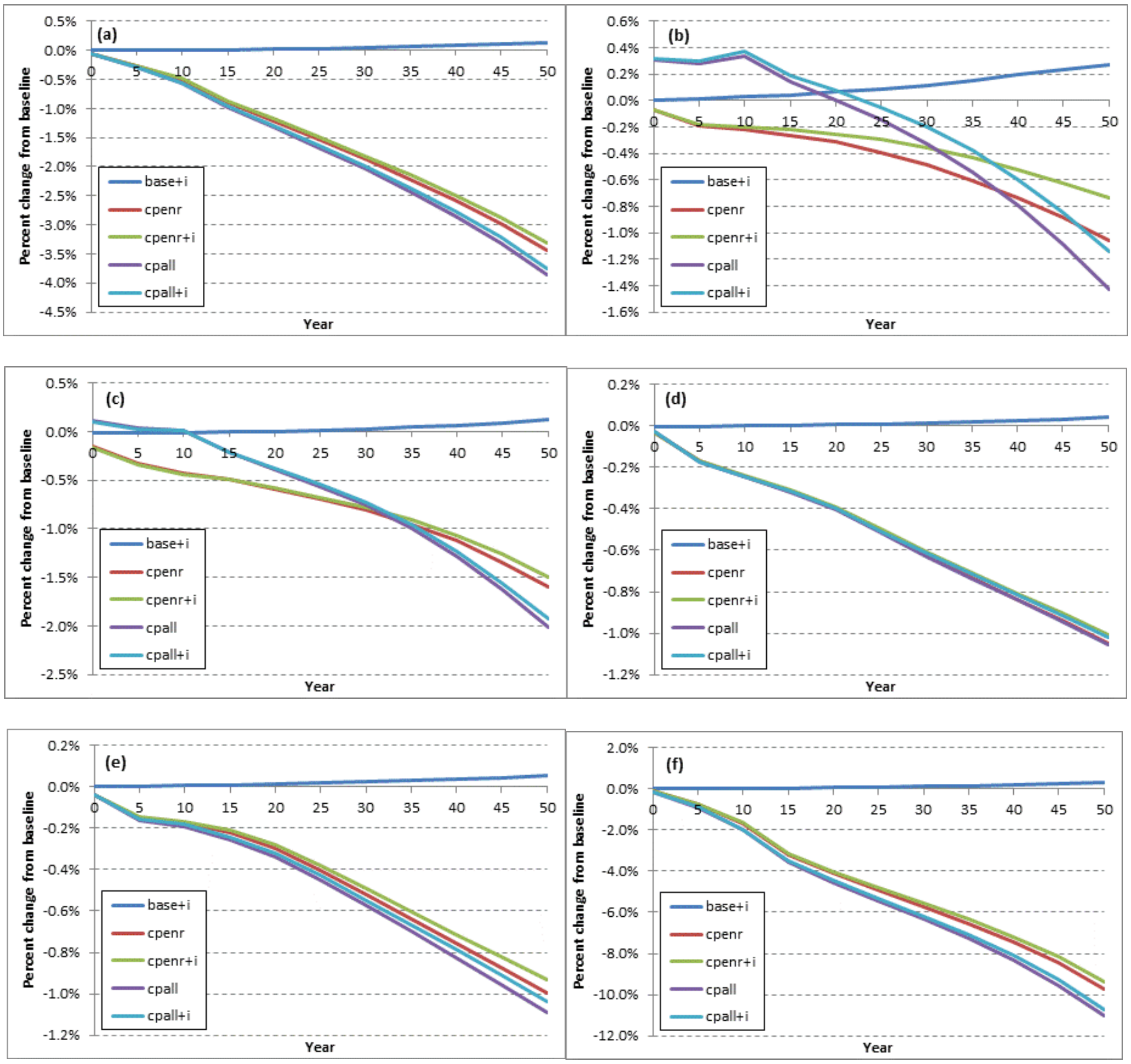

Figure 44: Policy scenario estimates of regional non-energy intensive sector output relative to the baseline; (a) global, (b) New Zealand, (c) Australia, (d) North America, (e) rest of OECD, and (f) rest of the world.

Prices

Figure 45 shows regional market prices for non-energy intensive sector outputs relative to the baseline. Relative prices increase under the carbon pricing scenarios as a result of the increasing cost of energy sector inputs to the non-energy intensive sector. This effect is small because the share of the cost of energy inputs to the total cost of inputs to this sector is small.

For the rest of the world, relative prices are lower and decline initially (Figure 45e) due to lower global demand associated with a negative income effect (Figure 28). Relative prices then increase as the carbon tax is applied in the rest of the world, leading to a growing cost of inputs from the energy sector, such as electricity, to the non-energy intensive sector.

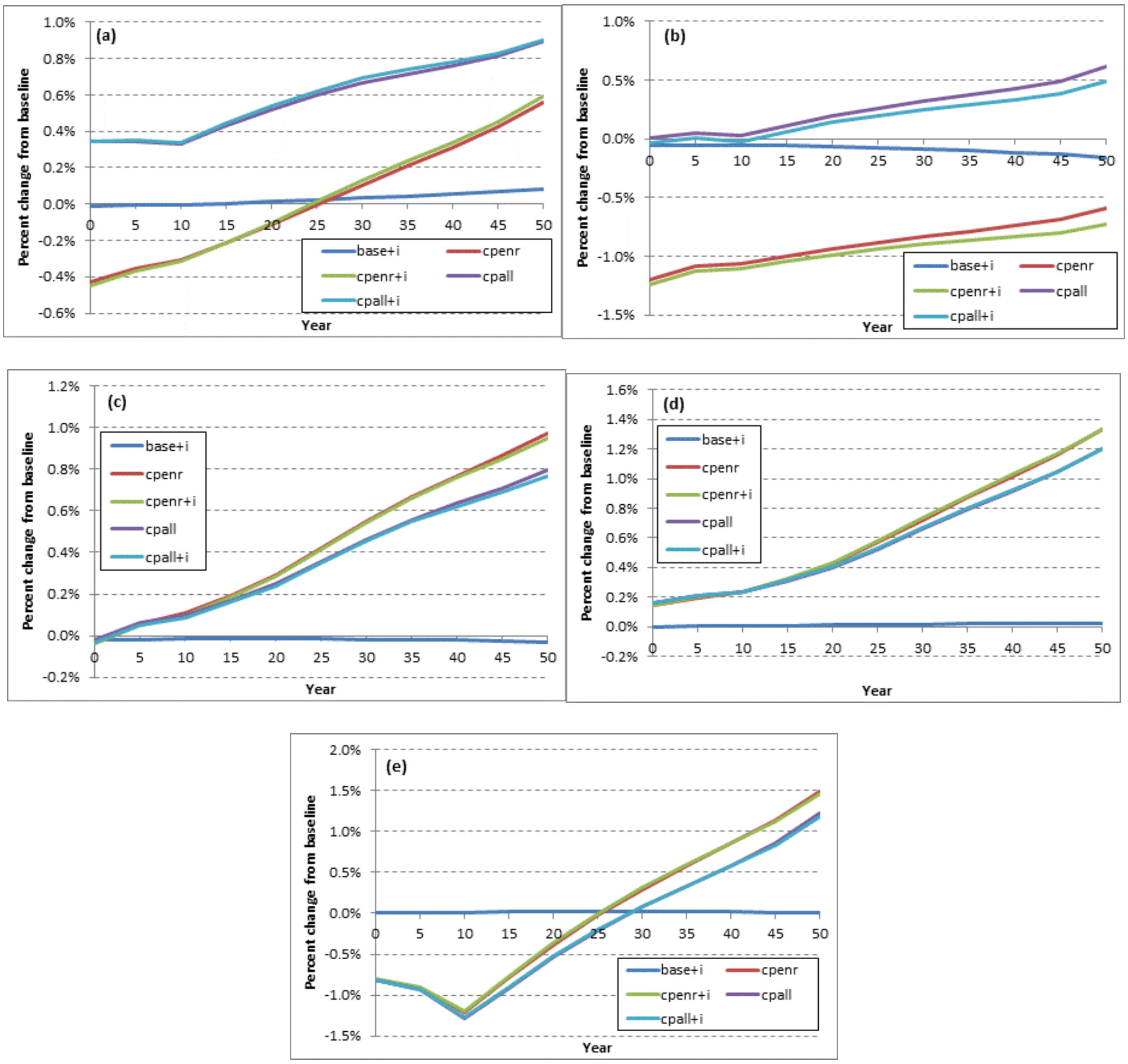

Figure 45: Policy scenario estimates of non-energy intensive sector market prices relative to the baseline, by region; (a) New Zealand, (b) Australia, (c) North America, (d) rest of the OECD, and (e) rest of the world.

GHG Emissions

Figure 46 shows the global GHG emissions from the non-energy intensive sector. Global emissions are 20% lower by year 50, relative to the baseline. There is practically no difference between the carbon policy scenarios in the relative emissions. This is because first, most global economic activity in this sector is subject to carbon pricing in all scenarios, and second, impacts on global output that lead to income effects are similar across the four scenarios.

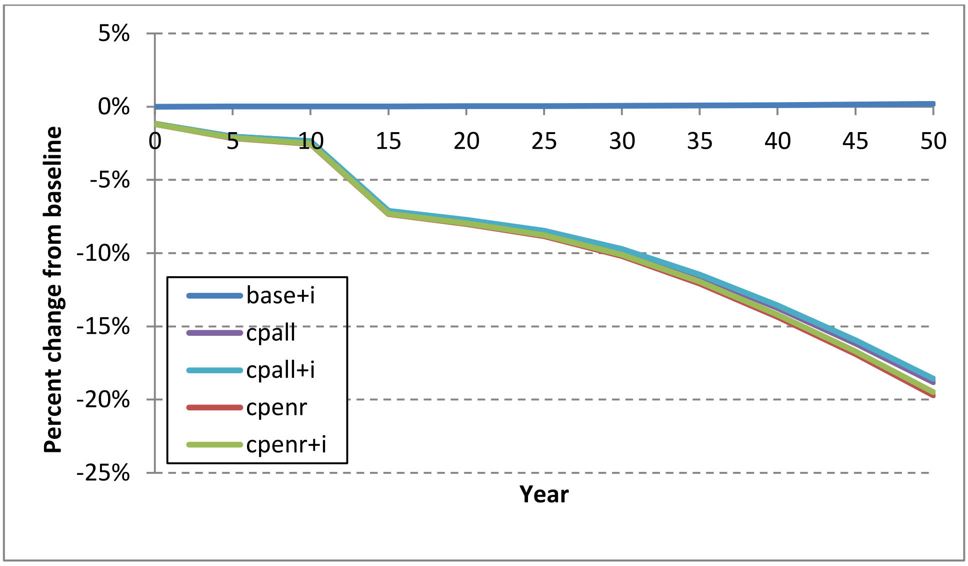

Figure 46: Estimates of the percent change in global GHG emissions from the non-energy intensive sector relative to the baseline (%), by policy scenario.

GHG emissions from the non-energy intensive sector in the rest of the world are 24% lower in year 50 under a carbon tax applied to all sectors, relative to the baseline. The reduction in emissions from this sector in the rest of the world is the main source of the global reduction in emissions from the non-energy intensive sector (Figure 47).

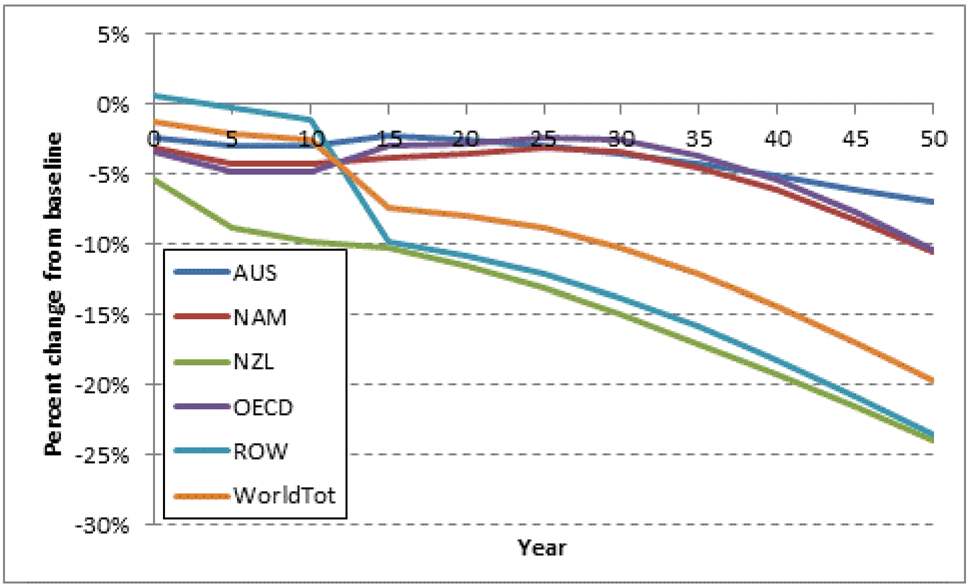

Figure 47: Estimates of the percent change in GHG emissions from the non-energy intensive manufacturing sector relative to the baseline (%) for the cpall scenario, by region.

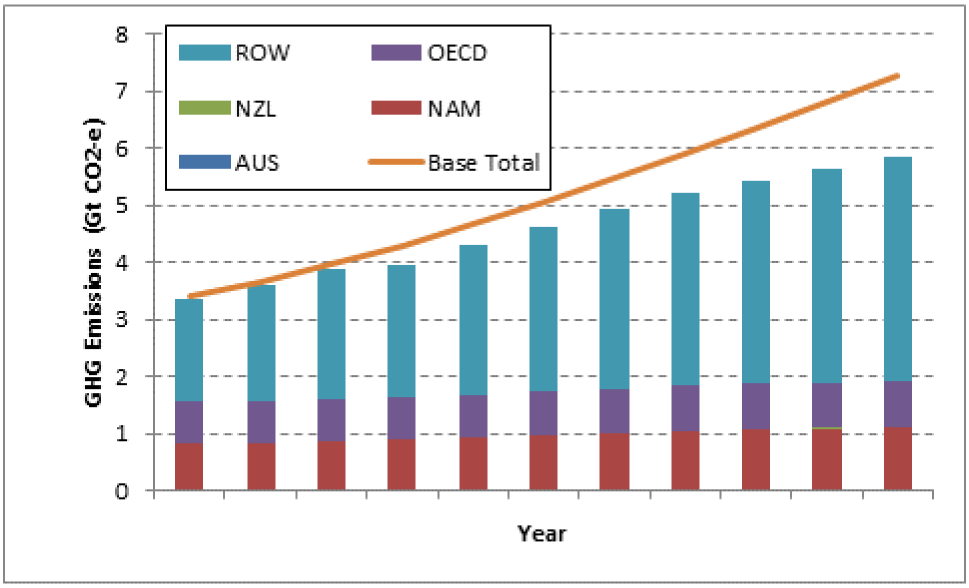

Figure 48: Estimates of GHG emissions from the non-energy intensive sector relative to the baseline for the cpall scenario, by region.

Value-added Agriculture

Value-added agriculture includes both food products and harvested wood products.

Output

Figure 49 shows output from the value-added agricultural sectors under each of the scenarios relative to the baseline, by region. Reflecting higher primary production sector output under climate impacts (base+i), the output from the value-added agricultural sectors globally and across all regions (except Australia) are relatively higher. Under the carbon pricing scenarios output for the value-added agricultural sector is lower. This is due to a combination of lower demand (due to negative income effects) and the higher cost of inputs from the secondary energy and primary production sectors. New Zealand differs from other regions in that value-added agricultural sector output under a carbon tax applied to the primary and secondary energy sectors is largely unchanged, relative to the baseline. This is due to the large share of New Zealand primary and secondary energy produced from carbon-free sources (Figure), which means the cost of energy inputs to value-added agriculture does not increase as much as in other regions under a carbon tax (similar to Figure 35).

When carbon pricing is applied to all sectors (cpall), output from the valued-added agriculture sector is much lower, relative to the baseline, in New Zealand, Australia, and the rest of the world, compared with the other regions. This reflects the larger share of value-added agriculture output in these economies, and possibly a shift to increased output from the primary production sector (Figure 54).

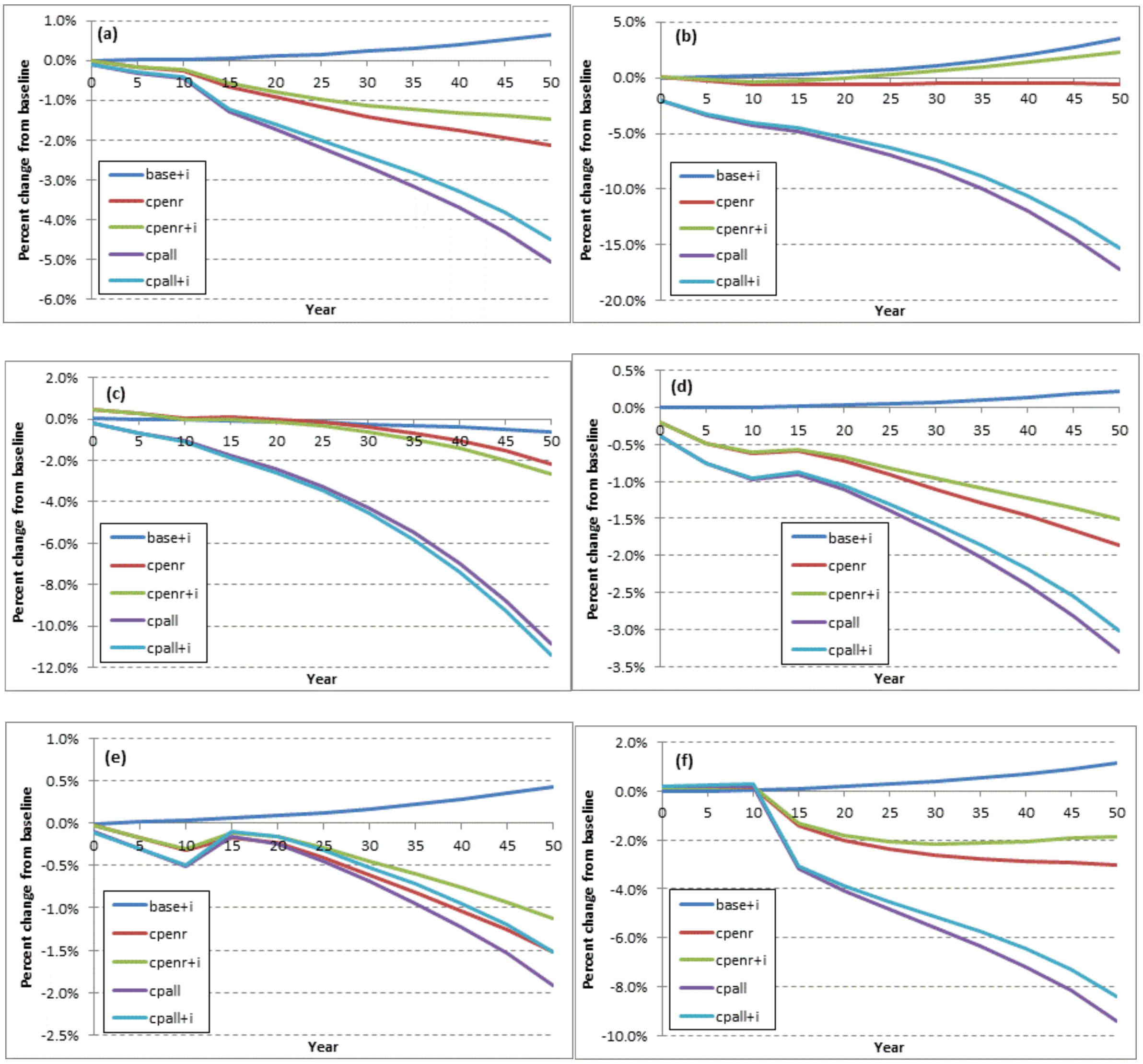

Figure 49: Policy scenario estimates of the regional value-added agricultural sector output relative to the baseline; (a) global, (b) New Zealand, (c) Australia, (d) North America, (e) rest of OECD, and (f) rest of the World.

Prices

Figure 50 shows the estimates of market prices for value-added agriculture under climate impacts (base+i) and carbon pricing in all sectors (cpall). These two scenarios represent the extremes for policy scenarios. Prices for both food products (FOO) and harvested wood products (HWP) are slightly lower under the climate impacts scenario (base+i) due to increased land productivity, reducing the cost of primary products going into the value-added agricultural sectors.

Prices for food products (FOO) are higher under carbon pricing in all sectors (cpall), relative to the baseline. This is particularly the case for New Zealand and Australia, and to a lesser extent for the rest of the world. This is in line with the higher prices for primary products, especially raw milk (RMK) and cattle, sheep and goats (CTL), in these regions under carbon pricing in all sectors (Figure 54a,b,e). The effect of carbon pricing in all sectors on harvested wood product (HWP) prices is much more modest. This reflects the small increase in log prices under carbon pricing, due to the lower emissions intensity of forestry, compared with agricultural production.

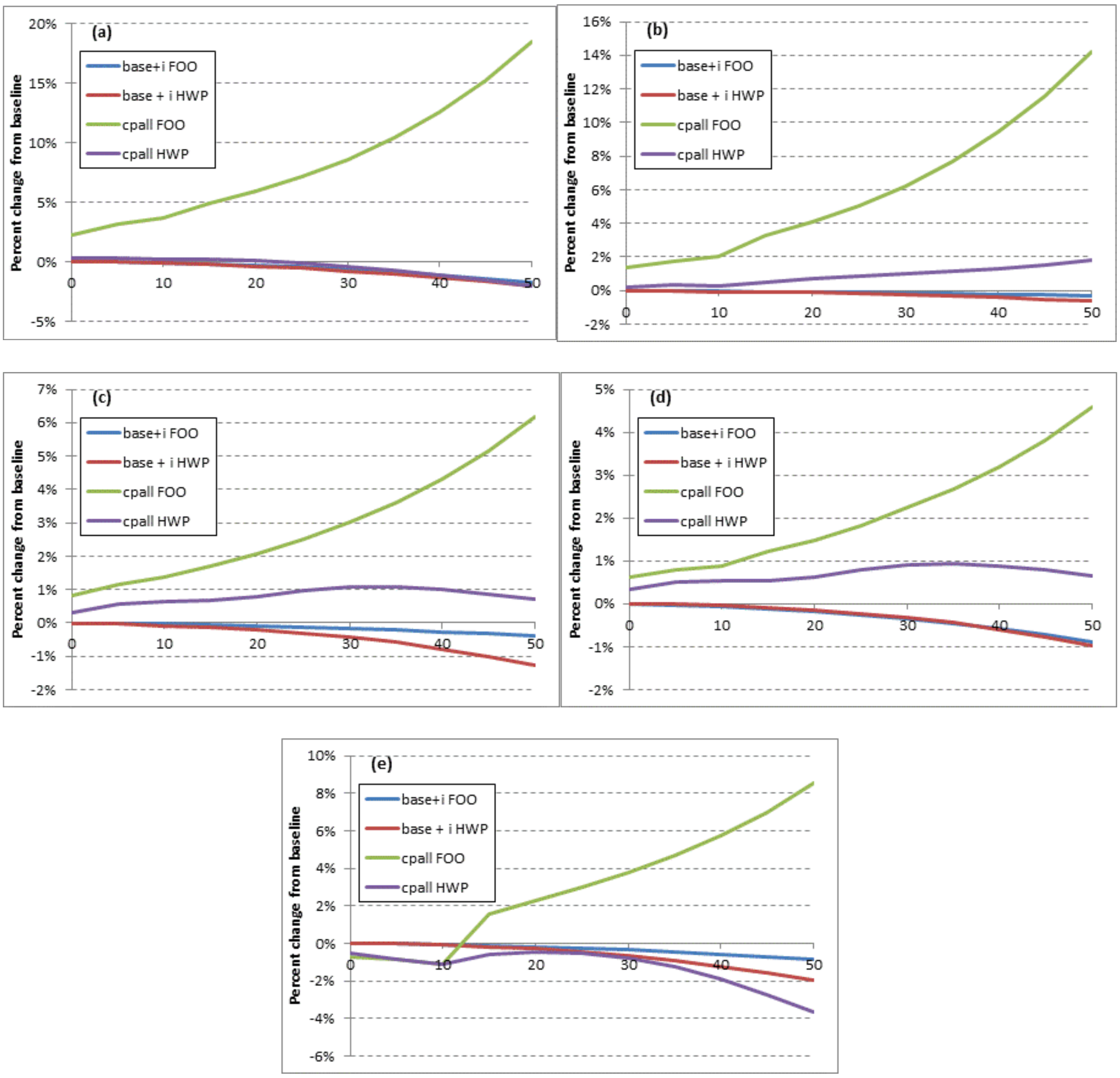

Figure 50: Policy scenario estimates of food product (FOO) and harvested wood product (HWP) market prices for the base+i and cpall scenarios relative to the baseline, by region; (a) New Zealand, (b) Australia, (c) North America, (d) rest of the OECD, and (e) rest of the world.

GHG Emissions

Figure 51 shows the global GHG emissions from the value-added agriculture sector. Global emissions from this sector are 50% lower by year 50, relative to the baseline. There is practically no difference between the carbon policy scenarios in the relative emissions.

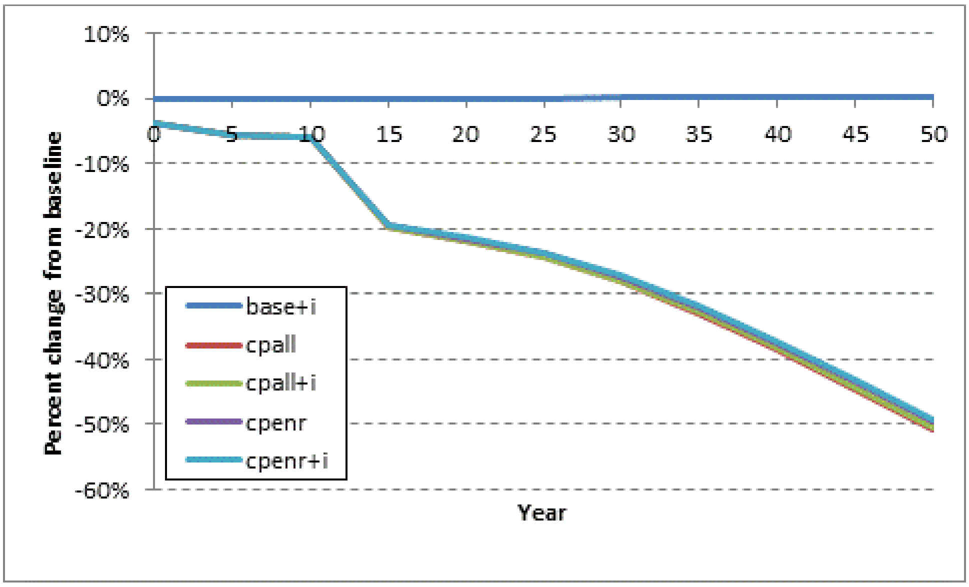

Figure 51: Estimates of the percent change in global GHG emissions from the value-added agriculture sectors relative to the baseline (%), by policy scenario.

GHG emissions from the value-added agriculture sector in New Zealand and Australia are 70% lower by year 50 under a carbon tax applied to all sectors, relative to the baseline (Figure 52). This is, in part, due to the large reduction in output from the value-added agriculture sector in these regions, relative to the baseline (Figure 53).

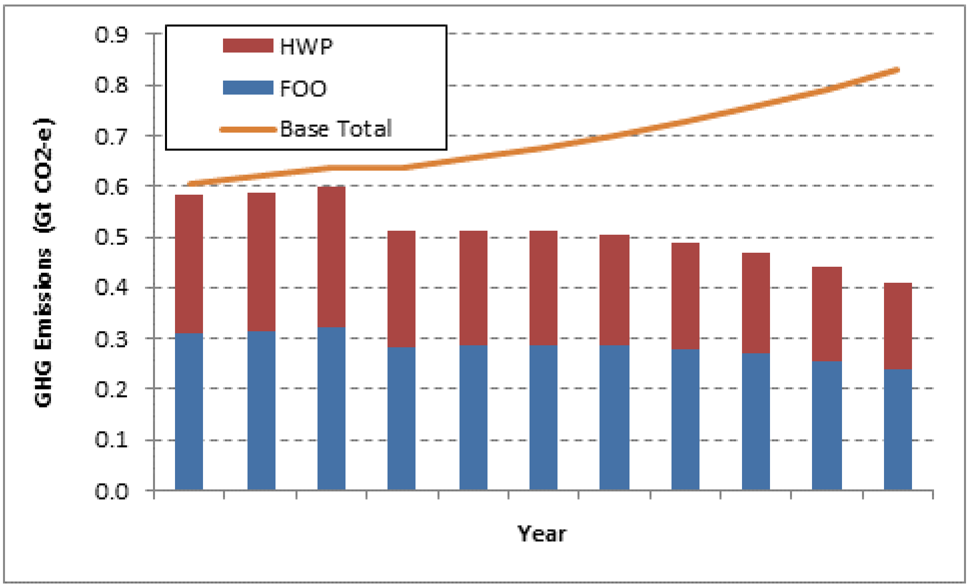

Figure 52: Estimates of GHG emissions from the value-added agriculture sector relative to the baseline for the cpall scenario, by sector.

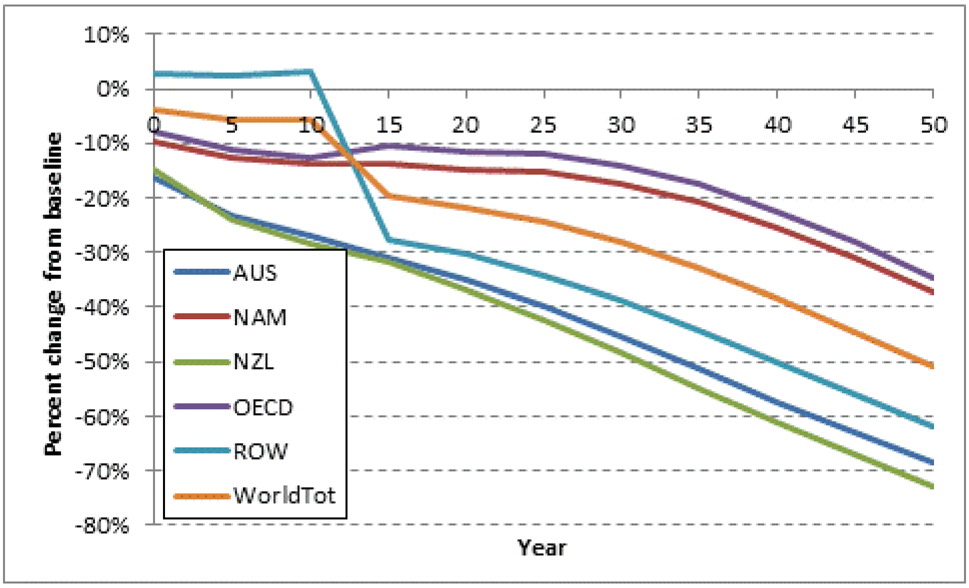

Figure 53: Estimates of the percent change in GHG emissions from the value-added agriculture sectors relative to the baseline (%) for the cpall scenario, by region.

4.3.5 Primary Production Sector Scenario Estimates

Output

Figure 54 shows estimated output of primary products, by policy scenario, for each of the regions. Climate impacts on primary product output are modest, with New Zealand being notable for having a slightly more positive output than other regions, relative to the baseline; 3.6% by year 50. Primary product output is lower under the carbon pricing scenarios, especially with a carbon tax applied to all sectors. Interestingly, Australia is estimated to experience a strong positive effect from carbon pricing (cpall) on primary product output; being 12% higher, relative to the baseline, by year 50. This is due to increased output of cattle, sheep and goats (CTL) under this scenario (Figure 55).

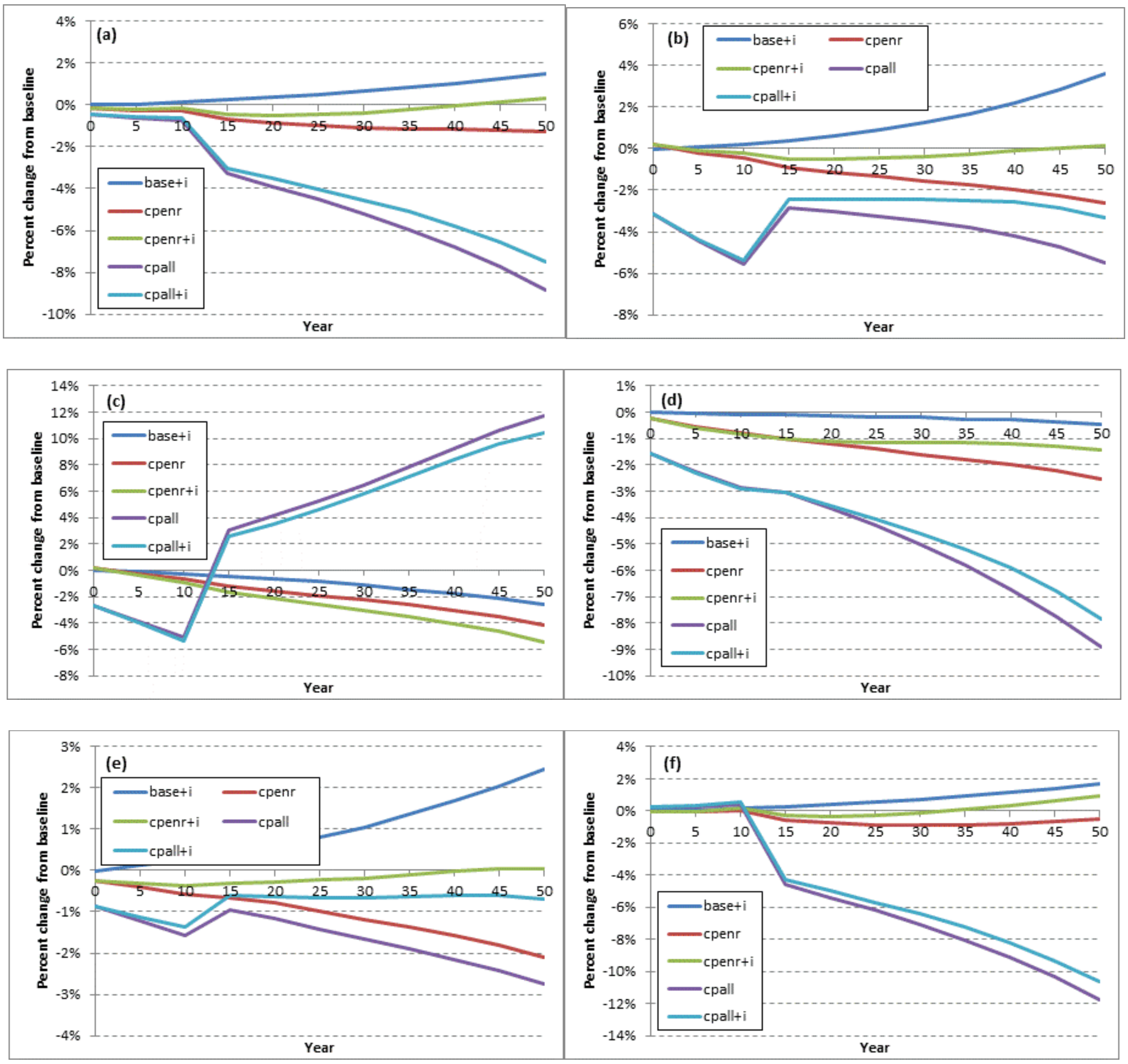

Figure 54: Policy scenario estimates of the regional value of primary production output relative to the baseline; (a) global, (b) New Zealand, (c) Australia, (d) North America, (e) Rest of OECD, and (f) Rest of the World.

Figure 55 shows the estimated output of primary products, by region, for the climate impacts (base+i), carbon tax on the energy sector (cpenr) and carbon tax on all sectors (cpall), relative to the baseline. Climate impacts (base+i) have a positive effect on primary product output across most regions. New Zealand’s output of oil seeds (OSC) and grains (GRA) increases most in percentage terms relative to the baseline, although this is from a small base. Australia and North America are notable for experiencing an estimated negative effect of climate impacts on some primary product output, e.g. cattle, sheep and goats (CTL) and grains (GRA) in Australia.

Carbon pricing in the energy sectors has a negative effect on primary product output for all regions, largely due to the negative income effect and, to a lesser extent, to the higher cost of energy inputs to primary production. In the version of the model used for the analysis presented here, energy production from biofuels was not activated. As such there is no effect of the switch to biofuels on primary product output, such as grains and oil seeds.

Carbon pricing in all sectors has a generally negative effect on primary product outputs across all regions. The notable exception is cattle, sheep and goats (CTL) from New Zealand, Australia, and the rest of the OECD. This is probably due to the large reduction in output of these products from the rest of the world, as evidenced by the initial lower cattle, sheep and goat (CTL) output in New Zealand, Australia, and the rest of the OECD, until the rest of the world takes part in carbon pricing in year 15. The strong negative impact of carbon pricing on cattle, sheep and goat (CTL) output is possibly due to higher emissions intensity of production from this sector in the rest of the world. As a result, output shifts to regions with lower emissions intensity.

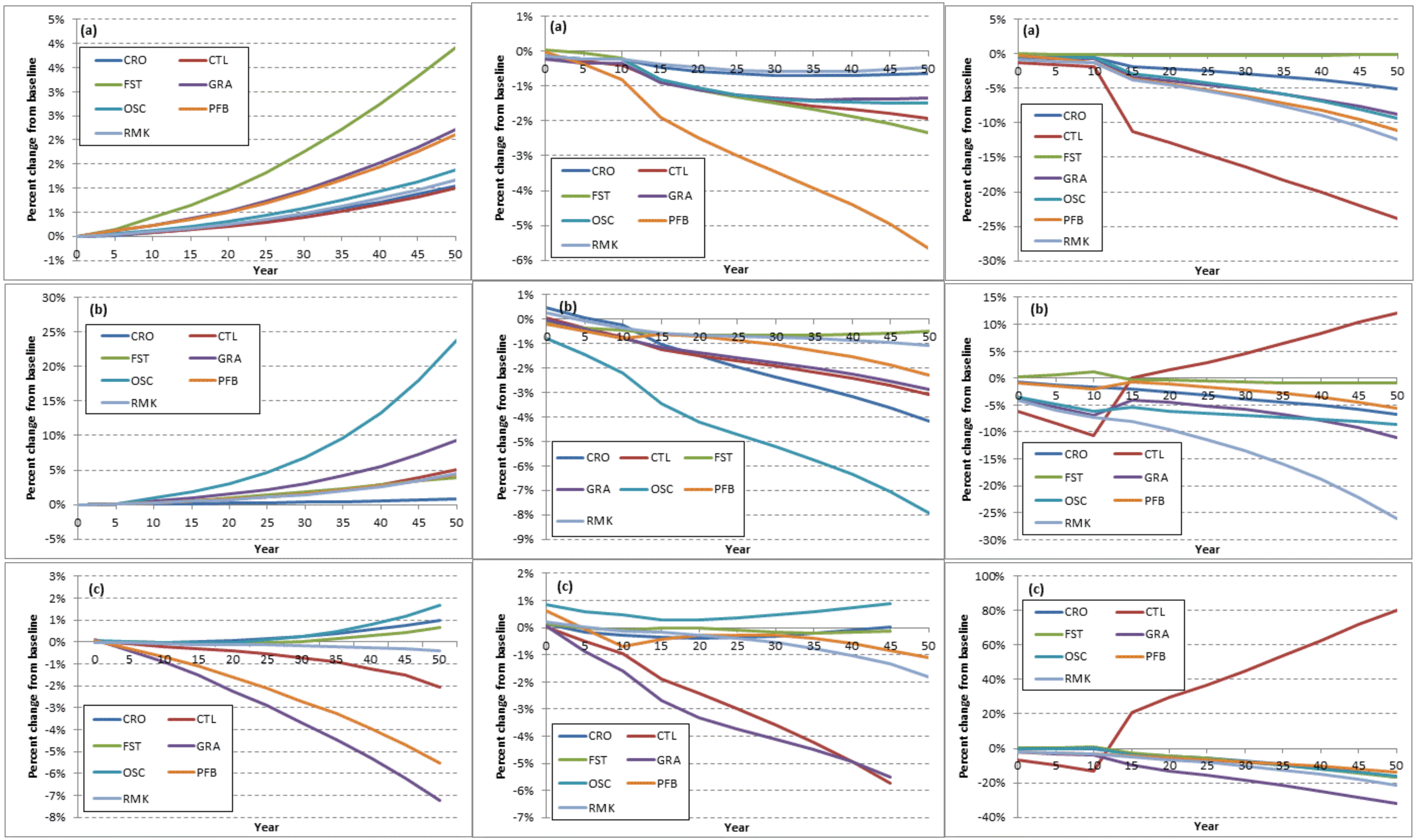

Figure 55: Policy scenario estimates of the regional value of primary production output under the base+i (left), cpenr (middle) and cpall (RIGHT) relative to the baseline; (a) global, (b) New Zealand, (c) Australia, (con't on next page)

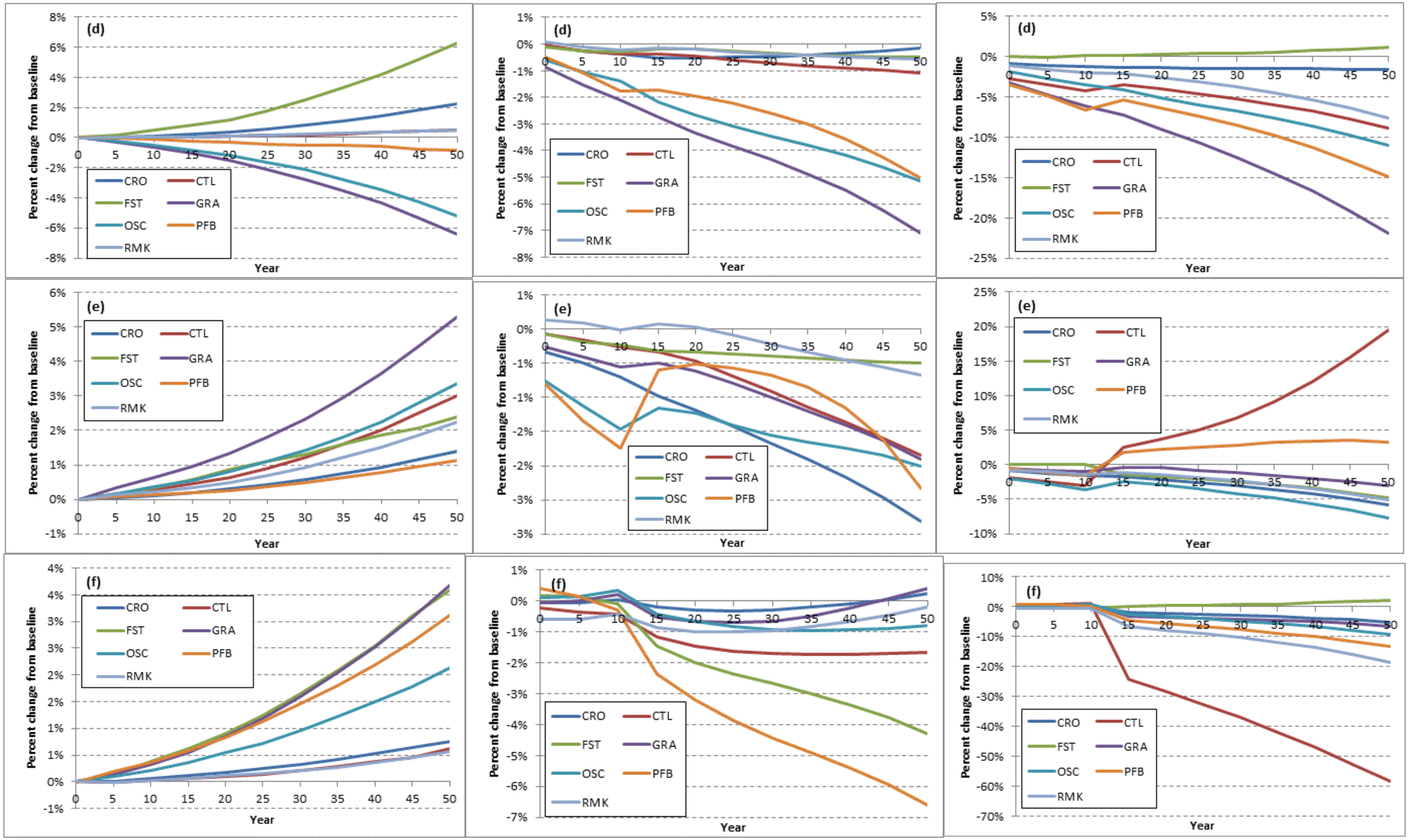

Figure 55 (con't): (d) North America, (e) rest of OECD, and (f) rest of the world.

Prices

Figure 56 shows the effect of climate impacts (base+i), carbon pricing in the energy sectors (cpenr) and in all sectors (cpall) on primary product market prices, relative to the baseline. As expected, increased land productivity due to climate impacts (base+i) results in moderately lower primary product prices, relative to the baseline, across all regions. For New Zealand, prices are 4–8% lower by year 50.

For carbon pricing applied to the primary and secondary energy sectors (cpenr), all primary product prices, across all regions, are lower relative to the baseline. This is due to the negative income effect, and the very small share of energy costs in primary product production. As such, the negative income effect outweighs the small positive effect of higher energy prices on the relative market price of primary products.

For carbon pricing applied to all sectors (cpall), primary product prices relative to the baseline are higher across all regions and products, with the exception of logs from forestry. Forestry relative prices are moderately lower, possibly due to the income effect being greater than the effect of pricing emissions. As a result of its low emission intensity, the effect of pricing emissions is a small cost in the forestry sector (FST). The higher emissions intensity of the cattle, sheep and goats (CTL) and raw milk (RMK) sectors is a likely explanation for the higher prices for these products, which have a relatively higher cost associated with emissions than other primary products. For New Zealand, raw milk (RMK) prices are 40% higher and cattle, sheep and goat (CTL) prices are 70% higher by year 50, relative to the baseline. The relatively larger increase in prices for cattle, sheep and goats is due to the larger reduction in output of these products in the rest of the world.

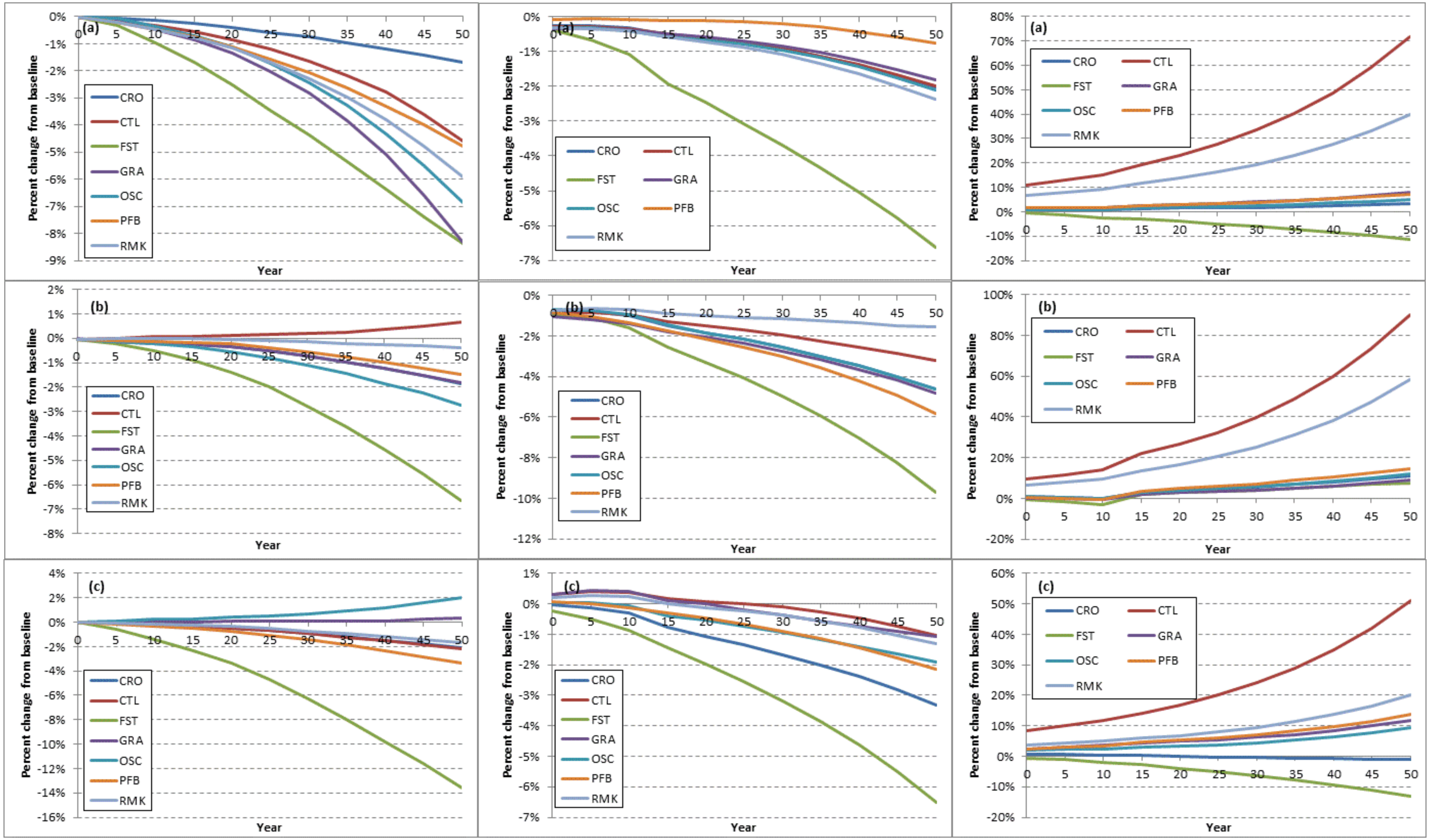

Figure 56: Policy scenario estimates of regional market prices of primary products under the base+i (left), cpenr (middle) and cpall (RIGHT) relative to the baseline; (a) New Zealand, (b) Australia, (c) North America, (con't next page)

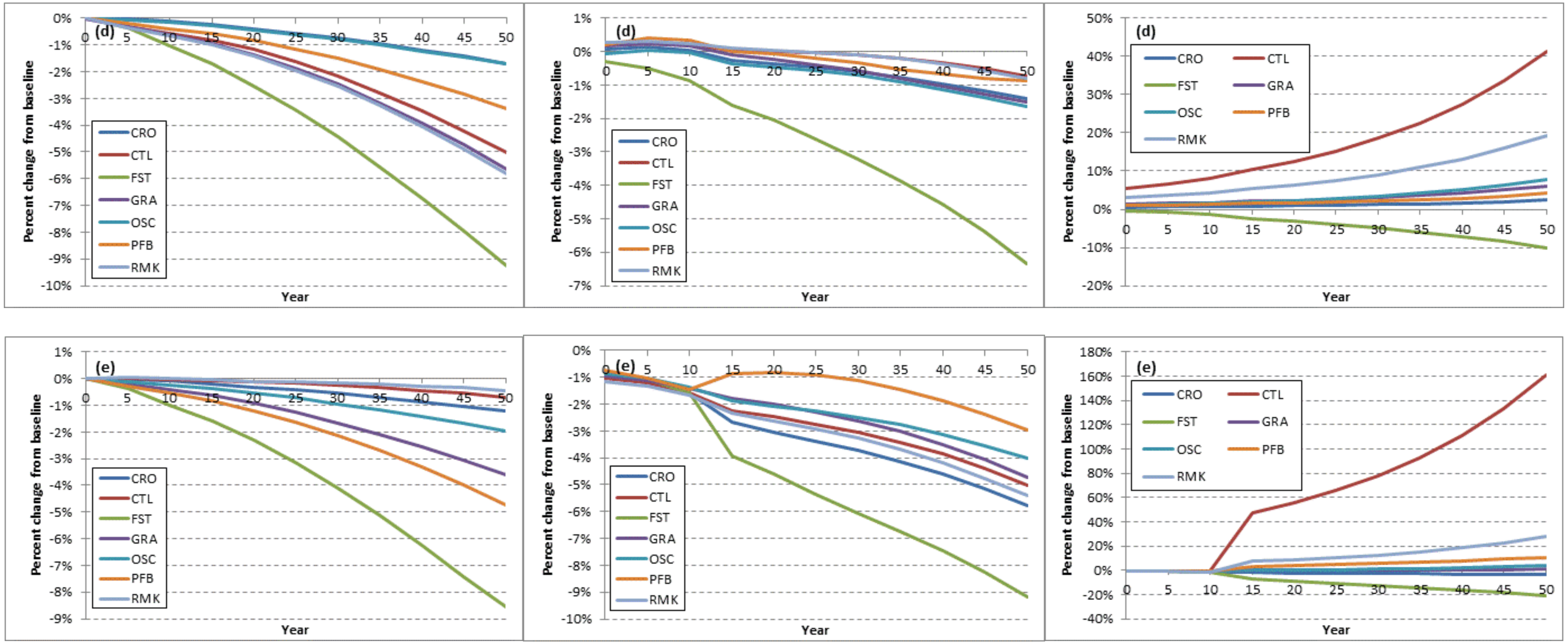

Figure 56 (con't): (d) rest of OECD, and (e) rest of the world.

Land Use

Figure 57 shows the effect on land use of climate impacts (base+i), and carbon pricing in the primary and secondary energy sectors (cpenr) and in all sectors (cpall), relative to the baseline.

Impacts of climate on land productivity (base+i) have a moderate effect on land-use change across all regions, with ±6% change by year 50, relative to the baseline. There is considerable regional variation in the land uses that cover larger area under climate impacts. This, in part, reflects regional differences in the impact of climate on productivity of different land uses. New Zealand is estimated to experience a small increase in the area of forestry (FST) (1.5% by year 50) and other crops (CRO) (2.9% by year 50), relative to the baseline.

For carbon pricing applied to the energy sectors (cpenr), land-use change across all regions is moderate: ±4% change by year 50, relative to the baseline. Again there is considerable regional variation in land-use change, relative to the baseline. This is due to regional differences in the relative change in primary product output. For example, New Zealand output of forestry (FST), raw milk (RMK), and plant-based fibres (PFB) is moderately lower, relative to the baseline, while output of other crops (CRO) and oil seeds (OSC) is much lower. Correspondingly, there is a shift from land in other crops and oil seeds into forestry (FST), raw milk (RMK), and plant-based fibre (PFB) production.

For carbon pricing applied to all sectors (cpall), land-use change is more impacted than for the other scenarios. For most regions the dominant change is a relatively higher land use in cattle, sheep and goats (CTL) due to a decrease in land use in the rest of the world. The elasticity for land use does not allow for a dramatic rapid change in any land use. For New Zealand, land appears to shift from raw milk (RMK) production (land use 19.5% lower, relative to the baseline) to cattle, sheep and goat (CTL) production (land use 20.5% higher relative to the baseline) due to a relatively larger increase in production of cattle, sheep and goats than raw milk, and also to the higher GHG emissions associated with raw milk than cattle, sheep and goats in New Zealand in the base data.

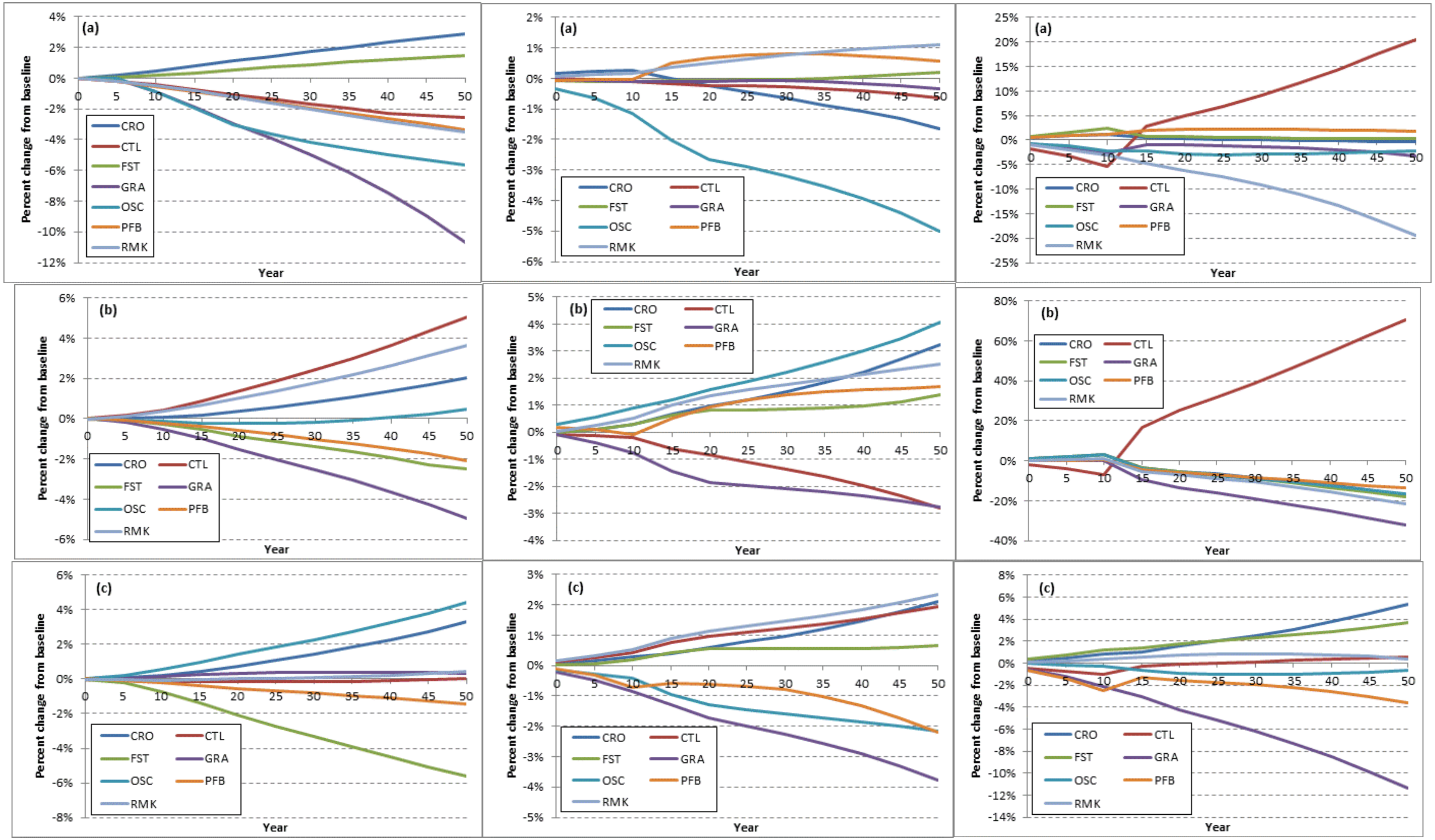

Figure 57: Policy scenario estimates of regional land use under the base+i (left), cpenr (middle) and cpall (RIGHT) relative to the baseline; (a) New Zealand, (b) Australia, (c) North America, (con't on next page)

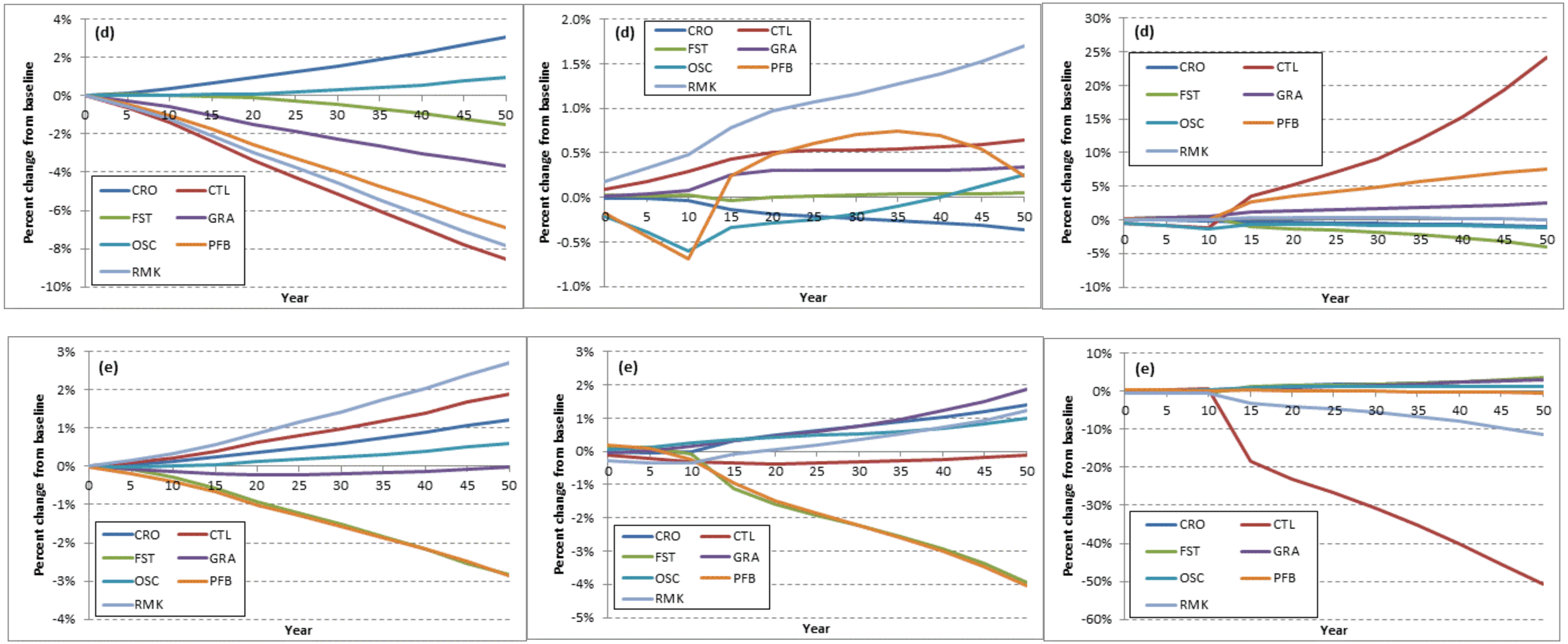

Figure 57 (con't): (d) rest of OECD, and (e) rest of the world.

GHG Emissions

Figure 58 shows the global GHG emissions from the primary production sector. Not surprisingly, global emissions from this sector are much lower: 40% by year 50 under the carbon pricing in all sectors scenario (cpall), relative to the baseline. This is predominantly due to a reduction in primary product output under this scenario, and, to a lesser extent, to a shift in the mix of primary products produced and region of production to lower emission intensity products and regions. Global emissions from the primary production sector are slightly lower under carbon pricing in the primary and secondary energy sectors (cpenr), relative to the baseline; 8.4% by year 50. This reduction is due to lower output as a result of a negative income effect.

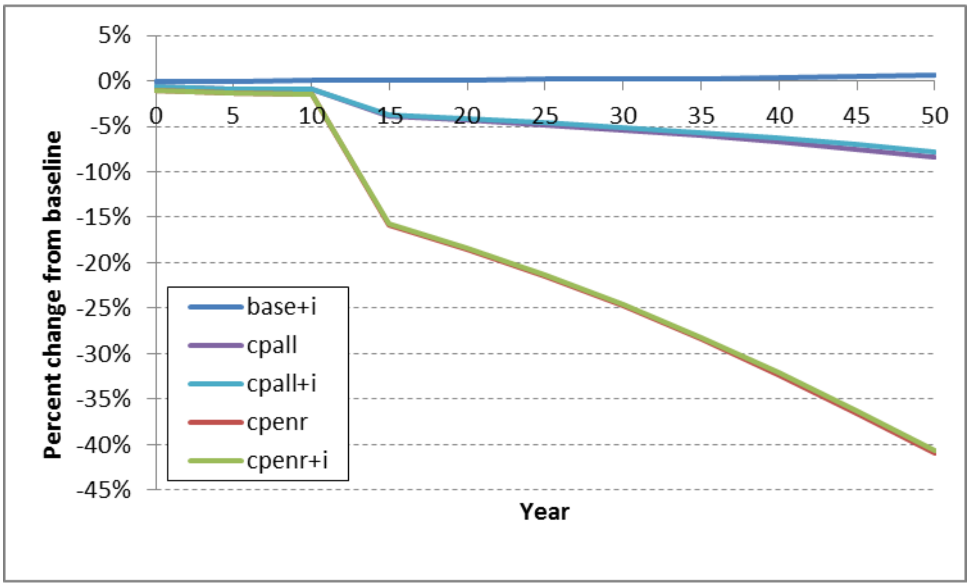

Figure 58: Estimates of the percent change in global GHG emissions from the primary production sectors (excluding FST) relative to the baseline (%), by policy scenario.

Figure 59 shows regional GHG emissions under carbon pricing in all sectors, relative to the baseline. While most regions have lower relative emissions, Australia experiences higher emissions, relative to the baseline, likely to be due to the higher cattle, sheep and goat (CTL) sector output by Australia under this scenario. New Zealand GHG emissions are 6% lower by year 50 under this scenario, relative to the baseline.

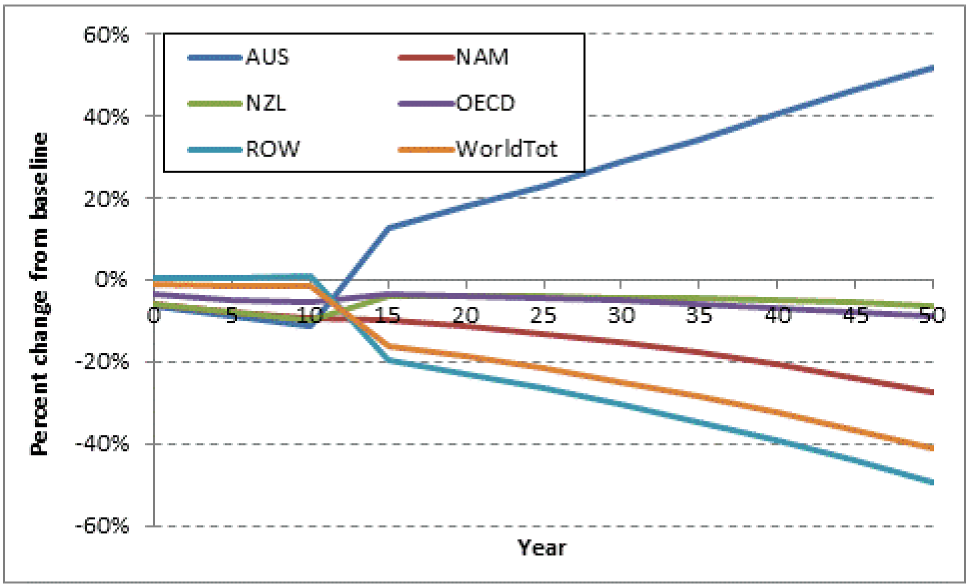

Figure 59: Estimates of the percent change in GHG emissions from the primary production sectors (excluding FST) relative to the baseline (%) for the cpall scenario, by region.

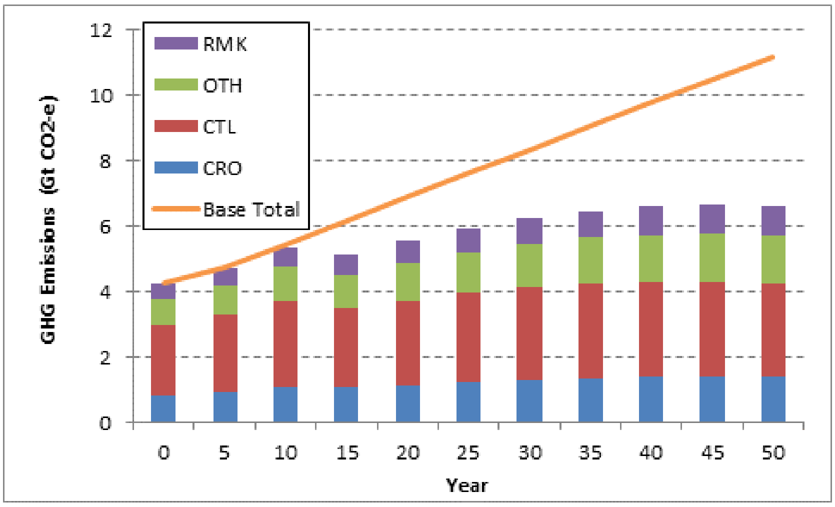

Figure 60: Estimates of global GHG emissions from the primary production sectors (excluding FST) relative to the baseline for the cpall scenario, by sector.

4.3.6 Summary

For the version of the model run for this study, climate impacts alone have a very modest effect on outputs and prices within the 50-year period of analysis presented here. The carbon pricing scenarios have a more significant effect on output, prices and emissions relative to the baseline. Not unexpectedly, a carbon tax on the energy sectors is estimated to lead to a significant reduction in electricity output, and a shift from fossil-based to carbon-free electricity. Modelling suggests this will lead to a large reduction in emissions from the secondary energy sector, relative to the baseline. New Zealand is unique among the regions considered in our modelling, in that it already has a large share of energy output that is from carbon-free electricity. This moderates the scope for New Zealand to reduce GHG emissions from the secondary energy sector, compared with other regions.

Applying a carbon tax to all sectors affects primary product output, and hence value-added agricultural output, land-use change, and emissions from this sector. Most significant is an estimated reduction in cattle, sheep and goat output from the rest of the world, leading to an increase in output of these products in New Zealand, Australia, and the rest of the OECD. This is predicted to result in relatively higher prices both for cattle, sheep and goats (CTL) and for raw milk (RMK), a relatively lower output of raw milk, and a change in land use in New Zealand from raw milk production to cattle, sheep and goat production, relative to the baseline. The GHG emissions associated with raw milk production in New Zealand are higher than those associated with cattle, sheep and goat production in the GTAP base data, implying raw milk production is less energy efficient. This also contributes to the shift in land away from raw milk.

The predicted increase in cattle, sheep and goats output appears to differ to findings by Saunders et al. (2009b). Using the Lincoln Trade and Environmental (LTEM) partial-equilibrium model, Saunders et al. found that for a global carbon pricing policy the percentage increase in dairy producer returns would be more than double the percentage increase in sheep meat and beef producer returns (Saunders et al.; Table 8.5). Saunders et al. applied a carbon pricing scenario to all Annex-I countries, but not to non-Annex-I countries, that included a lower carbon price than the one used in our study. In our study we have applied the carbon pricing scenario to non-Annex-I countries in the rest of the world, which the model has estimated will result in a large reduction in cattle, sheep and goat output from the rest of the world.

5 Future Research

The following section will describe the on-going research in development of the NZIAMS as well as the limitations of the version of the model used for this report.

5.1 Hard-link of PE-GE model

The linkage between the GE and PE models described in section 2.2.3 can be characterised as a ‘soft link’. The GE model describes the entire global economy with a relatively coarse description of land resources and land-based production. The GE model is solved and the commodity and factor prices and commodity demands from this solution are used as inputs into the PE model. The PE model provides a more detailed description of land resources and land-based production, given simplified assumptions about the supply of non-land factors of production and non-agricultural commodities (i.e. their prices are fixed) and the net demand for agricultural commodities (demands are linearised around the solution point of the GE model). Inconsistencies can arise between the two models. This can cause issues if there is a strong feedback from the primary sectors to the rest of the economy, as can occur if these sectors strongly affect energy supply (in the case of biofuels) or carbon prices (in the case of agricultural emissions in a country such as New Zealand where these are relatively important, or in the case of forest carbon credits).

It would be preferable to ‘hard-link’ the GE and PE sub-models to obtain a mutually consistent solution (Böhringer & Rutherford 2008). This was the initial intention for this project and a hard-linking method was developed and tested. Numerical testing showed that the method worked as expected for two regions. In this case, the linking variables exhibit oscillations that decrease with the number of iterations and the models approach an overall general equilibrium. However, when the method was tested with three or more regions, the linking variables exhibited increasing oscillations. Despite extensive testing, we were not able to determine the cause of this problem or find any way to mitigate it within the frame of this project. Consequently, further research will be required for the hard-linking to be successfully implemented.

5.2 Limitations and possible future extensions of the GYE

In the current version of NZIAMS, we have relied on the DSSAT and MC1 simulations described above for our projected yields, and used only the Hadley AOGCMs (HadGEM2-ES for crops and HadCM3 for forest) for calibration of the GYE model. However, the GYE is designed so that it can relatively easily use any crop/forest model as input, provided the basic crop/forest model simulations are available at a global 0.5×0.5° grid for clearly specified underlying climate scenarios based on AOGCM simulations.

If using different models for different sectors (individual crops and forest), the issue of model bias becomes an important consideration. All models are imperfect and their predicted yields may be higher or lower than actual yields, with some models showing much greater effects from carbon fertilisation than others for a range of crops. By using models that are as similar as possible for different sectors, biases are more likely to be strongly correlated across sectors. This is desirable for many purposes, such as analysis of competing land uses.

The current crop model intercomparison projects, AgMIP[19] and ISI-MIP[20], are generating a large amount of crop model data sets using consistent experimental protocols (and indeed the DSSAT data used in this study were produced as input to the ISI-MIP intercomparison). Once these datasets become publicly available, this will in principle allow a straightforward and internally consistent user-selectable choice of crop and forest models as well as alternative AOGCMs for NZIAMS runs. Once the regression coefficients have been derived (off-line) for each combination of crop/forest model and AOGCM, the NZIAMS can then be run with multiple combinations to study the influence of differences in crop/forest models and AOGCMs on policy-relevant questions, such as whether different crop models, different climate models, or different policy choices have the biggest impact on, e.g. projected future commodity prices or returns to New Zealand farmers.

A limitation of the current approach is that the change in yields in any given region is based on the yield change within the currently cropped area as estimated by SAGE (Monfreda et al. 2009). As a result, the model is ‘blind’ to yield changes in areas that currently are not cropped, but could become productive in future. The advantage of restricting the GYE to the currently cropped area is that there is no step change between the historical period and the forward simulation by the NZIAMS (since for some regions, a crop may appear to be suitable based on DSSAT simulations but local regulations, trade or traditional practices may currently prohibit the production of the crop). However, under climate change, some areas that are currently unsuitable for cropping would become suitable in the future (particularly in mid- to high northern latitudes), and one could expect that over time cropping would shift into those areas.

In its current configuration NZIAMS assumes a more static approach to future land use than will apply in the real world. This is not necessarily a major issue since the assumption applies to all world regions equally, but it may be more restrictive in some regions than others (which in turn depends on how regions are defined).

Lifting the restriction to the currently cropped area is not easy, since the quantity that matters for CliMAT-DGE is not the total yield in a region, but the yield for the area that is actually cropped at any given time. If and when the model is extended to allow a greater disaggregation of regions, this restriction will become less relevant, and would disappear entirely if the model were run in grid mode (which is currently not feasible due to computational and numerical constraints).

5.3 Incorporating other economic or biophysical models into NZIAMS

Currently, CliMAT-DGE is hard-linked to MAGICC and the GYE, but soft-linked to a partial equilibrium sub-module. The modularity of the CliMAT-DGE makes it relatively easy to link economic and biophysical models if they are formatted so that information can be passed between the modules in a consistent manner to create feedback loops. There are, however, practical computational limits. Adding other models and detail to the NZIAMS typically increases complexity, which can impact on the time and ability for the model to converge to a feasible solution.

[19] http://www.agmip.org/

[20] http://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities/isi-mip

The modularity of the framework also makes it feasible to switch biophysical models. One consideration that needs to be taken into account when choosing biophysical models is their computational complexity. If they take hours to solve, this will increase the solve time of the NZIAMS to days, calling into question whether the cost of representing a biophysical impact slightly more accurately in the model is worthwhile. There is a trade-off between a minimal improvement in the realistic representation and computational simplicity.

5.4 Backstop technologies

As well as the ordinary model sectors for which benchmark data are available, CliMAT-DGE defines several 'backstop' technologies. In the present context, backstops are known technologies that currently have no (or very limited) market penetration because they are not yet cost-competitive. Under carbon pricing however, they are expected to experience cost reductions as a result of technological progress and become cost-competitive. Currently, CliMAT-DGE includes tentative representations of the following technologies:

- Biofuel refining using forest products as a feedstock.
- Bioelectricity production with carbon capture and storage (CCS) using forest products as a feedstock.
- Coal-fired electricity production with CCS.

These technologies are described using production functions similar to, although somewhat simpler than, the regular production function (see Appendix 2). However, while production functions for most sectors are calibrated using the benchmark database, backstop production functions are calibrated using data drawn from various literature sources that study the technical and cost characteristics of these technologies in detail. Since the specification of these technologies in CliMAT-DGE is independent of the benchmark dataset, it is easy to modify the structure and/or the data for backstop technologies to test different assumptions or represent different technologies.

It is widely recognised that backstop technologies having zero or even negative emissions are necessary to achieve ambitious emissions reductions targets (van Vuuren et al. 2011). For this reason, we hoped to include backstop technologies for the simulations presented in this report. However, we found that the model became more difficult to solve at a large scale when backstops were included. These numerical difficulties may be resolved through further research. Currently, backstop technologies can only practically be included in CliMAT-DGE if the model is run with just two regions and a modest number of sectors.

5.5 Forest dynamics

In the version of the model used for this report, the forestry sector (in both the GE and PE models) employs a single-period production function, as does the agricultural sector. That is, forestry uses land and other inputs and produces wood and other forestry products as outputs within the same period (of 5 years). In reality, however, it takes many years and sometimes many decades for trees to reach their harvest age. A more realistic model of forestry production would account for the use of land over the length of a rotation. In a dynamic model, this is possible using an explicit multi-period production function or, equivalently, by modelling the growth of forest stocks from one period to the next.

Such a dynamic representation of managed forests has been implemented in the PE model, as has a representation of the clearance of natural forests (i.e. deforestation). Our implementation closely follows that described in Steinbuks and Hertel (2012), but as well as allowing for endogenous determination of the optimal rotation length, we also allow for endogenous determination of the optimal management intensity. Deforestation is modelled as yielding both forest products and new managed land, which is subsequently allocated between pastoral and cropping uses, as well as managed forestry.

The production functions combine land and other inputs to produce logs for some specified harvest age. The inputs included in the production functions can include planting inputs, together with land and logging inputs. Depending on the forest management regime, it may additionally be desired to model silvicultural management inputs (e.g. thinning) at one or more periods, and there may be associated secondary outputs (e.g. thinnings). Non-timber secondary outputs (e.g. forest carbon credits) can also be modelled. The important restriction on this production function is that the land input is the same in all periods, as production of logs requires the trees to grow on the same piece of land until they are harvested.

The dynamic representation of forestry was not used in this report because it requires further empirical calibration and testing. This is a complex process, particularly because we wish to calibrate the model to simulate a plausible baseline trajectory of planting, harvesting and deforestation. A further challenge with using the dynamic forestry version of the model is that it is less consistent with the GE model, in which forestry is modelled using a single period production function.

Another avenue of investigation that was pursued earlier in the project was to integrate a dynamic representation of forestry directly within the GE model. We were able to develop a theoretically consistent representation and successfully implement it in a computational model (Lennox et al. 2011a, b). In that version of the model, forest harvest age and management intensity are endogenously determined for each rotation. Further explanation and mathematical details may be found in Lennox (2011a and b). Unfortunately, we were unsuccessful when attempting to implement the same structure at a larger scale (i.e. with more sectors and regions). A numerical solution became much more difficult to solve and in some cases, appeared unstable. Our conclusion is that our approach used in this report is the best suited representation of a single age-structured forest estate within a single country/region.

5.5.1 Modelling forest carbon sequestration and REDD

The model presented in this report does not track forest carbon sequestration. This is because the version we used for the illustrative scenarios treats forests like agriculture (same production function) and does not include explicit forest stocks or carbon sequestration.

As we currently do not track primary forests and deforestation, the model is unable to account for payments for reducing emissions from deforestation and degradation (REDD).

The Bioelectricity+CCS backstop technology sector can be programmed to produce carbon credits, since it is assumed that any CO_2 sequestered represents a net removal from the atmosphere, while any CO_2 emitted is carbon-neutral. The biofuel sector can also produce carbon credits, as the CO_2 emissions from users of biofuel cannot be distinguished from those of refined petroleum. Therefore, the credit serves as an offset against emissions from biofuel combustion.

5.6 Data updates

The New Zealand input–output (IO) table included in the GTAP v7.1 database is based on an IO table originally created in 1996. This has since been updated and will be incorporated in the next interim-release of the GTAP v8 database expected in December 2013. This model will include more up-to-date and accurate data on New Zealand that may cause the results to change. As a result, some of the GHG emissions factors associated with NZL may also change, providing a more accurate representation of the emissions and land-use change under various policy scenarios.

6 Summary

The NZIAMS was developed with a New Zealand focus to provide policy makers with better information on the trade-related impacts of climate change and climate policy. It consists of three main component models that focus on the economy, climate, and biophysical impacts, with the core model being the economic model. These main components are not only linked but also provide feedback loops allowing them to optimise across these components and thereby account for the impacts of the climatic and biophysical changes.

The modularity of NZIAMS provides a degree of flexibility to link relatively easily with other biophysical or partial equilibrium economic models not currently included in NZIAMS. It also allows the exploration of the relative importance of the choice of climate, crop or forestry models for results. This is a key innovation over standard IAMs, which usually have a particular forestry, climate and/or crop model hard-wired into them. Because it is global in nature but specifies New Zealand as a stand-alone region, NZIAMS can be used to estimate the impact on the country's economy of changes in global commodity prices and productivity.

Through illustrative scenarios it is possible to set climate change policy decisions to acquire a better understanding of the effects of that policy on New Zealand. The modelling framework allows researchers to assess a range of policies and scenarios. Examples of policies that can be explored using NZIAMS include: introduction of emissions or offsets trading for agriculture and/or forestry in different countries (Lee et al. 2007); adjusting consumer preferences through marketing aims such as carbon labelling (Saunders et al. 2009a); liberalisation of agricultural trade (Verburg et al. 2009); and imposition of border carbon adjustments (Ballingal et al. 2009). In this report we modelled the impacts of climate change on the agriculture and forestry sector as well as a hypothetical policy that places a carbon tax on energy, industrial, and agricultural GHG emissions.

- Modelling climate impacts exclusively has a very modest effect on outputs and prices within the 50-year analysis presented in this report. The carbon pricing scenarios have a more significant effect on output, prices and emissions relative to the baseline. Not unexpectedly, a carbon tax is estimated to lead to a negative effect on global GDP. The main impact of a carbon tax on the energy sectors alone is a significant reduction in electricity output, and a shift from fossil-based to carbon-free electricity. Modelling suggests such a shift will lead to a large reduction in emissions from the secondary energy sector, relative to the baseline.
- Applying a carbon tax to all sectors produces a larger negative effect on global GDP growth. The main impact is on primary product output, and hence on value-added agricultural output, land-use change, and emissions from this sector. Value-added agricultural sector output is lower, due to a combination of lower demand (due to negative income effects) and the higher cost of inputs from the primary production sectors. The most significant impact of a carbon tax is an estimated reduction in cattle, sheep and goat output from the rest of the world, leading to an increase in output of these products in New Zealand, Australia, and the rest of the OECD.[21] For the model

[21] For details on aggregation see Appendix 3.

assumptions used here,[22] this is predicted to result in relatively higher prices for cattle, sheep and goats and raw milk, a relatively lower output of raw milk, and a change in land use in New Zealand away from raw milk production to cattle, sheep and goat production, relative to the baseline.

[22] The GTAP data have higher GHG emissions associated with producing raw milk than with cattle, sheep and goat production in New Zealand. This higher emissions factor causes raw milk to be more costly to produce with a carbon price and hence there is a shift away from raw milk in New Zealand.

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Appendix 1 – Disaggregation of GTAP electricity sector into carbon-free and fossil electricity shares and baseline forecasts

Coal, oil, gas, petroleum refining, carbon-free electricity and fossil electricity sectors are always defined as separate sectors, as this is required by the model structure. Note that carbon-free and fossil electricity generation sectors have been disaggregated from the single GTAP sector: ‘electricity’. This was done by allocating all fossil fuel inputs to the fossil electricity sector and distributing the remaining outputs in their original proportions, pro-rated to achieve market shares derived from IEA generation data.

The baseline forecasts of the carbon-free and fossil electricity shares were estimated at the individual country-level (for the GTAP Database v7.1 countries) using regional forecasts from 2000 to 2035. Baseline data at the country-level allows flexibility in the regional aggregations used in CliMAT-DGE. To develop the baseline we used existing regional level forecasts of electricity generation using alternative energy sources and fossil fuel supply from the International Energy Agency World Energy Outlooks (2004–2009) (International Energy Agency 2004, 2009; Organisation for Economic Co-operation and Development and International Energy Agency 2007).

To develop country level forecasts, from 2000 to 2035, of electricity generation using renewable, nuclear, hydro, fossil and other energy sources (Table A.1) the following steps were undertaken:

1. Electricity generation by source, *k*, (renewable, hydro, nuclear, fossil and other), E_{ikt0} were estimated from International Atomic Energy Agency (2011); International Energy Agency (2010), along with the total country level electricity generation, E_{it0}. Where base year is $t0$ = 2010 and country level is *i*.
2. Estimated country level total electricity generation, E_{it}, in the forecast year, *t*, from
    a) Country level GDP indices (Fouré et al. 2010) from the base-year Y_{it0} to the forecast year Y_{it},
    b) Base year total country-level electricity generation, E_{it0}
    c) Forecast total regional electricity generation, E_t (International Energy Agency, 2011)

by solving the following optimisation problem for forecast year *t*:

$$\min \left[\sum m \quad (\quad - m \quad) \right] m$$

subject to $\quad \sum m \quad (\quad - \quad) m$

Country-level total electricity generation was then calculated as:

$$(\quad - m \quad) m$$

1. Estimated country level electricity generation by source, E_{ikt}, in the forecast year, t, from
   a) Country-level total electricity generation, E_{it}, in the forecast year
   b) Regional-level electricity generation, E_{kt}, by energy source in the forecast year

by solving the following optimisation problem for forecast year t:

$$\text{in}\left[\sum\left(\text{m}-(\quad-\text{m}\quad)\right)\;(\quad-\sum\quad)\;(\quad-\sum\quad)\right]\text{m}$$

subject to

Additional constraints were added to this optimisation to set country-level electricity generation from nuclear to zero if this was zero in the base year (2010).

An example of the New Zealand forecast electricity generation, by energy source is shown in Figure A.1.

Table 9: World Energy Outlook energy sources and aggregates of sources

Renewable	Hydro	Nuclear	Fossil	Other
Solar photovoltaic	Hydro	Nuclear	Coal	Biomass
Wind	Geothermal		Oil	Waste
			Gas	

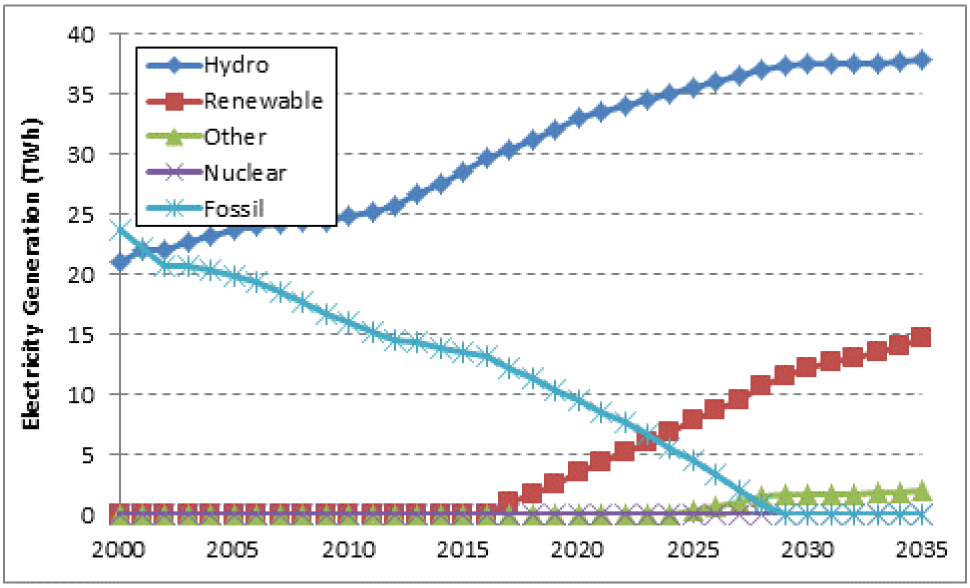

Figure 61: Forecast electricity generation, by source, for New Zealand from 2000 to 2035.

Appendix 2 – NZIAMS Production Function

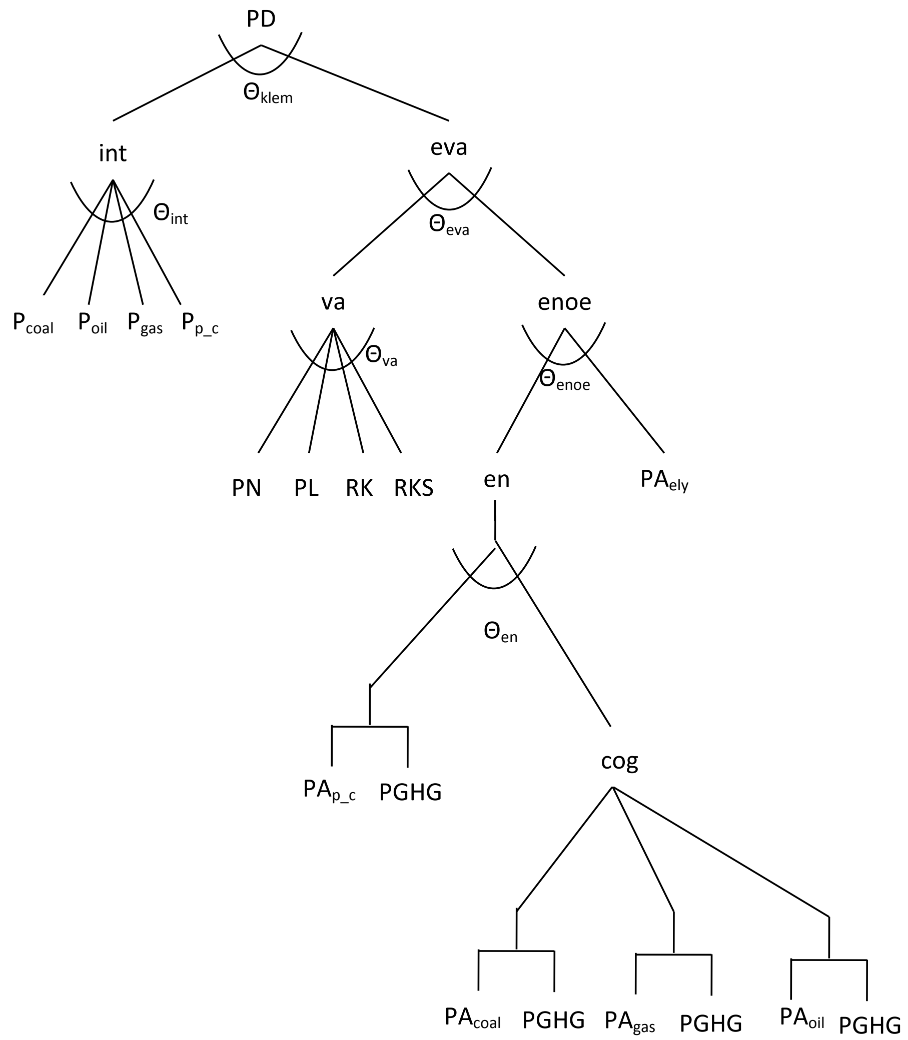

Figure 62: Regular production function.

PD	Price used for outputs	va	Capital and labour
PGHG	Price of GHG	en	Energy
PA	Price used for inputs	enoe	Electricity
P	Price used for intermediate inputs	cog	Coal, oil and gas
PN	Rental rate of land		
PL	Price of effective sectoral labour	p_c	Petroleum products
RK	Rental rate of capital (not sector-specific)	ely	Electricity
RKS	Rental rate of sector- specific capital		
		Θ_{klem}	Elasticity of substitution between capital, labour, energy and intermediates
int	Intermediates		
eva	Energy, capital and labour	Θ	Elasticity of substitution

Appendix 3 – NZIAMS Data and Aggregation

Table 10: NZIAMS Aggregation from GTAP v7.1

NZIAM Regions	GTAP Regions	Notes
NZL	NZL	New Zealand
AUS	AUS	Australia
NAM	USA, MEX, CAN	North America
OECD	JPN, KOR, SGP, CHL, AUT, BEL, CZE, DNK, FIN, FRA, DEU, GRC, HUN, IRL, ITA, LUX, NLD, POL, PRT, SVK, SVN, ESP, SWE, GBR, CHE, NOR, XEF, TUR	Rest of OECD + Singapore, Chile, Turkey, and Korea
ROW		All other regions in GTAP 7
NZIAM Primary Production Sectors	**GTAP Sector**	**Notes**
GRA	PDR, WHT, GRO	Grains including rice
CRO	V_F, OCR	Other crops
OSC	OSD, C_B	Oil seeds and sugar cane
PFB	PFB	Plant based fibres
CTL	CTL, WOL	Bovine cattle, sheep and goats, horses
RMK	RMK	Raw milk
FRD	FRD	Deforestation
FST	FRP	Forests
NZIAM Manufacturing and Value Added Sectors	**GTAP Sector**	**Notes**
FOO	CMT, OMT, VOL, MIL, PCR, SGR, OFD, B_T	Food products
HWP	LUM, PPP,	Harvested wood products
EMT	OMN, CRP, NMM, I_S, NFM, OTP, WTP, ATP	Energy-intensive manufacturing and
NSV	OAP, FSH, TEX, WAP, LEA, FMP, MVH, OTN, ELE, OME, OMF, WTR, CNS, TRD, CMN, OFI, ISR, OBS, ROS, OSG, DWE	Non-energy-intensive manufacturing

Table 11: Primary Sector Yield Impacts in NZIAMS

NZIAMS sector	NZIAMS description	DSSAT and MC1 proxy	Notes
PDR	Paddy rice	rice, irrigated	Rice generally irrigated
WHT	Wheat	wheat, non-irrigated	Unirrigated as default. C3 plant. In some regions, irrigation may be more significant, but choosing unirrigated when there is a mix can be considered the most pessimistic case for impacts.
GRO	Cereal grains not elsewhere classified	maize, non-irrigated	Cereal grains includes maize and it doesn't include wheat, so that is the best proxy available. Un-irrigated is the most pessimistic case for impacts.
V_F	Vegetables, fruit, nuts	nothing (not modelled, no yield change over time)	No proxy
OSD	Oil seeds	maize, non-irrigated	Rapeseed (C3) and oil palm would be most important. Use maize.
C_B	Sugar cane, sugar beet	maize, non-irrigated	Sugar cane is C4.Use maize proxy but concerned the climates will be too different.
PFB	Plant-based fibres	wheat, non-irrigated	This is mainly cotton, C3. Use wheat as proxy.
OCR	Crops not elsewhere classified	nothing (not modelled, no yield change over time)	Includes cash crops but also forages. No proxy.
CTL	Bovine cattle, sheep and goats, horses	wheat (using pasture spatial distribution), non-irrigated	Pasture -> unirrigated wheat
RMK	Raw milk	wheat (using pasture spatial distribution), irrigated	On the grounds that dairy production is likely to be in wetter climates or else be irrigated (mainly in NZ). Wheat because it's a grass.[23]
WOL	Wool, silk-worm cocoons	wheat (using pasture spatial distribution), non-irrigated	By contrast, sheep production is less intensive therefore likely to be unirrigated but often water-constrained.
FST	Production forest (MC1)	forest vegetation carbon	Use MC1 model on forestry

[23] Wheat was used as a proxy for pasture.

Appendix 4 – Centre d'Etudes Porsprectives et d'informations Internationales (CEPII) projections for CliMAT- DGE dynamic baseline (Fouré et al. 2010)

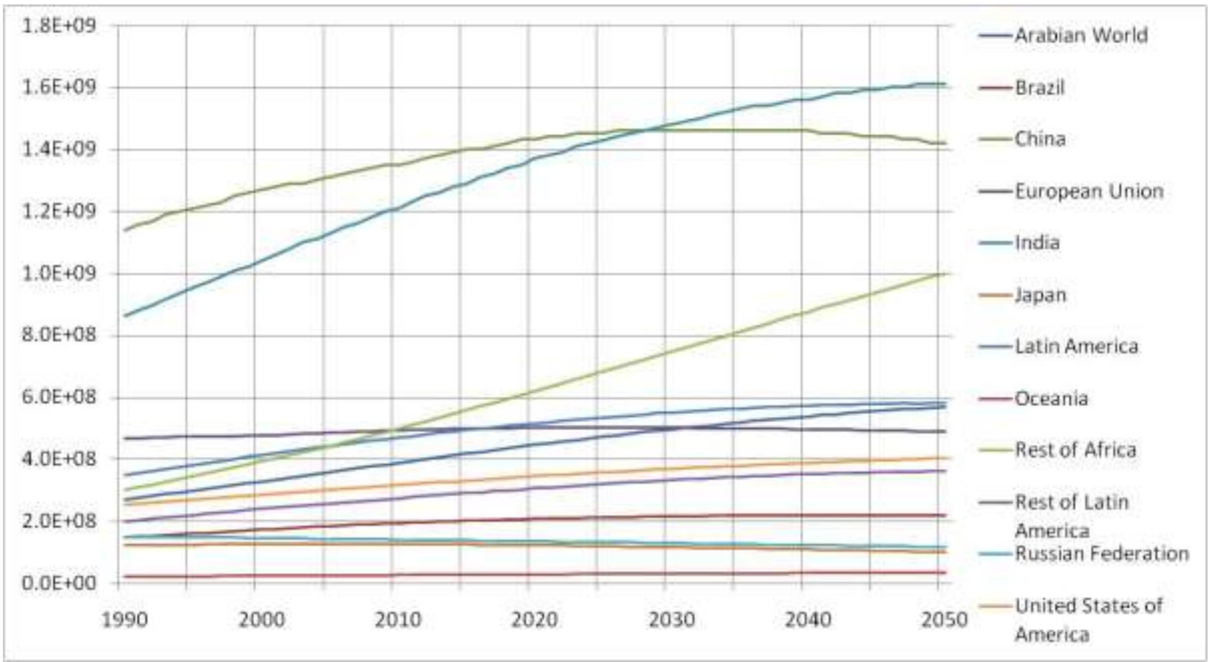

Figure 63: Population projection

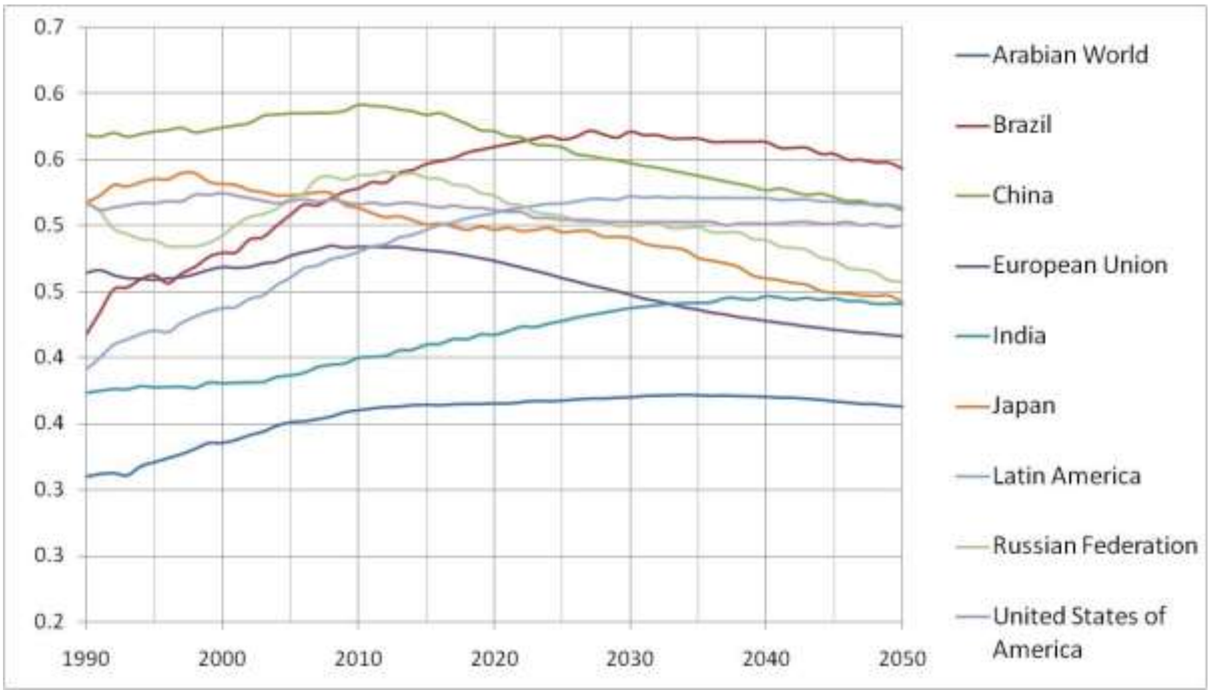

Figure 64: Labour Full Time Equivalents (FTE) per capita

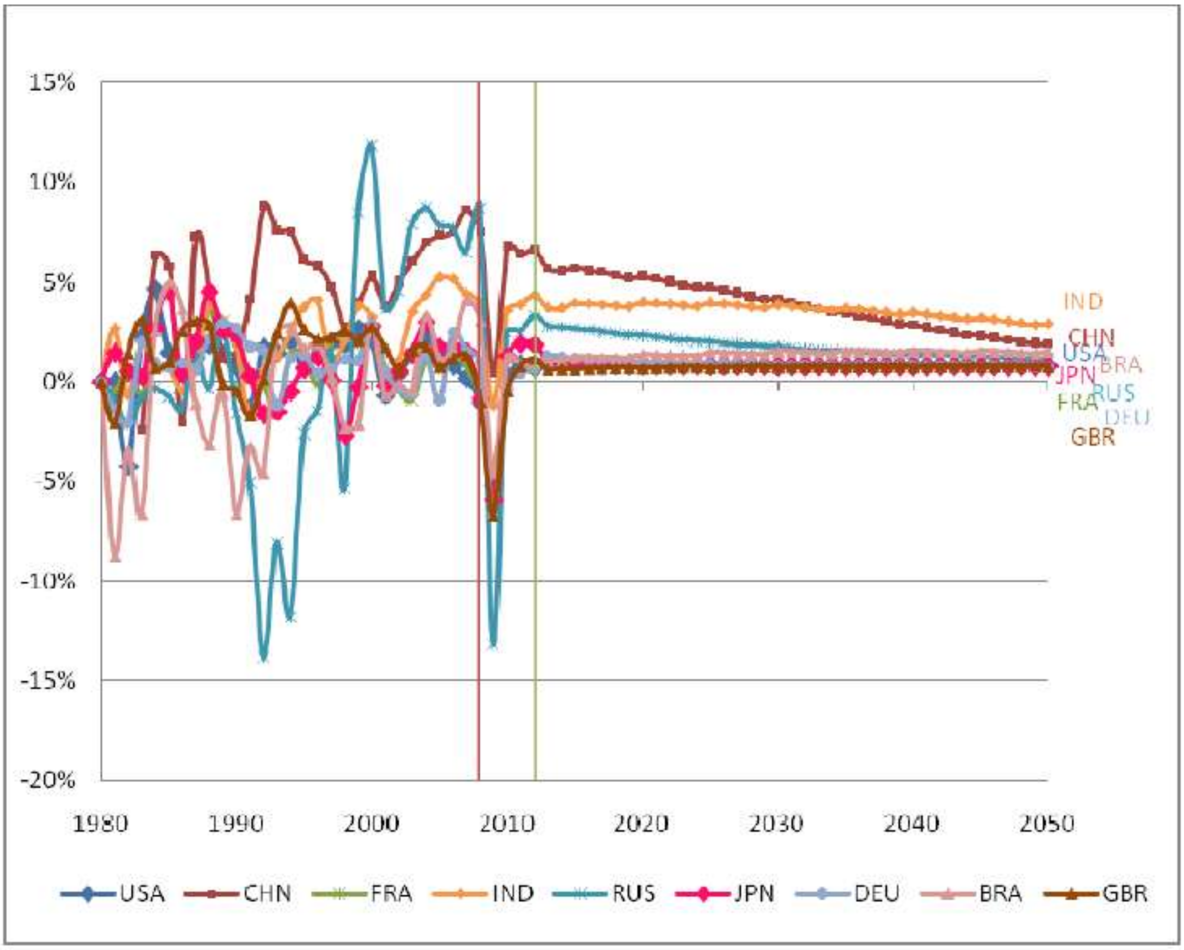

Figure 65: Total Factor Productivity (TFP) growth 1980-2050, % per year.

Appendix 5 – Baseline Estimates for Australia and New Zealand

The following graphs are the baseline estimates for Australia and New Zealand from the NZIAMS.

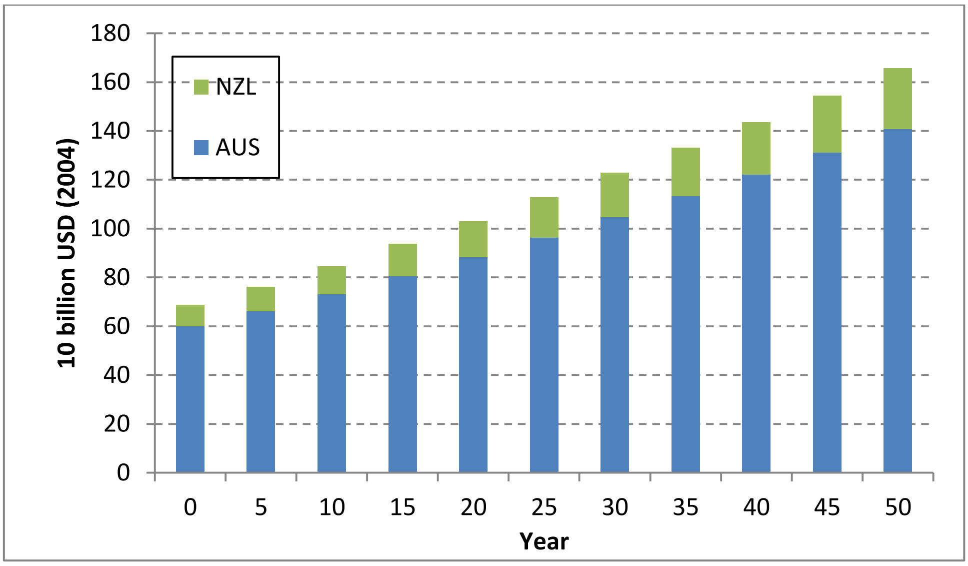

Figure 66: Baseline GDP.

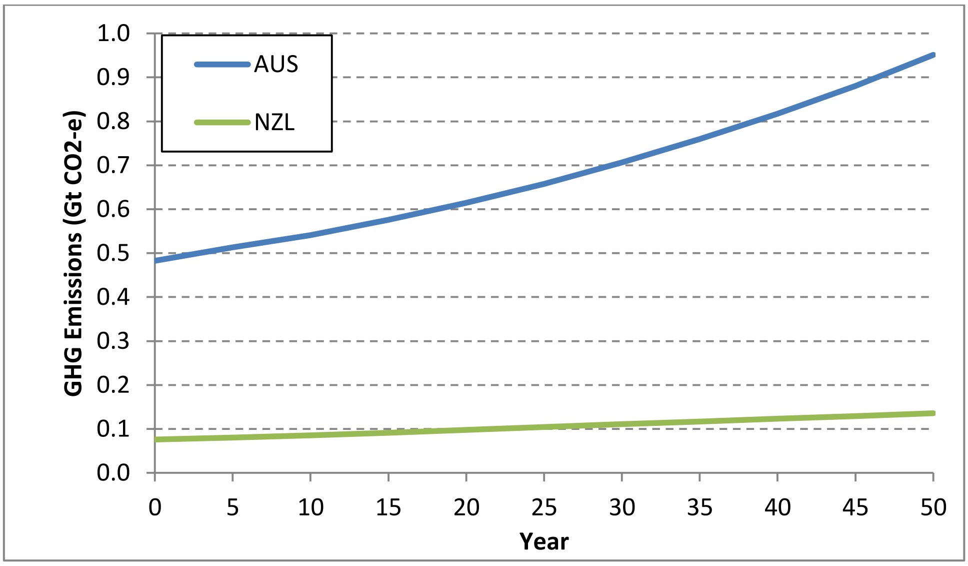

Figure 67: Baseline GHG emissions.

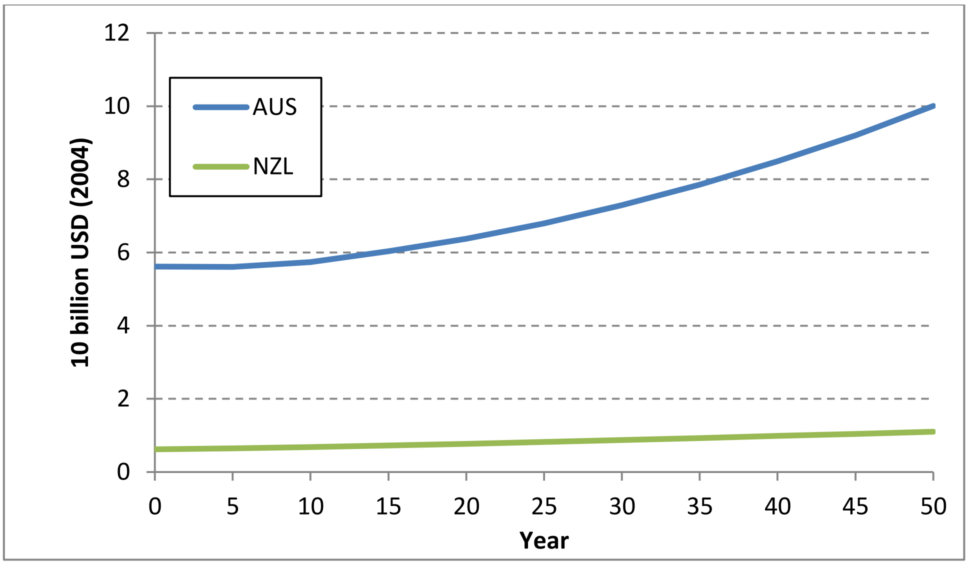

Figure 68: Baseline output in secondary energy sector.

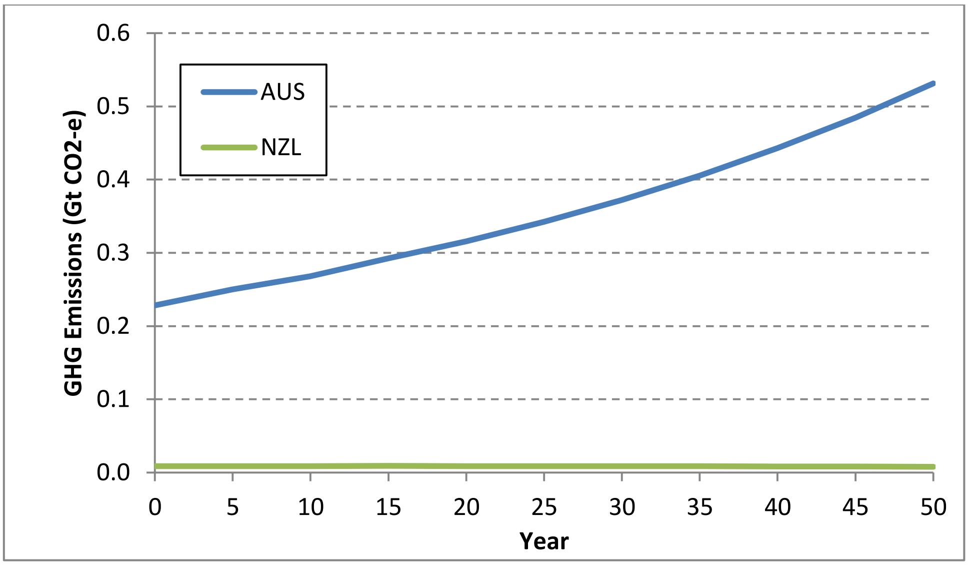

Figure 69: Baseline GHG emissions in secondary energy sector.

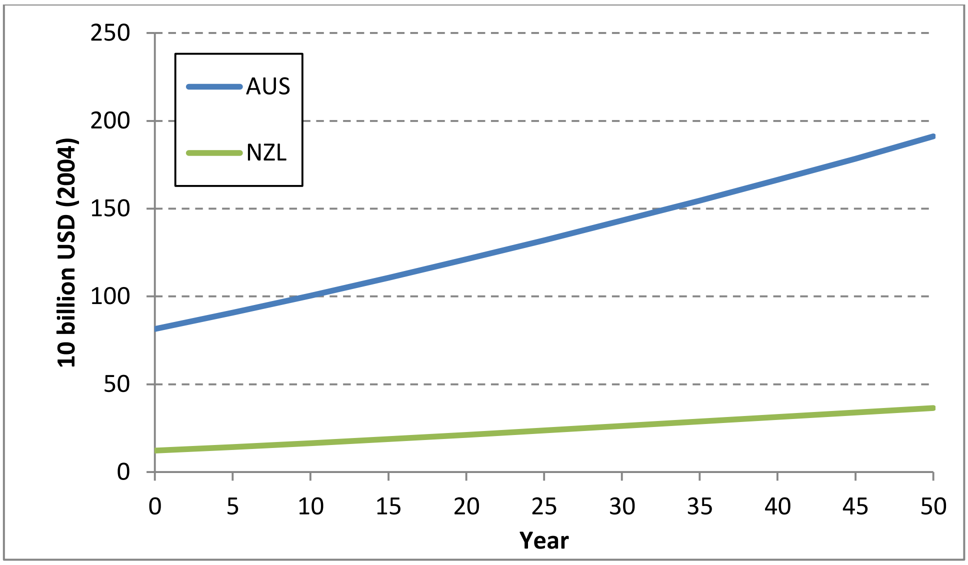

Figure 70: Baseline output in energy-intensive manufacturing.

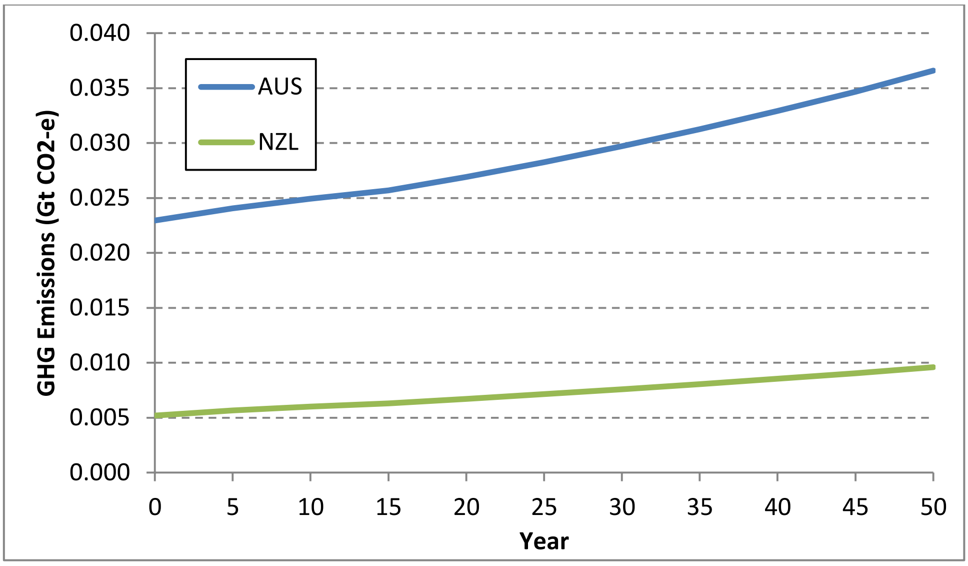

Figure 71: Baseline GHG emissions in energy-intensive manufacturing.

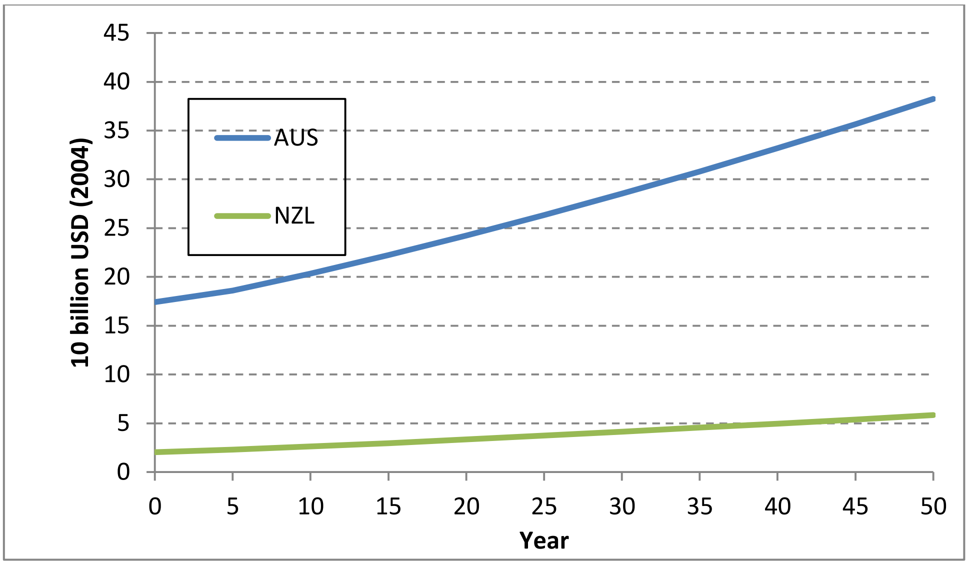

Figure 72: Baseline output in non-energy intensive-manufacturing and services.

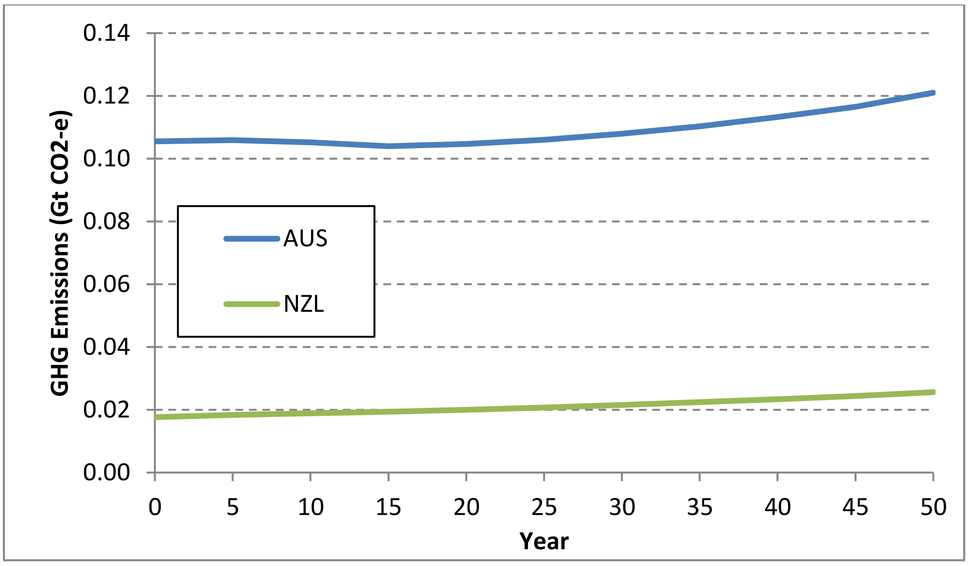

Figure 73: Baseline GHG emissions in non-energy-intensive manufacturing and services.

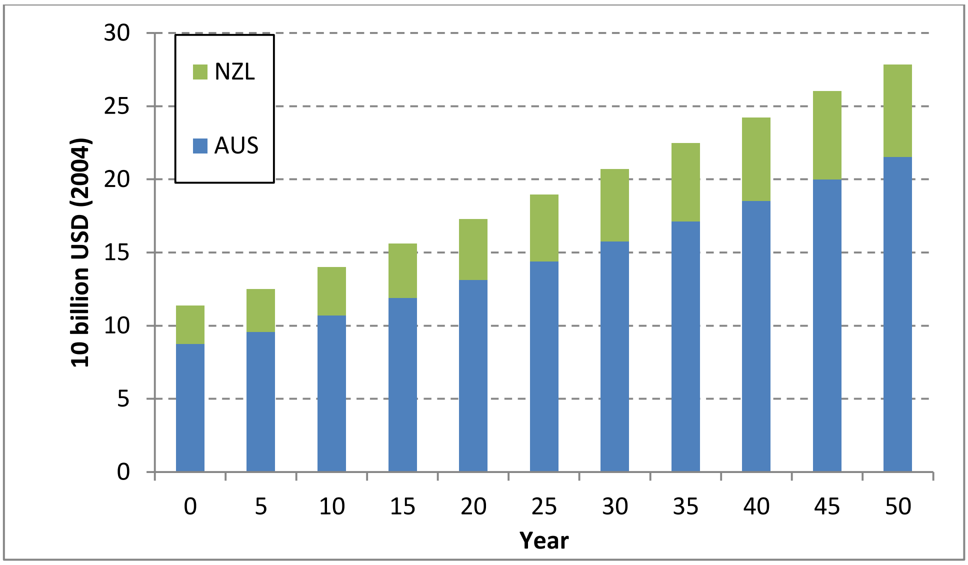

Figure 74: Baseline output in the value-added agriculture sector.

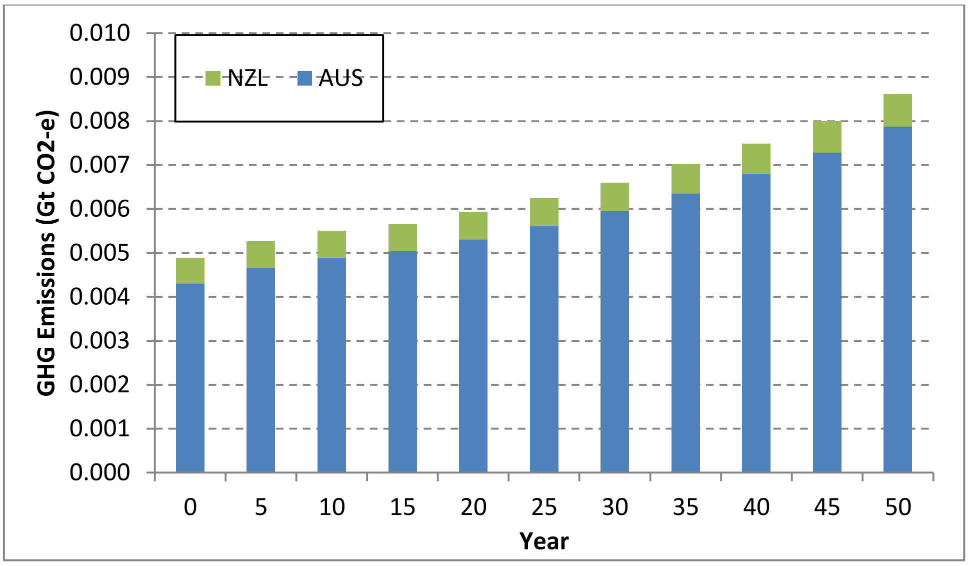

Figure 75: Baseline GHG emissions in the value-added agriculture sector.

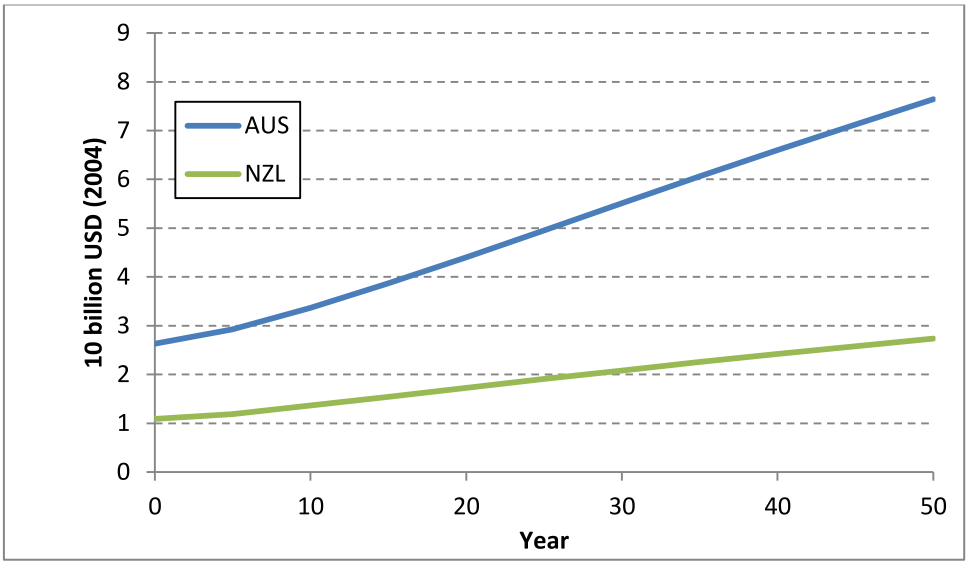

Figure 76: Baseline output in the primary production sector.

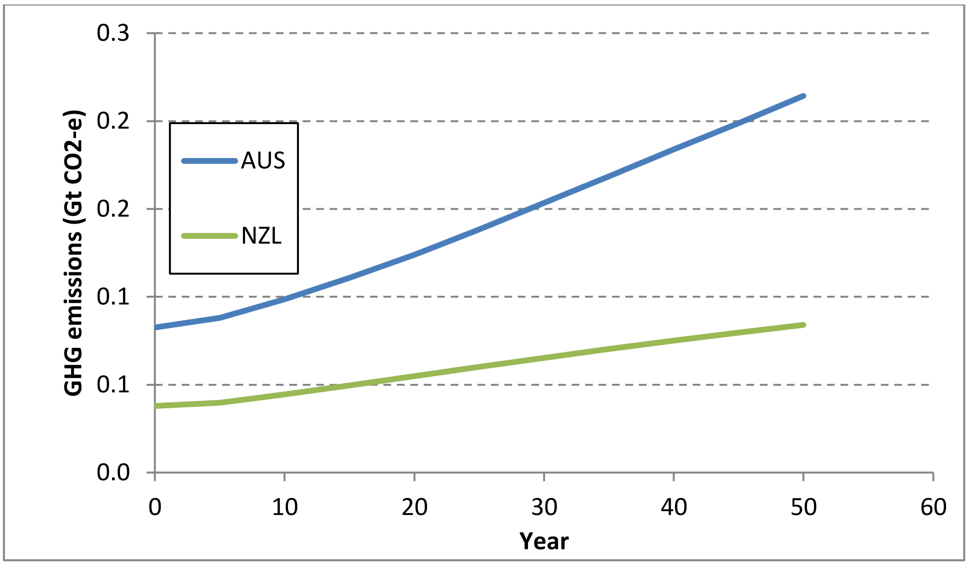

Figure 77: Baseline GHG emissions in the primary production sector.