Long-term modelling of global agricultural markets

A thesis
submitted in partial fulfilment of
the requirements for Degree of
Doctor of Philosophy

at
Lincoln University
by
John T. Saunders

Lincoln University
2021

Abstract of a thesis for the Degree of
Doctor of Philosophy

Long-term modelling of global agricultural markets

by
John T. Saunders

The 20th Century saw declining real food prices. Rising prices and volatility in the 21st century, however, have called this paradigm of declining real food prices into question, increasing concerns about global food security. Additionally, many of the challenges facing global agriculture manifest over a long time horizon such as: land-use change; climate change; and agricultural productivity. There is a need, therefore, to understand the structural changes in agricultural supply and demand underlying these price increases, as well as a need to take into account the current long-term challenges for global agriculture. However, many of the traditional tools used for assessing changes in agricultural markets are focused on the medium- or short-term.

This thesis addresses this gap by examining real price impacts in global agriculture over longer time horizons using a partial-equilibrium modelling framework. This analysis provides informed perspectives on long term relationships in global supply and demand of agricultural commodities in order to assess the impacts of population growth, climate change, and R&D spending on real commodity prices, and thus the long term prospects for agricultural production and food security. Special consideration is given to TFP growth from returns using long-lags in spending on agricultural R&D.

The modelling finds stable or declining agricultural commodity prices over the long-term, with the exception of non-ruminant products, which are expected to rise under most modelled scenarios. TFP supported by investment into agricultural R&D is key to maintaining stable or declining world prices, as well as mitigating emissions from livestock. The modelling also indicates the importance of utilising endogenous measure of productivity growth.

Keywords: Agriculture; Climate Change; Economic Modelling; Food Security; Mathematical Programming; Partial-Equilibrium; Productivity; Total Factor Productivity.

Acknowledgements

I would like to acknowledge all of those who gave their support and assistance during the writing of this thesis. I am greatly indebted to the many people who have assisted me during this process in offering insight, corrections, and encouragement.

To my family and friends for their support and love during this thesis. In particular, MC and Freya (although admittedly Freya was pretty late to the party).

To the AERU whānau (literal or otherwise), for the encouragement and continuing to be the best colleagues and friends I could ask for.

To my supervisors Paul Dalziel and Anita Wreford for, showing me proper grammar and being tireless in their efforts to help me get this work over the line.

To Caroline Saunders for reading through many drafts and keeping me in touch with applied agricultural management.

To Jonathan Brooks for inviting me to the OECD to start this work, and for his and Marcel Adenauer's guidance and support during the development of the LAO model. Additionally, to everyone at TAD/ATM for the support, insight, assistance, and muffaans.

To Martin Von Lampe for being present and engaged during early discussion on the formation of the model, and for bailing me out on some difficult questions.

To Thomas Hertel who was incredibly forthcoming with materials and information on the SIMPLE model at the inception of this work, and Uris Baldos whose work with Thomas Hertel on the SIMPLE model formed the inspiration for this work.

To Tiffany, Simon, and Leonie for shared pain, and coffee during their own PhD's.

To Tim for music chat about what's really important.

And finally, to the music video for the David Bowie song 'Blue Jean' for getting me through the hardest times.

Abbreviations

AgMIP	Agricultural Model Intercomparison and Improvement Project
CE	circular economy
CGE	computable general equilibrium models
CGIAR	Consultative Group on International Agricultural Research
CO2	Carbon Dioxide
EF	Emissions Factor
ETS	Emissions Trading Scheme
EU	European Union
FAO	Food and Agriculture Organizations of the United Nations
GDP	Gross Domestic Product
GE	general equilibrium
GHG	Greenhouse gas
GLOBIOM	The Global Biosphere Management Model
GTAP	Global Trade Analysis Project
IAM	Integrated Assessment Models
IFPRI	International Food Policy Research Institute
ILO	International Labour Organization
IMAGE	Integrated Model to Assess the Global Environment
IMPACT	International Model for Policy Analysis of Agricultural Commodities
IPCC	Intergovernmental Panel on Climate Change
LAO	Long-term Agricultural Outlook [model]
LTEM	Lincoln Trade and Environment Model
MAGNET	Modular Applied General Equilibrium Tool
mil	million
OECD	Organisation for Economic Co-operation and Development
PE	partial equilibrium
R&D	research and development
RCP	Representative Concentration Pathways
RTAs	Regional Trade Agreements
SIMPLE	Simplified International Model of Agricultural Prices, Land use and the Environment
SDG	Sustainable Development Goals
SSE	sum of squared errors
SSPS	Shared Socio-economic Pathways
SWOPSIM	Static World Policy Simulation Model
t	tonnes
TFP	Total Factor Productivity
UN	United Nations
US	United States of America
UNDESA	United Nations, Department of Economic and Social Affairs, Population Division
WTO	World Trade Organisation

IP Usage

The intellectual property for the LAO model is owned by the OECD, used under license by Lincoln University for teaching and research purposes.

Table of Contents

List of Tables

List of Figures

1. Introduction

There have always been concerns over whether there is sufficient food to feed the human population either regionally or globally, and they have taken many forms. Famously, in 1798 Malthus suggested that increases in living standards would lead to greater population growth, creating a cycle of boom and bust in which famine and food scarcity were certain (Malthus, 1798). Furthermore, Malthus also conjectured that the growth of human population was inexorable and would exceed the growth of the productive capacity of our agricultural lands, thus rendering food scarcity inevitable.

These suppositions proved to be false. The industrial revolution brought hitherto unimagined productivity growth across many industries, including agriculture, which continued to grow at rates beyond Malthus' expectations. Birth rates have proved to be varied rather than interminable, with higher income countries experiencing declining birth rates.

While Malthus' particular arguments are no longer consequential, the central concern of his thesis remains relevant. Is humanity's capacity for consumption greater than the biosphere's capacity for production? In particular, is the potential demand of agricultural goods in excess of the potential supply, which will lead to increasing food prices?

Currently global agricultural food systems are facing many challenges which are intensifying or manifesting over a longer time horizon than is usually considered using the tools of economic policy analysis. These challenges include population growth, income growth, environmental pressures, and climate change.

In terms of demand for food, the United Nation's medium fertility variant projections of total population shows global population stabilising around 11 billion people at the end of this century, with most regions expected to have declining populations within this century (UNDESA, 2019a). Additionally, global incomes are expected to rise, which will increase demand for food and modify the demand for food (such as a shift towards richer, high protein food stuffs) in current and future populations (Alexandratos, 2005; FAO, 2017).

The contribution of yield growth to higher total crop production has increased, and further, of the components of yield growth, global growth in total factor productivity has been most instrumental in maintaining low food prices (FAOSTAT, 2021; Hertel, 2014a). Yield growth rates, however, have been declining since the 1990s partially due to a lack of investment in agricultural research and development (Alston, Beddow & Pardey, 2009; Grassini et al., 2013). Some regions are failing to realise yields comparable to those in similar regions (FAO, 2008). Furthermore, increases in intensity may lead to the degradation of environmental goods and the yield potential of agricultural land (Licker et al., 2010).

Climate change is also likely to have severe impacts on many facets of global agriculture potential. Likely impacts will include altered crop growing periods, incidence of pests and diseases, desertification of agricultural lands, location of suitable growing areas, water scarcity and reduced labour productivity (Bosello, Eboli & Pierfederici, 2012; FAO, 2018). Several studies project decreases in crop yields under the intensifying effects of climate change (Delink et al., 2019; Havlik, 2015; O'Neill et al., 2017; Rosenweig et al., 2014). Hence Malthus' central concern may be more relevant today. Over the next 80 years, the world will potentially experience the onset of impacts from climate change on our food systems, simultaneously with the peak of human population. Already, the general trend of declining global food prices within the last century have been challenged by price spikes in 2007-2008 and 2010-2011. Therefore, understanding the productive capability and potential for growth in productivity of global food systems will be key in assessing the underlying trends in food prices and to inform the potential outcomes for global agriculture.

Economic models have been used to address issues concerning the balance of supply and demand in agriculture. However, they are often concerned with short to medium term timeframes. Climate and integrated assessment models do assess developments in agriculture over a longer time period but are not pure economic models and often incorporate economic theory as a secondary focus. Thus, there a gap in the literature of economic models with a long-term focus, as well as those with an integrated function for productivity

One approach for addressing this methodological gap was presented by Baldos and Hertel (2012), in the SIMPLE model, a partial equilibrium model which utilised a highly aggregated regional and commodity coverage, more suited to performing long-term analysis in an economic modelling framework. This thesis builds on this approach put forward by Baldos and Hertel to develop a novel long term economic model (see also Saunders, Adenauer & Brooks, 2019). The aim of this model is to assess the implications for global agricultural markets given the key factors of agricultural supply and demand, drawing on the body of previous literature in the field of agricultural economics. The model contributes to the literature by providing a novel inclusion of animal products with a net trade approach in this style of model and a focus on the development of total factor productivity resulting from investments into agricultural research and development and a novel inclusion of animal products within this research and development framework, hitherto excluded from measures of endogenous productivity.

1.1 Outline of thesis

Chapter two outlines the background and context of this thesis. This includes a discussion of the history of thinking around these challenges brought on by population growth, income growth, trends in real prices of food and changing environmental and climatic profiles, and the previous methodologies used to consider their impacts on global food security and agricultural production. This includes the impact of climate change in particular, as it will be a significant driver of change in agriculture over the long term.

Chapter three summarises the relevant literature on economic modelling approaches and the key drivers in supply and demand. Particular attention is given to the theories concerning agricultural production and the growth of total factor productivity in agriculture, due to their importance to the novel contributions proposed in this body of research. This discussion covers general equilibrium and partial equilibrium models, including notable examples of these models and their usages in applied research.

The fourth chapter presents the research aims and objectives. Identifying gaprs in knowledge from the literature, and outlining the overall aims of the research and three specific research objectives.

The fifth chapter describes the methodological approach adopted from a range of alternatives to address the aim and research objectives put forward in section 4.2. It draws on the literature review, and explains the case for developing a novel model as the most suitable approach and also outlines the range of scenarios to be used within the model in order to illustrate the key developments in agriculture over the long-term.

The sixth chapter details the scenario analysis that was examined using the model. Nineteen scenarios are presented alongside the component sources from macro-economic and exogenous data used to construct them, primarily projections of GDP, TFP and population.

The seventh chapter presents the results from the model across the 19 scenarios. The model variables relevant to each tested scenario are presented, these include world price, total production and demand by use type. Most scenario results are centered on the developments of world prices for comodities over the modelled period (2012-2050). Some analysis of the results is presented alongside the figures.

Chapter eight contains the discussion of the results from Chapter seven, which provides some wider context and relevance of the models findings and implications across the academic, industry and policy contexts. The projection of agricultural world prices are stable or declining for crops and ruminant products, and rising for fish and non-ruminant products. Continued growth in agricultural total factor productivity is key in restraining growth in real agricultural prices, and the potential income growth in South Asia is a key driver of uncertainty in the model’s results.

The final chapter will show how the model’s findings address the research objectives, and thus the overall research aim of the thesis. The limitations of this research, and possibilities for future research endeavours are also included in this chapter.

2. Background: History of Supply and Demand in Agricultural Markets

2.1 Introduction

In order to understand the dynamics of agricultural supply and demand which feed into global food security, it is important to understand the history of developments in the key drivers of supply and demand. This chapter provides this historic context around the issue of food security in relation to agricultural markets by describing how population growth and demand has changed over time compared with developments in agricultural production. This is also framed with the context of contemporaneous thought on food security and the development of agriculture.

Outside of the main drivers of supply and demand, the development over time of real food prices and causes for historic variability is presented, highlighting the distinction between structural change and short-term volatility.

This chapter also discusses more contemporary challenges for agriculture, which may impact upon food security and food prices into the future, such as climate change. Finally, the chapter also includes a summary of the role economic modelling has filled in evaluating and understanding these market dynamics and their implications into the future.

2.2 Population Growth and Demand

Concerns over the planet's bio-physical ability to provide enough food for a growing human population has been a concern for centuries. Malthus famously framed the problem in his 1798 work: *An essay on the Principle of Population (1798)*: If agricultural production increases arithmetically (linearly), while population increases geometrically (exponentially), then the latter will eventually outstrip the pace of growth of the former. Ultimately Malthus' argument was centered largely on the dynamics of population, and was less concerned with the potential for agricultural production, but the idea of imbalance in global food security took root and has been expressed in various forms ever since.

Ricardo advanced Malthus' proposition with the idea that the growth in agricultural production will be limited by the increasing volume and quantity of inputs required to uphold the same level of yields on each additional parcel of land, and this will utimately outweigh the level and value of ouputs provided by that additional piece of land, that is diminishing marginal returns. This view represents 'Ricardian scarcity', where the increasing costs of production limit the feasibility of expansion, rather than any particular input becoming wholly exhausted (known as 'Malthusian scarcity') (Barbier, 1989). This view however, does not take into account the possibility of returns to scale, increased quality of inputs or enhancements in technology or institutions which could add to the productive potential of land. Therefore the Ricardian limit to agricultural productive potential is not self-evident (Barnett & Morse, 1963).

Malthus saw technology as essentially unchanging (Barnett & Morse, 1963) and thus not a compensating factor able to promote agricultural productivity against the growth of population. However while flawed, these arguments gained traction historically and have become frameworks for thinking around resource-scarcity and usage. Mills stated that contrary to Ricardo's theory of diminishing returns for growth (associated with agricutural land-use), the highest quality agricultural lands are not used initially, thus yields may be maintained by using additional land. Furthermore Mills thought the additional gains from development in society (technological growth) came at a diminishing cost, that each new technology would promote further discoveries. However even considering this insight, Mills did not think that this benefit from technology could ultimately alter the progression of the Malthusian and Ricardian scarcity in natural resources, that instead technological growth would merely postpone reaching these limits (Barnett & Morse, 1963).

As with technological growth, stocks of knowledge were historically thought to be relatively static. Marshall believed in diminishing returns on improvements; that perhaps technological advancements were a limited resource (Barnett & Morse, 1963). Myrdal, similarly to Mills, called the proliferation of technological progress a "principle of circular and cumulative causation." Advancements lend themselves to further advancements. Marshall deemed that economic growth in production would not be limited by the declining quality of land due to the increased production from organisations (Barbier, 1989).

The views on the potential of technological and institutional growth to accelerate progress began to strengthen. The new belief is summarised by Barnett and Morse, who recognise the importance of knowledge and institutional capitals as a means of offsetting diminishing returns to production.

> What we are saying is exceedingly simple: our debt to future generations will be discharged to the extent that we maintain a high rate of quantitative and qualitative progress… the heritage of knowledge, equipment, and economic institutions that the industrial nations are able to transmit to future generations is sufficient to overcome the potentially adverse effecs of continual and unavoidable shift to natural resources with properties which, on the basis of past technologies and products, would have been economically inferior. The industrial nations have learned, in short, how to maintain technological progress, to avoid quantitative diminishing returns. An open question is whether they have also learned how to maintain social progress, to continue improving the quality of life, to avoid qualitative diminishing returns.
>
> - Barnett & Morse (1963, p. 250)

Engaging with these historical viewpoints today, first we can address Malthus' original assumption that population growth is geometric. Of course in many developed nations there are declining populations, as birth rates stabilise. Here Malthus assumed population growth rates to be growing continuously, rather than in a non-linear fashion, as they truly are. Birth rates are linked to income levels, but also the extent to which improvements in liveihood are experienced, with *per capita* gross national income (GNI), being a secondary predictor of birth rates to other social indicators, such as education, employment, equitable income distribution , and infant mortality (Meadows, Randers & Meadows, 2005). These relationships are in part due to children being one viable source of investment for a family with few other investment or income potentials.As children can provide income streams or additional family labour, this relationship can be summed up colloquially by the phrase "the rich get richer, the poor get children!" (Meadows, Randers & Meadows, 2005).

World population is expected to stabilise at around 11 billion people before the end of the century (medium variant) (UNDESA, 2019a). Most major regions are expected to experience population decline before 2100, with most additional population growth and uncertanty hinging on Sub-Saharan Africa, whose population is projected to more than triple over the next 80 years. While life expectancies are increasing worldwide (even with significant, and worrying gaps between regions) fertility and birth-rates are decreasing leading to an overall reduction in projected populations.

Then if we are primarily concerned with the burden brought on by total population, we expect the foreseeable peak of human population to occur within the next 80 years. Thus potentially the highest stress point off all periods of the anthropocine brought on by the burden of population will occur this century. This then is the key consideration on the demand-side of the problem, understanding the quantity of foodstuffs needed to provide for this peak of global population. The supply-side of this issue then relates to the capacity and capability of world agriculture to produce sufficent food, and at what cost.

The implications of population growth for food demand are also key to understanding the prospects for food security. Alexadratos (2005) suggests that the stabilising of global population does not dispell concerns about population growth outstripping agricultural growth as some countries which currently experience inadequate nutrition and difficulties with food supply are predicted to have large population increases. Most of these countries also have little material wealth, poor economic development prospects, and inadequate potential for their agricultural development. This implies a further need for food imports. However Alexandratos raises concerns that there is low potential for the expansion of export markets for some possible cash crops in these countries such as coffee or cocoa due to already saturated demand in industrial countries with stagnant population growth. Rising global incomes will lessen some of the issues related to access to food. However, Alexandratos (2005) cautions that income growth alone does not necessrily translate to significant benefits in the availability of food. Interstingly, population growth is also a component world economic growth, contributing 0.8 per cent of total annual growth over the long run (Peterson, 2017).

Alexadratos and Bruinsma (2012) in their assessment of world agriculture in 2030 and 2050, make the point that global food production does not have to necessarily meet the growth of world population growth. The disparity in per-capita consumption varies greatly between regions and between commodity types. Thus a population increase in a low-income region will have a very different impact on the aggregate demand for food, than an increase in a high-income region.

Likewise the composition of diets has changed in relation to income and other factors. Per capita demand for animal products in China, Brazil, Korea, Malaysia, and Saudi Arabia has increased rapidly since the 1980s (Alexandratos & Bruinsma, 2012). Urbanisation also influencesconsumption patterns (FAO, 2017). Changing preferences and regional differences in demand for foodstuffs will also influence the trajectory of future global demand for food.

2.3 Agricultural Productivity and Supply

Generally, agricultural productivity has improved significantly over the past two centuries. This has been driven by advancements in agricultural technologies and production methods, greatly increasing the production potential of agriculture. Between 1700-1900 production began increasing in Europe as less arable land was left in fallow. This was a result of three-field rotations, and the use of root vegetables and legumes in crop rotation for nitrogeon fixing in arable soils (Griggs, 1992). Elsewhere, arable land expansion in America and Russia also contributed to growing agricultural production.

In the 20th century, however, growth in western agriculture came predominantely in the form of yield improvements rather than the expansion of agricultural lands. The rise of intensive production systems replaced many mixed farming systems mid way through the 20th century: chemical fertiliser use increased dramatically after the second world war (7 times between 1950 and 1980), the use of herbicides reduced the need for tillage, and pesticides reduced the time spent managing crops (Griggs, 1992). The beginning of mechanisation in agriculture had occurred earlier with the invention of the tractor in 1892, the automated reaper in 1820, and the combine harvester in the 1840s. The uptake of these technologies grew in the 20th century, and in particular with labour shortages in World War Two. Nevertheless, in the 1950s, horses and oxen still accounted for 85 per cent of draught power on European farms (Griggs, 1992).The post-war period was characterised with other nations catching up to the high levels of productivity[1] achieved by the United States before a slow down due to the 1966 financial crisis (Kendrick, 1973; Bergeaud, Cette, Lecat, 2015). In terms of agriculture the period is notable for an increase in the use of material inputs[2] and the increase in the quality of traditional inputs (Alston et al., 2012). Public R&D in agriculture grew from this period, from $5.4 billion (PPP) worldwide in 1960, to $33.7 billion in 2009. With the US accounting for 21 per cent of this spending in 1960, to 13 percent in 2009 (Pardey, Alston & Chan-Kang, 2013).

Several other factors contributed to the overall growth of agricultural productivity. Griggs (1992) describes factors in Europe such as: the advent of cheaper freight transportation, which reduced the cost of inputs; the consolidation of parcels of agricultural lands; an abundance of cheap farm labour due to a population boom following the industrial revolution; and advancements in seed hybridisation, selection, export, and production.

In other parts of the world, changes in agricultural productivity were more uneven. US agricultural productivity grew during the 20th century alongside European developments, even eclipsing the per worker productivity of European agricutural production with the emergence of factory farming and high rates of land to labour ratios (O'Brien and De La Escosura, 1992). Key yield improvements for cereals across South America and Asia (India in particular) came in the last century with the uptake of cross-breeding and high yielding cereal varieties, predominantly following the 1960s Green Revolution and development of high yield dwarf wheat (Briggs, 2009; Lobell, Cassman & Field, 2009). The Green Revolution also saw the rise of input intensive and irrigated agriculture spreading across the globe. Although there are criticisms of the social and environmental impacts of high intensity agriculture (Glaeser, 2011), the increases in global agricultural output reduced concerns about food security in many vulnerable regions such as India, following food shortages between the 1950s and 1960s. The effects of the Green Revolution, however, were felt less in Africa where rice and wheat, which saw the greatest gains in yield, were less predominate staples (compared with cassava, maize,

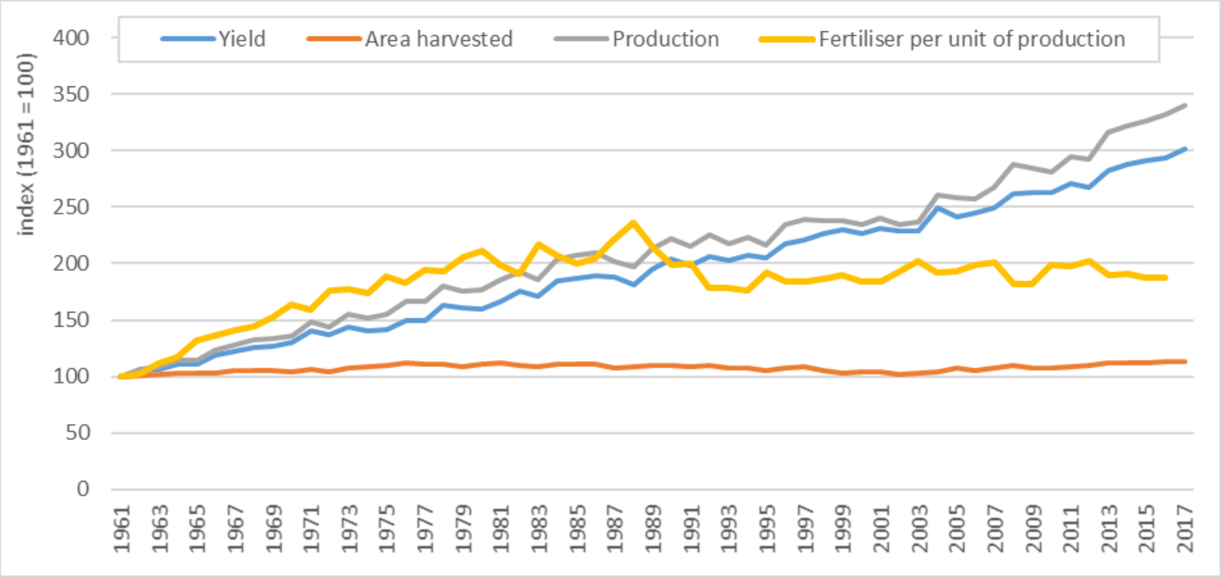
---

[1] Across all sectors of the economy, not specifically agriculture.

[2] Partly due to the decrease in the cost of producing ammonia fertiliser, and high returns on pesiticide use (Gardner, 2002).

sorghum and millet) and most agricultural systems were rain-fed, rather than irrigated, which was a key input for the succes of the high yielding varieties. Agricultural productivity in China grew principally after the implimentation of the household responsibility system in 1978. Agricultural Total Factor Productivity (TFP) accounted for over 50 per cent of total agricultural growth in China between 1961 and 2013, with the switch between largely labor-intensive production to more capital driven production occuring between the 1980-1990, then again from 2003-2013 (Sheng, Song & Yi, 2017).

Figure 1: Production and composition of growth in global cereals, 1961-2017



Source: FAO (2021)

Overall since 1961 yield growth has become the predominant contributor to the growth in global crop production. This is illustrated in Figure 1 by the relative growth in area harvested and yields for cereals worldwide. Furthermore an increase in inputs is not necessarily responsible for this increase[3], evidenced in part by the decline in relative volume of fertiliser use by unit of output in the late 1980s[4].

2.4 Trends in Food Prices

Real food prices have steadily declined over the 20th century partly as a consequence of increasing crops yields and production (albeit with large spikes due to wars, weather events, and other significant events). Figure 2 illustrates this trend in real prices for maize in the United States, showing

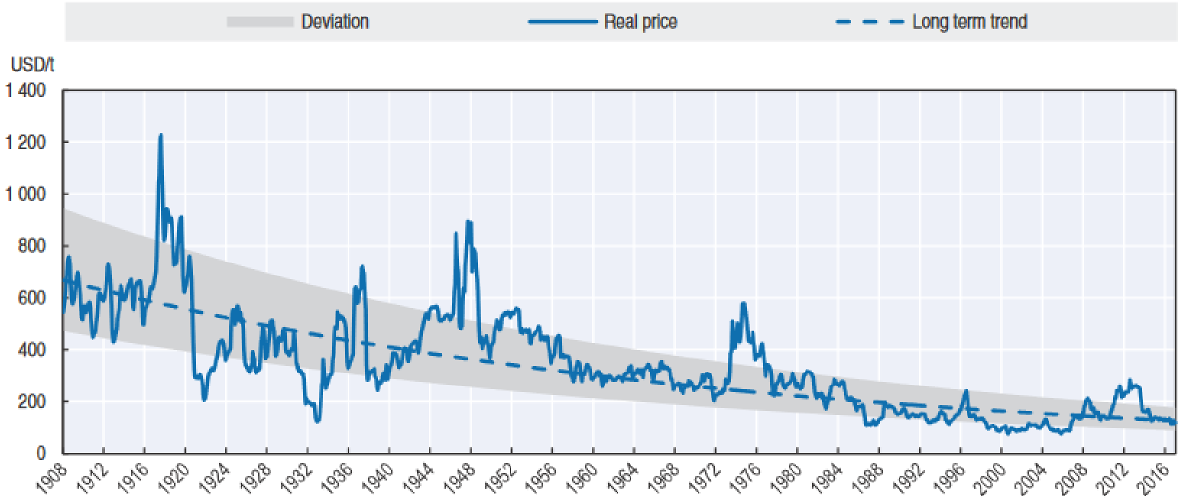
---

[3] Global statistics on agricultural labour and capital since 1960 are less readily available. ILO statistics for agricultural workers show a modest 8% increase between 1991 and 2003, before decreasing to -10% from 1991 levels in 2018 (WTO, 2022). Gross Fixed Capital Formation for agriculture, forestry and fishing increases between 1995 and 2020 over 112% (FAOSTAT,2022).

[4] Nitrogen prices had spike in the 1970s due to the energy crisis, but overall decreased by 28% in real terms between 1960 and 1980 (Gardner, 2002).

significant spikes in prices associated with two world wars (1914-18; 1939-45), the OPEC oil crisis in 1973 and economic crashes such as the great depression in the 1930s, but overall experiencing a downwards long-term trend. Other factors such as China's increasing importance as a global producer of maize, may also influence the decrease in prices.

Figure 2: US Real prices for maize 1908-2016

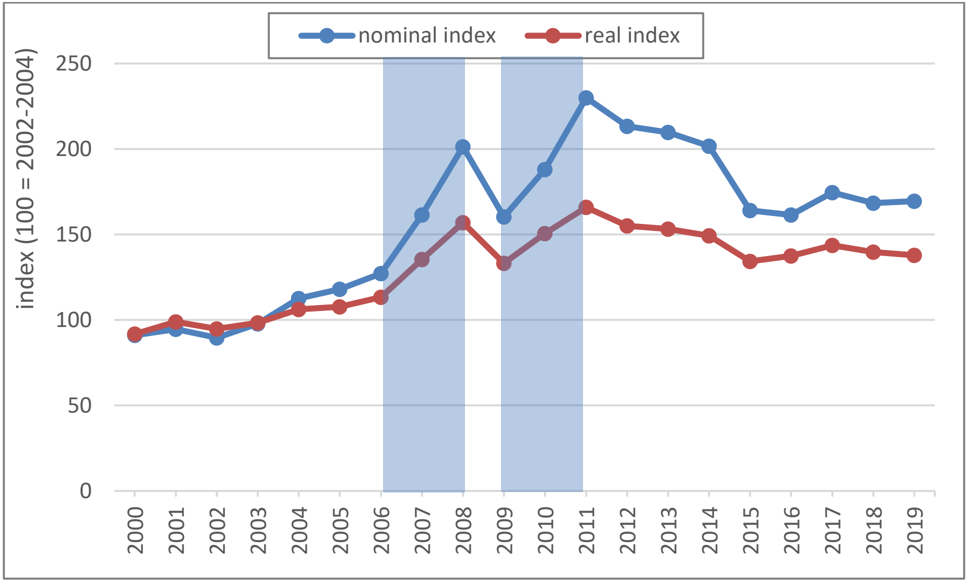


Source: OECD-FAO (2017)

Building upon this observed long term trend of declining food prices, IFPRIs International Model for Policy Analysis of Agricultural Commodities (IMPACT) Delgado, Rosegrant and Meijer (2001) projected declining real prices for milk (12 per cent), meats (4-7 per cent), rice (21 per cent, and wheat (13 per cent) between 1996-1998 and 2020. This showed their was an expectation around the turn of the century, that real food prices were expected to continue to fall.

However this idea was challenged by two price spikes, the first in 2007-2008 and another in 2010-2011. Illustrated in Figure 3, the FAO's index of food prices shows the two food price. Real food prices increasd by 38 per cent in 2007 to 2008, then again by 25 per cent over two years by 2011. These spikes in prices called into question the likelihood of declining real food prices over the long term, causing The Economist to lead with a cover title 'The end of cheap food' in 2007 (Economist, Dec. 8th).

Figure 3: FAO food price index 2000-2019



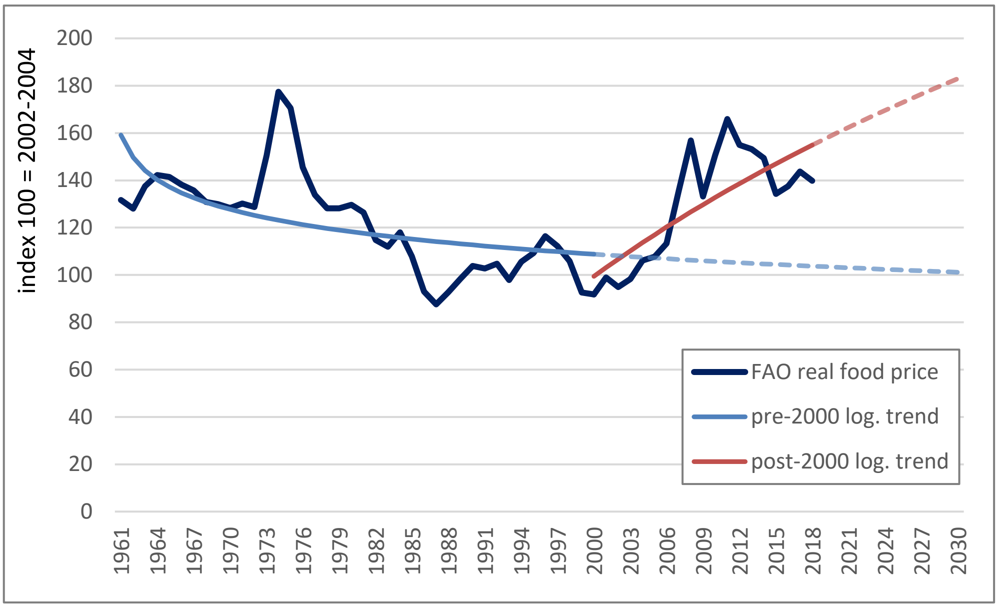
Source: FAO (2019a)

A number of converging factors led to the food price spikes in 2007-2008: increased demand for feedstocks for biofuels (maize in particular), increasing demand for animal products also putting pressure on feedstocks; high oil prices; volatility in cereal markets, exacerbated by an increase in speculation on agricultural commodity markets; and historically low stock levels in cereals (FAO, 2009).

The later spike in food prices between 2010-2011 was caused by extreme weather events in Eastern Europe and Pakistan. A heatwave across Europe decreased cereal yields, with particularly strong impacts on Russia’s production, where total grain harvested decreased 33 per cent from the previous year (Wegren, 2011) .This in turn led to Russia banning food exports, further tightening global agricultural markets (Barriopedro et al 2011; Watanabe et al 2013). Flooding in Pakistan also put increased pressure on global food systems (Mann et al., 2017). The severity of the price spikes was also exacerbated by speculation in agricultural commodities (Spratt, 2013).

Global food prices are not an adequate measure of food security, but in general give an account of the relative interplay of global supply and global demand. Thus while declining real food prices do not imply that sufficient food is getting to those who need it most, it does indicate that food is becoming more affordable in general. Likewise, increasing or volatile overall food prices are a cause for concern as the relative availability and affordability of food will impact upon the world’s poorest and indicate a rise in global hunger. Rising food prices can also cause poor households to purchase more staple foods for their high caloric content, which can compromise their intake of proteins and nutrients (FAO, 2018).

Figure 4: FAO food price index 1961-2019 with logarithmic projections to 2030



NB: dotted lines represent logrithmic projections beyond the years informing the projections
Source: FAO (2019a)

Comparing the trajectory of real food prices from the 20th century to 21st centuries (presented in Figure 4), a logarithmic trend of food prices (shown in blue) preceeding the year 2000 suggests steadily declining real prices for food, whereas after the year 2000 a similar trend (shown in red) suggests the opposite. While the turn of the century is an arbitrary cut-off point, and this is a crude predictive measure, and does not consider the underlying drivers of change in food prices, it does speak to the general mood and expectation around the developments in food prices. Previously, despite some significant periods of volatility the long term trend was suggesting continued declining prices, but following the spikes in 2008-09, and 2011-12 the question was raised whether these upward trends and increased volatility implied a ‘new normal’ in food prices, that the underlying structural drivers of food prices had shifted and we could expect a paradigm of higher food prices throughout this century. Both Figure 3 and Figure 4 do indicate lowered prices following the last price spike (2013-2020), but they are still far higher than the optimistic levels predicted from the last century, as demonstrated by Delegado et al. (2001).

Some additional factors may be partially responsponsible for the change in food prices in this millennium, such as the proliferation of regional trade agreements (RTAs), which rose from 81 in effect in the year 2000, to 213 in 2010, and then 311 in 2020 (WTO,2022). By their nature RTAs are exclusionary and thus not all countries may benefit from reductions in import restrictions. They may also divert attention away from more unilateral trade agreements. Burfisher, Robinson and Thierfelder (2004), however, argue that RTAs are net-trade creating and create positive welfare impacts for memebers and non-members. Furthermore, China’s accession to the World Trade

Organization in 2001 and its increasing demand for high protein foods may have placed additional pressure on global food markets.

2.5 Food Security (SDGs, FAO etc)

Many intergovernmental and multinational organsiations and institutions are engaged in assessing and addressing these developments in agricultural markets and their implications on food security.

The United Nations sustainable development goals are an advancement on the millenium development goals targeted from 2015 to 2030 (Griggs et al., 2013), aimed at promoting growth within a paradigm of ensuring the protection of earth's 'life-support systems'. Goal 2 of the SGSs in particular is based on achieving food security over the long term.

The Food and Agriculture Organization of the United Nations (FAO) aims to '…eradicate hunger, food insecurity and malnutrion'. As part of this remit the FAO engages in research assessing the state of global agriculture and fisheries, short-comings in these global systems, and potential paths towards global food security (FAO, 2019b).

There are some key FAO publications which give a detailed synthesis of the global challenges for achieving food security. The World Agriculture Towards 2030/2050 (Alexandratos & Bruinsma, 2012) report states that given the projected levels of population growth and dietary change there 'should be no major constraints' towards global agriculture satisfying the level of demand for food projected by 2050. However while the potential for world agriculture to satisfy global demand is apparent, achieving this would require the appropriate investment, appropriate policy incentives, and growth realised in key vulnerable areas. The FAO estimate world agricultural production would have to grow by almost 50 per cent from 2012 levelsin order to meet future global demand for food in 2050 (FAO, 2017).

2.6 Global Climate Change

The advent of anthropogenic climate change presents a unique and significant challenge to humanity, and to the prospects of sustained growth in agriculture and achieving global food security.

Climate change is expected to cause sustained and wide-spread damage to all sectors of the economy. A study by Dellink, Lanzi and Chateau (2019) quantified the damage to global GDP associated with some of the predicted impacts of climate change, finding negative impacts on GDP for all regions, with the most significant impacts projected for India, and Sub-Saharan Africa, of up to negative four per cent. Interestingly Russia and Canada were expected to have positive GDP responses (of around 1 per cent).

Climate change brings with it a host of additional challenges for agriculture, and food security. First, rising global temperatures have a variety of implications for the growth and growing period of crops, including: shorter growing periods in lower latitude regions; cell damage; increased sterility; and increasing the frquency of extreme weather events which may damage crops (FAO, 2018). Higher temperatures can also be beneficial for invasive weeds, challenging productive crops and pasture for resources, and for vector-based diseases and pests affecting both crops and livestock. There is also likely to be a decrease in the production capability of labour due to additional heat stress (Bosello, Eboli & Pierfederici, 2012). This will also impact on the yield and production potential of agriculture, especially for regions and crop types which are more dependant on labour inputs.

Many impacts will be highly variable between regions. Projections of the impacts from changing climate show some regions increasing their agricultural outputs. A study using the Modular Applied General Equilibirium Tool (MAGNET) model (FAO, 2018) tested the IPCC Shared Socio-economic Panel on Climate Change (SSP) (O'Neill et al., 2017). The modelling projected increases in crop yields due to climate change in some regions of up to 28 per cent (between 2011 and 2050). However, these results do not account for animal products, specific mitigation options, or increased volatility in weather and extreme weather events, which may imply an understatement of the potential negative impacts on crops.

A study using the GLOBIOM model (Havlik et al., 2015) projected global average crop yields would decrease by between 2 and 10 per cent by 2030 (depending on the extent of CO_2 fertilisation, and the political economic future scenario used). Rosenweig et al. (2014) compared the crops yields under different warming scenarios between seven gridded crop models. The paper found beneficial yield effects in temperate regions with moderate warming (1-3°C), but negative yield effects in tropical regions with even low levels of warming (1-2°C). By 2050, up to 0.2 absolute deviation in average yield from the group average was found between models.

Overall the reduction in yields as a result of climate change are expected to be of secondary importance to long-term food security compared with changes in income and population change, which are the key drivers of global demand (FAO, 2018). In terms of the whole economy, global contribution of agriculture to GDP was predicted to drop by 9% by 2060 according to a modelling study by Dellink et al. (2019)(using the ENV-Linages model).

Agricutural export markets have become more concentrated, with the majority of exports coming from a few sources, or even a singular country for some commodities, such as other oilseeds in Canada (54% of total exports) or roots and tubers from Thailand (56% of total exports) . This trend is expected to continue into the future (OECD-FAO, 2018), and to become more pronounced under certain scenarios of climate change (IPCC Representative Concentration Pathways 8.5) (Porfirio et al., 2017). This is indicative of a competitive advantage in the production of certain goods and according to economic theory would imply lower costs of production. While this is beneficial for lowering food costs it my also be a cause for concern. As climate variability and the incidence of extreme weather events rise under climate change, so do the vulnerabilities in regional production. Higher concentrations of global production may also imply higher global vulnerabilities to climate shocks. Global trade has the potential to mitigate some of the damage caused by lost production at the regonal level, where shortages in one area can be supplemented with imports from unaffected regions. A higher degree of concentration, however, creates a risk of having 'all our eggs in one basket'. If the production of a particular crop is too centralised in one country or region, a singular drought or poor growing season could limit a significantly large proportion of global production. Then with fewer alternative suppliers able to compensate for the losses in one key region, the effect on price and availability of food of a singular regional weather event would be compounded, and felt on a global scale.

2.7 Computer Modelling

Computer modelling has been used to assess the future prospects of the global supply and demand of food. One notable early example is the analysis of the Club of Rome, that used the 'world' model to track the natural resources of the earth and thus the sustainability of civilisation across various growth scenarios. The results from this endeavour were published under the title *Limits to Growth* (Meadows et al., 1972) and its subsequent re-isuues and updates. The model investigated trends in five key areas: industrialisation, population growth, malnutrition, non-renewable resources, and the environment. Part of this exercise concerned the productive capacity of agriculture, and land-use.

The general message from the initial *Limits to Growth* publication (Meadows, Randers & Meadows, 1972) is the likeihood of global 'overshoot and collapse', in which unsustainable continued industrial growth depletes non-renewable natural resources and builds up a large capital stock which is ultimately unsustainable as it physically depreciates. This 'overshoot' results in a decrease in population, followed by a compromised standard of living over the long-term. Agriculture in particular was predicted to become increasingly reliant on inputs from other industries, which would then also be limited with the 'overshoot'. The timing of this overshoot was unclear other than it was estimated to occur before 2100. All scenarios of various resource abundance and technological advancement still results in a eventual overshoot of population and capital, painting a Malthusian picture of economic consequence.

> We can thus say with some confidence that, under the assumption of no major change in the present system, population and industrial growth will certainly stop within the next century, at the latest.
>
> - Meadows et al.(1972 p. 126)

The world model used by Meadows et al. in 1972 was a simplistic one, and one which has been outgrown in terms of modelling and computer capacity, but is nonetheless a significant benchmark in the use of computers for assessing these questions balancing productive and demand potential. The general approach of the model also demonstrates how to reduce the complex systems of the global economy and society in a useful way. Regardless of the detail, we can explore the consequences of industrial growth, in the same way a philosophic argument can abstract a problem to its most essential logical root.

A follow-up edition of *Limits to Growth* was published in 2005 (Meadows et al., 2005). In this update the general prediction of global 'overshoot and collapse' was reinforced. In the updated model (World3-03), continuous population growth was experienced until widespread high incomes were reached, and economic growth would continue unless constrained by a limit of inputs or the accumulation of pollution. In these proposed scenarios, the world was predicted to experience declining levels of living standards within the century.

The productive capacity of global agriculture suffers in these scenarios as production moves onto increasingly marginal land (similar to Ricardo's original proposition of diminishing returns), with yields being maintained by increased input usage. Thus, yields depend on continued industrial growth in non-agricultural sectors. which under most proposed scenarios fail to maintain growth due to a shortage of non-renewable resources[5]. If the supply of non-renewables is increased an accumulation of pollution from the increased industrial output will impact land fertility and thus constrain agricultural production. In actuality, the shortage of non-renewable resources may increase the investment into renewable technologies which may help alleviate some of the pressures on non-renweables and the environment (Solow, 1973).

With the addition of technological progress (the 'comprehensive technology' scenario), the World3 model scenarios predicted a delaying of the overshoot and collapse model, but not a reversing of this trend. Land-degradation and the build up of pollution were identified as the key challenges for agriculture. The only scenario which avoided overshoot and collapse ('stabilized world') did so with immediate investments into technologies which increased agricultural yields combined with contemporaneous technologies to abate pollution, land degredation, and industrial dependence on fossil-fuels. This scenario still resulted in a decrease in global welfare, but at a gradual rate, rather than in a single breaking point with a collapse in global population. A 2021 paper (Herringon), compared the results of the 2005 Limits to Growth update to real data, finding the 'business as usual

---

[5] Limits in renewable resources such as water and forests were also considered.

2’ and ‘comphrehensive technology’ scenario to most closely mirror reality. ‘Buisness as usual 2[6]’ proejcts a collapse due to pollution and ‘comphrehensive technology’ a quality of living decline.

The ideas of the *Limits to Growth*, were also advanced in with the concept of the nine planetary boundaries and doughnut economics (Rockström et al., 2009; Raworth, 2017), which attempts to assess the biophysical and circulation systems of the earth and identifying the tipping points and limits associated with them.

The development of the concept of circular economy (CE) has also developed from these concerns of a global overshoot of our environemental and resource capacities. CE aims to reshape global economic and resource use paradigms in order to foster wellbeing with minimal input and environmental costs. This is achieved broadly through the actions of reduction, reuse and recycling, creating a system which is regenerative rather than explotative, and inclusing such specfic initiatives as achieving zero-waste, decoupling growth from environmental impacts, and recovering waste resources (Ghisellini, Cialani & Ulgiati, 2016). Circular economy differs from sustainabiltiy in its motivations and aims, CE focuses on economic actors and environemental benefits through minimisinal input usage, while sustainability had broader goals to emphasise environmental, social and economic benefits equally (Geissdoerfer et al., 2017).

The goals of CE would reduce the resource use of global human activity, and thus would steer global economies towards something like World3-03’s ‘stabilzed world’ scenario. Given that the depletion of natural resources and the build-up of pollution were the two main contributing factors to collapse and delcine outcomes, two factors that CE aims to alleviate. Korhonen, Honkasalo, and Seppälä (2018) caution however, that the core concepts of CE may be idealistic if they do not accept the limits brought by factor’s such as the impossibility of complete recycling, the increase in consumption brought on by reducing production costs, or unintentionally deferring environmental impacts.

2.8 Conclusion

This chapter has provided the background of the issues surrounding food security and the challenges facing the global agriculture sector, presenting some of the history of thinking concerning challenges to food security, and how these challenges have impacted on food prices over the last century.

Historically the discussion has centred around misconceptions about the productive possibility of agricultural, and thus advancements in farm technologies, management practices, lowering input costs and increases in productivity have been important in outpacing population and demand

---

[6] The ‘business as usual 2’ scenario doubled the natural resources in the ‘business as usual’ scenario, this was in response to the original World3 scenarios underestimating the available global pool of exploitable natural resources (Herrington, 2021).

growth, as the overwhelming story of agricultural prices in the 20th century has been one of decreasing real prices for food.

This trend has changed in the current century as these discussions have evolved over time, and have incorporated new challenges and stresses, climate change in particular, being a significant recent development in the journey to understanding and achieving food security and the maintenance of low food prices. Economic modelling has also provided insight into understanding these issues and helps balance the various facets of the concerns around food in a singular framework. Economic modelling will be an important contributor to the task of contributing new knowledge to this area of inquiry going forward.

The next chapter will summarise and present the existing literature on this topic and describe its relevance to these issues. While this chapter has focused more on the historic context around agricultural markets, the next chapter will be structured towards understanding the constituent sections of an economic model. Importantly the chapter will identify gaps in this body of literature where this thesis may contribute new knowledge.

3. Literature Review

3.1 Introduction

The previous chapter presented the history and context around supply and demand in agricultural markets, some of the challenges to food security, and the use of economic modelling to better understand these issues. This chapter progresses on from the use of economic modelling to examine issues of agricultural supply and demand by presenting a review of the literature on modelling the supply and demand in global agricultural markets.

This chapter involves two main sections. The first is structured to assess the component factors of an agricultural economic model's equilibrium of supply and demand and some issues surrounding them. The literature on constituent factors of supply equations includes: land-use; animal numbers; yield; input and TFP are examined, then constituents of demand equations: population; income; dietary change; use for bio-fuels; and intermediate inputs. Stocks are also examined as potentially belonging to either group; as well as how economic models incorporate the impacts of climate change, a key challenge for agriculture into the future.

The second section is concerned with the strengths, weaknesses, and usage of different modelling types. This discussion largely revolves around partial equilibrium (PE), computable general equilibrium (CGE), and integrated assessment models (IAM). Lastly, there is a summation of economic models and examples of some key models, representing different modelling approaches used for answering questions like those posed in this thesis.

Overall this literature review aims to understand the literature on economic modelling for agriculture, identify gaps in the literature for understanding as simulating global agricultural markets, and to determine which models and model type would be best suited to address these gaps.

3.2 Modelling Supply

On the supply side of the equation there are four key factors. These are the inputs into production as described in a typical production function. Where at its most basic, a production function usually focuses on the factors of labour and capital, in agricultural modelling for crops, the two key components are land and yield, the area devoted to producing a particular crop and the amount of crop harvested from a parcel of land, or in the case of animal production, animal numbers and product per head. The specification of yield can be broken down into its constituent inputs. These physical inputs include labour, machinery, fertiliser, pesticide, and herbicide.

3.2.1 Agricultural land-use

The issues surrounding the role of agricultural land in the supply of agricultural goods are the potential for expansion in the future and the suitability of land for agricultural uses. Alexandratos and Bruinsma (2012) point out the importance of the location of prime agricultural lands with 60 per cent of un-utilised land classified at least as ‘good’ for rain-fed agricultural production (designated by the Global Agro-ecological Zones study, Fischer et al., 2011) being situated in only thirteen countries[7]. This concentration of potentially viable agricultural land demonstrates the importance of regional issues and the global constraints upon the potential for expansion of agricultural land. Furthermore, the majority of this prime agricultural land may be under rainforest or other sensitive uses, limiting the ability to fully utilise these lands without serious local ecological, social, or environmental consequences (Ramankutty et al., 2002).

However, the most significant issue in land-use for the productive potential of agriculture may not be a hard Malthusian limit of the resource, but rather a Ricardian one. Thus the additional cost of maintaining yields on new parcels of land outweighs the production potential of the output of the land itself. As put by Thomas Hertel (2011, p. 271): “…the question is not whether sufficient land will be available for agriculture, but rather: What will be the ensuing price?” This issue however will be borne out in the yield potential for agricultural lands.

3.2.2 Animal numbers

In the case of the animal products, animal numbers are the key component of production, rather than land-use. Increasingly, higher volumes of animal products are expected to come from increases in livestock numbers, primarily in developing countries and for ruminant animals. This will in turn have implications for demand for feed (Thornton, 2010).

The relevance of land-use in the production of animal products is less important because stocking rates (number of animals per parcel of land) are highly varied between countries and farming systems (ie. Intensive farming, vs pasture based). The amount of land utilised in the production of animal products is important as a competing land-use for crops, but is less directly related to production quantity. Increased animal number can however have implications for crop area in the demand for feed crops. Additionally, there are more instances of utilising land for multiple animal types making the direct link between area utilised and production output more difficult to quantify.

Livestock is a major contributor to climate change, due to methane emissions from ruminants through enteric fermentation and nitrous oxide emissions from anaerobic fermentation in the

---

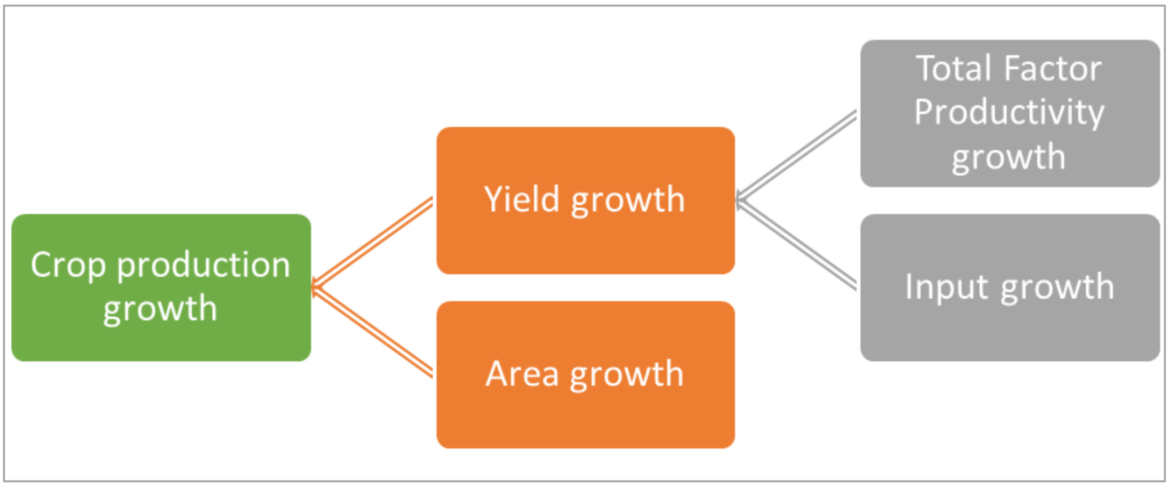
[7] In order of available land: Brazil, United States, Russia, Argentina, Australia, Sudan, China, Democratic Republic of the Congo, Kazakhstan, Angola, Canada, Mozambique, and Madagascar.

management of manure. The majority of livestock emssions come from cattle (65-77%) although emissions per head have decreased alongside the increase in productivity per head (IPCC, 2019). The growing production of animal products also has serious negative implications for the environment outside of the impact on GHG emissions, including on water-use and pollution, biodiversity, and land degredation (FAO, 2006).

3.2.3 Yield

As discussed briefly in Chapter 2, yield growth has steadily become the predominant factor in the rate of growth in crop output . The growth in yields has resulted from increased inputs, and from rising total factor productivity (Figure 5).

Figure 5: Total Factor Productivity as a component of total crop growth



Globally, yield growth rates have been decreasing since the 1990s; this decline may coincide with a decrease of investment in agricultural R&D (Alston, Beddow & Pardey, 2009). Grassini, Eskridge and Cassman (2013), discuss this trend and the best method for determining the correct statistical model for projecting advancements in yield. They conclude that many studies assume cumulative yield growth, neglecting the bio-phsycial limits of potential yields, or over-optimistic yield frontiers based on record yields (rather than a replicable yield). In their paper, six statistical models are tested for best-fit for maize, rice, wheat yields in 20 countries, and three regions of Africa. Many instances of linear models with ceiling plateaus in yields were identified as the best fit for growth of crop yields. This implies that many crops had already reached a ceiling in yields. In common with the conclusions of Alson, Beddow and Pardey (2009), these ceiling plateaus were attributed to insufficient or inefficient funding for agricultural R&D, along with higher input costs and scarcity, less favourable climate, and shifting production to areas with poorer quality soils.

Growth in yields between countries is not only tied to the sharing of technologies. The least developed countries, for example, are experiencing slower yield growth in agriculture, and aren’t achieving their full potential yields relative to the technologies availabile elsewhere (FAO, 2018). Aside from access to technologies, these discrepancies can be attributed to poor infrastructure, weak institutions, limited access to agricultural inputs (FAO, 2018), or additionally differing biophysical environments for growing, nutrient imbalances and deficiencies, pests, and lack of access to credit or knowledge (Lobell, Cassman & Field, 2009).

3.2.4 Inputs

As shown in Figure 5, we can think of yield growth as growth of TFP and growth in the intensification and use of various inputs.

In terms of capital accumulation, investment into agriculture has grown between 1991 and 2014 across all regions (FAO, 2017). There is a distinction in the level of capital inputs used in agriculture between developed and developing countries, proportionately more fixed capital is invested in agriculture than agriculture's share in total value added. This points to agriculture in developed countries being far more capital intensive than in developing countries even to the point of being over-capitalised. Overall capital intensity in agriculture is growing worldwide, suggesting an increasing share of capital inputs, and specifically a shift away from labour intensity in agriculture (FAO, 2017).

The increased use of inputs has been linked with some of the major periods of growth in agricultural productivity (Griggs, 1992; Briggs, 2009). However this increase in output can come at the cost of over-utilisation of natural resources leading to the degradation of soil, overloading groundwater nitrates, or salinization of ground and surface water. Unsustainable land-use practices can ultimately compromise the yield potential of lands (Licker et al., 2010).

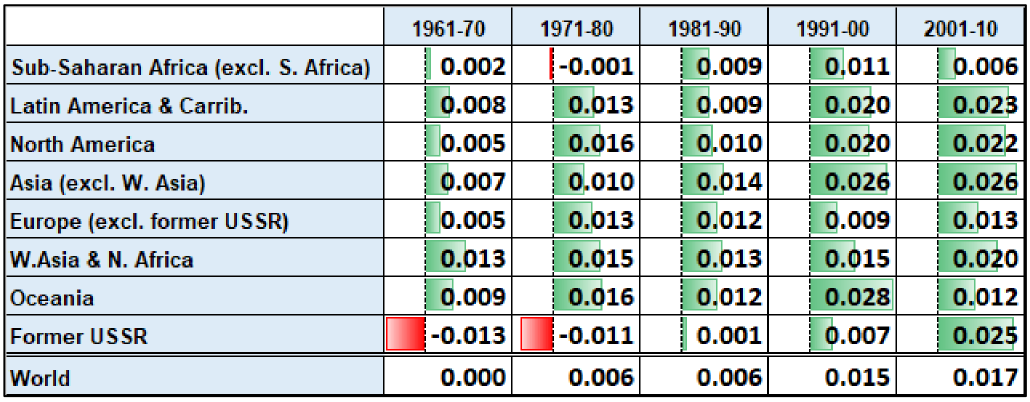
3.2.5 Total Factor Productivity

In addition to land use and the physical inputs used in agriculture, there is also an additional factor of production contributing to growth. This was originally discussed by Schultz (1956) who assessed where this additional growth in agriculture came from (he considered the source to be new technologies, and increased quality in labour). It was later elegantly conceptualised in Solow's (1956, 1957) growth model, as a residual factor, i.e. where the total observed output was not explained simply by the change in inputs. This additional element has since been decomposed and explained in various ways. One large component is technological growth, new technology can create new inputs or enhance the efficiency of inputs (ie. using a tractor rather than horse pulled ploughs or increasing the solubility of fertilisers for nutrient uptake). Additionally the particular composition of inputs can enhance the output, one hundred workers with one scythe would have a higher output than one worker with one hundred scythes.

The concept of total factor productivity (TFP) has been used to incorporate this residual growth into the total output. TFP measures gross outputs relative to gross inputs. The ratio of TFP describes the additional value of production above that made by the inputs. Due to the non-specific nature of this factor it is sometimes easily misidentified as simply technological growth or not explicity included in measures of productivty growth.

In terms of the growth of global agricultural TFP, Fuglie (2015a) presents historic growth rates of TFP, shown in Table 1. The table shows higher growth rates in Asia and North America and Latin America and the Carribean following 1991. TFP growth rates in Sub-Saharan Africa and Former USSR have notably low historic growth rates, but with Former USSR countries increasing TFP growth rates after 2001. Aggregate global agrivultural TFP rates have been increasing since 1961.

Table 1: Average agricultural TFP growth rate by region and decade, 1961-2010



	1961-70	1971-80	1981-90	1991-00	2001-10
Sub-Saharan Africa (excl. S. Africa)	0.002	-0.001	0.009	0.011	0.006
Latin America & Carrib.	0.008	0.013	0.009	0.020	0.023
North America	0.005	0.016	0.010	0.020	0.022
Asia (excl. W. Asia)	0.007	0.010	0.014	0.026	0.026
Europe (excl. former USSR)	0.005	0.013	0.012	0.009	0.013
W.Asia & N. Africa	0.013	0.015	0.013	0.015	0.020
Oceania	0.009	0.016	0.012	0.028	0.012
Former USSR	-0.013	-0.011	0.001	0.007	0.025
World	0.000	0.006	0.006	0.015	0.017

Source: Fuglie, 2015a

TFP has been an increasingly important component of productivity growth in agriculture. Fuglie (2015b) found that over a 50 year period, the rate of input growth deliced as the contribution of TFP to new agricultural growth increased. TFP accounting for two-thirds of agricultural production growth between 2001 and 2012 Furthermore, in one modelling exercise Baldos and Hertel (2014a) found that without TFP growth, the incidence of malnutrition in 2050, would be over four times the levels in their baseline, with higher food prices than those experienced in the 2006 price spikes. This also demostrates the potential dangers is mis-specifying or excluding TFP in studies of productivity growth.

3.2.6 Sources of Total Factor Productivity

As stated before growth in TFP can come from the selection of inputs, and technoloical change, but TFP can also increase with enhanced education of producers, improved breeding, or returns to scale. Grilliches (1998), however, states two key points of what he deems the ‘new’ growth economics. Firstly that technical change derives from deliberate investment by many economic units; and secondly without significant other externalities, spillovers or other sources of returns, economic growth is unlikely to proceed at a constant undiminishing rate in the future.

Expanding on the first of Grilliches' statements, Alston (2002) argues that among all other contributing factors, the predominant source of TFP growth in agriculture is investments into agricultural R&D. Grilliches (1998) for example, finds that roughly two thirds of TFP growth and up to half of output per worker can be attributed to spending on R&D. Grilliches comments on two types of estimates of returns to R&D spending in the literature: the first is rate of returns for particular inventions or innovations, and relies on in-depth knowledge of the area of interest. This approach however highlights only a narrow set of successful R&D outcomes, rather than the overall benefits. The second approach is performed through regression analysis, testing the relationship between output TFP and investment into R&D, or R&D capability. The short-comings of this style of study is that it is dependent on the metric used to measure output TFP, and the R&D inputs. Any problems with identification of the inputs or outputs can result in failing to capture the real benefits of research.

On the second of Grilliche's propositions, Alston (2002) discusses the importance of research 'spillover' between nations. According to Alston previous research has either neglected the impact of research in regions outside the subject of the study (Yee & Huffman, 2001), or has based the impact of research in other regions solely on the geographic proximity between the regions (Huffman & Evenson, 1996). Alston proposes that in the case of the relationship between agricultural R&D and agricultural productivity, the relative similarity of agricultural outputs is a better indicator of the likelihood of research being relevant, and thus effective.

The model described in Alston (2002) finds over half of total multifactor productivity growth comes from benefits from research conducted outside of the examined state (19% Federal; 36% other states). The modelling exercise was concerned only with research contributions internal to the US, rather than internationally. Alston reports on other studies which did assess international 'spillovers' in agricultural research. In particular Davis, Oram and Ryan (1987) found international research in regions with similar FAO agro-ecological zones (AEZ), accounted for between 64 and 82 per cent of total research benefits. In Alston et al. (2000b), a quarter of total agricultural outputs was attributable to cross-country R&D 'spillovers' in the Latin America and Caribbean region. Alston concludes that the cited literature evidences "…substantial international spillovers of agricultural R&D." (Alston, 2002 p. 333).

The impact of spillover R&D externalities on other research is difficult to measure because it is not embodied in any specific product. In order to directly measure the benefits, the anaylsis must assume they are manifest in a particular good or industry. Some public goods have similar measurement issues (roads, security services etc.). Overall there are two types of approach to spillovers, either to frame an overall pool of knowledge or research spending, or to specifically isolate the cross–firm or cross–region relationship between partners.

In a summary of the literature on estimated returns to R&D spending , Grilliches (1998) finds rates of return on public R&D spending of between 11-83 for livestock, and 20-62 for crops. Furthermore in the majority of studies, returns to generic (non-agricultural specific) R&D spending outside the examined industry were higher than returns within an industry, emphasising the importance of R&D 'spill-overs'. Using the upper-end of these estimates from the literature, Grilliches posits that returns on R&D can account for almost three quarters of total TFP growth, with the spill-over being the most significant part of this effect. Grilliches does admit that these results may be positively biased by the choice of included studies, having a potential upwards selection bias.

Alston et al. (2011) assessed the rate of returns to publically funded research and development funding in agriculture. This paper utilises an econometric model to define the Multi-Factor Productivity , a Fisher ideal index of agricultural productivity. The independent variables used were the stock of knowledge from agricultural research and development spending over a 50 year historic period (both in the studied state and a spill-over from research spending in other states); and an index for the condition of pasture and rangeland. The measure of spill-over from research spending in other states, was based on the approached developed by Jaffe (1989), where the relevance of research in other states is defined by the relative portfolio of agricultural production, i.e. research performed in states with similar agricultural commodity outputs would be more impactful and relevant than from those with disimilar outputs. The paper found national internal rates of return of between 7.7 and 11.7 per cent. Additionally the model used a lag length of 50 years in a gamma lag distribution for returns on investment from agricultural R&D spending, a lag of much greater length than found in many other studies of agricultural investment.

The length of lag in returns to agricultural R&D is questioned in an earlier paper by Alston and Pardey (2001). Lag lengths of 20 years or less are cited, partly due to pervading restrictions on useable time-series data requisite for constructing estimations of longer lags. Similarly the updated *Limits to Growth* (Meadows, Randers & Meadows, 2005) uses a implementation lag of 20 years for new technologies. Studies from Pardey, Craig and Hallaway (1989), and Chavas and Cox (1992), indicate that a lag of 30 years or greater would be needed to fully account for the effects of research funding. As shown in Alston et al.'s 2011 paper up to 50 year lags would later be used, although Alston, Craig and Pardey (1998) suggested a lag of infinite might be necessary as theoretically productivity is a factor of all relevant R&D investments throughout time. They go on to suggest finite lags should be used to measure incremental changes in the stock of knowledge, rather than the holistic relationship between productivity and R&D investments in agriculture.

Alston and Pardey (2001) test assumptions on the length of lags in econometric models (assessing internal rates of return on public R&D spending in agriculture), and found those using lags consistent with the unspecified infinite lag were 'statistically preferred', indicating the benefit of longer lags than previously had been considered in the literature. A meta-study of rates of return on agricultural R&D (Alston et al., 2000a) found of 292 publications examined, only 14 per cent of those with lags (148), used lags of over 40 years; and only 58 per cent included some form of gestation lag on research returns. This points to a short-coming in the consideration of research lags in the literature. This research covered international studies from all regions on a broad range of agricultural goods, although there was a greater number of crop studies over livestock and other agricultural goods, and a bias towards United States literature of the developed world.

The lag in Agricultural R&D represents first the gestational lag as the research is completed after spending, followed by a lag representing disemination and uptake. The shape of the lag simulates the bell curve of adoption from users of the technology and the realisation of its benefits. Griggs (2012) descirbes the 'early adopters', the roughly 16 per cent of farmers who adopt new technologies in the first quarter of their uptake. Griggs identifies broadly their characterisetics as younger (under 45), owning larger farms, having access to capital, better educated, and finally acustomed to environments in which change is commonplace. These traits suggest that agility, the capital to invest in new technlogies, and the ability to garner larger returns from investing in new technologies are all important factors in encouraging uptake of new agricultural technologies. Griggs also identifies other modifying factors on the uptake of new technologies, such as complexity, compatability with contemporary farming systems, prestige, spatial diffusion as new practices spread spatially, if the new techology can be trialed on a sub-section of a farm, or if the technology is labour saving.

3.3 Modelling Quantity Demanded

The drivers on the demand side of the market equilibrium in agricultural trade models primarily concern the number of consumers (population change), their income, and their preferences for different commodities at various level of income. Some demand components (feed stocks) are intermediate inputs, largely driven by the requirements of supply in other markets. Biofuels are also a unique case as their production is larely dictated by government mandates, and cross competition with the supply and price of oil.

3.3.1 Population change

Population size is a key component of aggregate consumption levels and a large source of uncertianty in modelling future demand for agricultural markets. As discussed in Chapter 2, population growth is often cited as the aspect of food security and resource use that causes most concern.. The ideas of a Malthusian world are based on how agricultural production may not be able to match the growth in global population. The modern idea of population growth however, does not match the geometric growth envisaged in the industrial revolution, as fertility rates have tended downwards. The average number of births per woman is decreasing (and is projected to continue to decrease) in all regions (UNDESA, 2017; 2019b), even to the point of decreasing population, as half of the world poulation already lives in regions with fertility rates below replacement rates.

Reliable projections of population growth are thus a key exogenous input into any discussions on future pricings and global food security.

Looking to some key insights from the UNDESA projections, global population could grow from 7.7 billion in 2019 to 8.5 billion in 2030, 9.7 billion in 2050, then decline to 9.2 billion by 2100. The reliability of this projection decreases with a range of 3.2 billion peoples between the 95 per cent confidence intervals by 2100. Furthermore, there is a 27 per cent chance of global population growth ceasing or declining before 2100. Sub-Saharan Africa is also expected to become the most populace region (SDG region) within this century (around 2062), accounting for over 50 per cent of projected population growth up until 2050.

3.3.2 Income

The income of consumers also affects levels of consumption of food, although this relationship is non-linear. Engel’s law states that the proportion of income spent on food declines in relation to income growth, which implies the income elascity of demand decreases as incomes rise.. This effect is supported in the literature on cross-country and inter-country studies (Anker, 2011; Seale & Regmi, 2006) and is an important component of changes in demand for food over the long-run.

In modelling income changes, exogenous inputs of projections of population and GDP are used to calculate the average income by region into the future. In this way GDP is another key input for understanding demand growth.

The distribution of incomes also has an effect on consumption patterns. In practical terms, per capita incomes are often used to measure levels of global poverty and inequality, and the incidence of hunger and starvation. One study by the FAO, IFAD and WFD (2015) examining the amount of global investment needed to eradicate hunger on a global scale, assumed those in extreme poverty earned less than $1.25 US PPP a day (or $1.75 allowing for a buffer for fluctuations in income and expenditure). In an earlier report, Alexandratos & Bruinsma (2012) using World Bank GDP and income predictions to 2050, found that an 80 per cent increase in global average per capita incomes.The study found that, due to inequalities in the distribution of these increases, this would be insufficient to raise incomes in 15 developing countries out of significant poverty.

3.3.3 Dietary change

As previously discussed in the previous section, as incomes change so do consumption patterns. Higher incomes allow the purchase of more 'luxury' or higher quality foods, and the proportionate consumption of staple food decreases. There are other motivators of change in diets however. For example with rising incomes, consumers in emerging economies elsewhere in the world are switching to more traditionally western diets (Gerbens-Leenes, Nonhebel & Krol, 2010; Baldos & Hertel, 2014a), leading to an increase in the consumption of meat and dairy products not predicted by historic consumption patterns. Particularly strong increases in meat consumption are being observed in Brazil, and milk consumption in South America and India (Delgado et al., 2001). Alexandratos & Bruinsma (2012) predict this trend to continue with a 13 per cent increase in per capita meat consumption in developing countries between 2005-2007 and 2050, and a 10 per cent increase in milk and dairy consumption projected over the same period. The consumption of vegetable oil is another area in which signifcant growth in consumption levels are predicted, with an increase of per capita global consumption of over 50 per cent between 2005-2007, and 2050 predicted by Alexandratos and Bruinsma (2012).

Additionally the increase in urbanisation is cited as changing people's dietary demands towards more processed foods, non-ruminant animal products and fruit and vegetables (FAO, 2017). These changes can be motivated by a number of factors, such as people moving away from ruminant products due to health and environmental concerns. They are therefore difficult to predict using models which are dependent on estimated historic trends and patterns of consumption. Scenario analysis using predicted changes in diet can however be used to estimate how these changes in diet affect world trade and production. Although there is some debate over whether the current growth rates seen in Brazil and China, would occur in other parts of the world. In India, for example, where religiously motivated diets are often vegetarian (Alexandratos & Bruinsma, 2012).

3.3.4 Biofuel consumption

Due to increasing global concerns on the reliance on unsustainable fossil fuels, there has been a politcal and consumer driven push towards bio-fuels. Blending mandates imposed by national governments around the world have increased the demand for first generation bio-fuels (using traditonal crops to produce, ie, corn and sugar). Global production of biofuels more than doubled from 2007 to 2015 (FAO, 2017), and was projected to continue to rise to 140 billion litres by 2020 (IEA, 2016). This has increased competition for land which would otherwise have been used for producing food. It has led to increased consumption of cereals between 2000 and 2011, of vegetable oil between 2000 and 2009; and of sugarcane between 2017 and 2019 (FAO, 2017; OECD-FAO, 2021). This is not a component of direct agricultural demand for food, but rather of intermediate demand for energy within total agricultural demand.

In future the demand for first generation bio-fuels may make way for second-generation biofuels (using waste plant matter, and agricultural biomass produced on marginal lands). The EU and US are increasingy pullng away from mandates for first-generation bio-fuels, alongside general decreases of fuel consumption. Increases in consumption of ethanol is expected in Argentina, China, and Brazil however, as China have increased ethanol mandates, and Argentina and Brazil are expected to increase fuel consumption, as their blending mandates remain (OECD-FAO, 2019a). One study using several economic models estimated the impacts of high bioenergy demand on agricultural prices of around an additional five per cent by 2050 (Lotze-Campen et al., 2014). Hertel, Steinbuks, and Baldos (2013) estimated land use for bofuel feedstocks could be 225 million ha in 2100.

3.3.5 Intermediate Input Demand

Similarly to demand for biofuels, there are other areas of demand for agricultural products outside of human consumption. There is a demand for agricultural products to be used in feeding animals. This demand for feed, is largely comprised of oilseeds and the meals of oilseeds (including soy beans), but also includes some grains; and of course is dependent on the total number of animals, and the particular farming systems (ie. wholly or partially pasture fed or intensive). There is also miscellaneous demand of other mixed uses such as for seeding.

3.4 Stocks

Agricultural commodity stocks are not strictly classified under either supply or demand, as they can factor on either side of the equilibirum, either in additonal demand as regions build up stocks, or in supply as stocks are released into the market. Alternatively, opening stocks could be considered in the supply side and closing stocks on the consumption side, or as with commodity supply balances, the change in stocks is factored as a offtake of consumption.

Stocks can act as a buffer against the effects of price spikes, and thus low-stock environments can contribute to the magnitude of price spikes (Bobenrieth, Wright & Zeng, 2013; Ott, 2014).

3.5 Modelling Climate Change

3.5.1 General climate change

A paper by Nelson et al. (2014) summarises some of the literature on the modelling of long-term impacts of climate change on agriculture, and performs a meta-analysis testing comparible climate shocks out to 2050 on nine different models, as far as is structurally possible, given differences in the models' frameworks. The paper refers to earlier studies (Tobey, Reilly & Kane, 1992; Reilly et al., 1996; Parry et al., 2004; Lobell & Gourdji, 2012) which had a somewhat optimistic outlook for the impacts of climate change, predicting that the fertilisation effects given by increased atmospheric concentrations of CO_2 would largely offset, if not totally compensate or reverse, any reductions in yield brought on by decreases in precipitation or unfavourably warm growing conditions . However more recently the literature has started suggesting overall negative outcomes for global agricultural yields under climate change (Nelson et al., 2009; IPCC, 2019). For example, depending on the severity of change in climate, and global human response, Nelson et al. (2009) found up to 100.7 per cent increase in price for some crops in 2050.

Nelson et al. (2014) comments that biophysical modelling approaches lead to more negative results for agricultural yields, whereas economic models indicate more favourable outcomes under climate change scenarios. Mendelsohn, Nordhaus and Shaw (1994) attributes this discrepancy to biophysical models not accounting for possible responses to changing environmental factors by producers, who can work to mitigate some of the negative impacts. Nguyen and Scrimgeour (2019) descirbe this effect with the possibility for farmers to transistion to more cliamtically suitable alternative crops, thus mitigating the full losses from decreases in their intial crop, which would not be picked up in some production function approaches.Furthermore, Nelson et al. (2014), finds a higher spread of projected prices between crop and economic models when simulating the effects of climate change, than between models focused solely on climate impacts.

Additionally Nelson et al. (2014) highlights three areas not covered in most crop model's accounting for future scenarios under climate change. These were: 1) the potential impacts of increased pest activity as vectors for invasive species may widen given increasing temperatures; 2) increased volatility of weather impacts, including extreme weather events; and 3) the rise of tropospheric ozone. While decomposing the complete impact of these three factors would be difficult, and would imply extremely varied impacts across different regions, contexts and crops, overall the outcome is expected to place additional downward pressures on crop yields. Thus any studies which have not considered these additional elements should be regarded as probably understating the true potential impact of climate on agriculture. In terms of the magnitude of these impacts, the IPCC (2007) estimates that the effect of extreme weather events will have a greater negative impact on agricultural output than the general expected change in temperatures and rainfall.

Ultimately, Nelson et al. (2014) find that amongst the suite of nine models they surveyed, all broadly report higher agricultural commodity prices across nearly all regions, and commodities. This is caused by smaller yield growth, in turn driving increases in harvested area and decreased consumption. Lobell, Baldos and Hertel (2013), find a 0-2 per cent loss in yields per decade due to the negative impacts of climate change on crop productivity growth. Furthermore a paper on the future of food and agriculture (FAO, 2017) indicated that rainfed small holder agricultural systems in the tropics and highlands account for 60 per cent of all agricultural output. This is concerning as these farm-types are particularly sensitive to changes in rainfall.

3.5.2 CO_2 fertilisation

One outcome of increased concentrations of greenhouse gases in the atmosphere is that carbon dioxide (CO_2) has a fertilising effect on some types of crop growth. Overall the issue of CO_2 fertilisation falls under a wider question on potential yield growths into the future, which is at the core of analyses addressing the potential for agriculture and food security under climate change. CO_2 fertilisation is more significant in crops with the C3 photosynthetic pathway, including rice, wheat, and oilseeds, key food staples and feed crops (Nelson et al., 2014).

The specific impact the fertilisation effect will have on yields is regionally and crop specific. Tobey, Reilly, and Kane (1992) cites earlier studies which suggested a range of between 17-33 per cent increases in crop yields. Lobell and Gourdji (2012) predict a roughly 1.5 per cent yield increase due to the impacts of CO_2 fertilisation. Fischer (2009) describe the outputs of the HadCM3 model under the A2 SRES climate scenario, finding a yield gap of between two and seven percentage points in rainfed wheat crops; and between 4 and 6 percentage points for all cereal types (rainfed), with or without CO_2 fertilisation. This was reflected in a 11 percentage point difference in the price for cereals in 2050 (10 % for total crops; and 7% for all agriculture) in the same modelling scenarios compared with a base of 1960-1990.

A further consideration, converse to the positive effects of CO_2 fertilisation, is that some studies have found that under CO_2 rich environments the mineral and protein content of crops can decrease, while the carbohydrate content increases (FAO, 2018). This disparity could increase the potential for malnutrition under climate change.

3.6 Economic Modelling Approaches for Agriculture

Mathematical programming (usually non-linear optimisation) is employed to find a price vector which ensures equilibrium between supply and demand in a multi-product multi-country/region modelled global economy with trade. External (or exogenous) drivers on both sides of the equation influence the level of supply and demand, producing a new market state, for which the model must find a new equilibirum. The resulting economic states, at these equilibiria, can be analysed to assess changes in a constructed economy over time, or given particular exongeous drivers of supply and demand.

Two main types of economic trade models are available: partial equilibrium (PE) models, and general equilibrium (GE) models. Computer models using a GE framework are often specified as 'computable general equilblirum models' (CGE). Both types of model function by searching for the point at which the economy, or a section of the economy, are in equilibrium, be it by balancing relationships between supply and demand (PE), or payments between different agents in the economy (government, producers, households) (GE).

3.6.1 Differences between partial and general equilibrium models

The Agricultural Model Intercomparison and Improvement Project (AgMIP) produced a meta study that compared different models used to study agriculture. The project used scenario analysis to compare the similarities and differences between model structures and results. Robinson et al. (2014) described five areas where there are major differences between the two modelling approaches:

1. The link between producers and consumers in income generated
2. The specification of supply and inputs into production
3. How changes in productivity are included
4. The modelling of consumer demand
5. How trade between regions is treated

As part of the AgMIP programme, Von Lampe et al. (2014) compared the outputs of 10 models (6 CGE and 4 PE models). In assessing the differences between the model types. A major point is that shocks typically have a less pronounced impact in CGE models due to their broad sectoral coverage. Any shocks in a singular industry will be distributed across a wider range of industries offering additional substitutability of production factors across various industries. Thus, the impacts of exogenous shocks (production constraints, or changes to demand) are not solely focused in one industry. Consider the impact of climate change on agriculture. If additional labour or capital inputs from other industries could work to offset a loss of production from climatic changes, this could be modelled endogenously in a CGE model (unless input factor shares were fixed), whereas a PE model would generally need to assume exogenous inputs to simulate an increase in inputs from other industries. This would lead to the PE model overstating the total effect of the shock, since part of the potential response and offset from higher inputs would not be accounted for. The authors conclude that this will lead to PE models overstating impacts with higher and more sustained price changes. The meta-study of these models in Von Lampe et al. (2014), found a statistically significant difference in the price estimation between the two modelling approaches, pointing to 3 per cent higher world average producer prices in PE models over those estimated in CGE models.

Conversely, Von Lampe et al. (2014), also examined the possibility that the use of bi-lateral trade in spatial CGE models (using either Armington or trade cost approaches[8]) may over report price changes as the markets are simulated as more segmented than in a net trade approach (used by non-spatial models). Their empirical analysis found the opposite, with statistically significant lower price estimations in spatial models (those mapping trade bi-laterally). The reasons for these discrepancies were not identified in the paper. Interestingly the paper also found CGE models to have smaller price impacts associated with climate change scenarios, although this was partially attributed to the different manner in which these scenarios were implemented between the two model types; and partially to the aforementioned dampening of exogenous impacts through the flexibility of factor substitutions in CGE models.

In general these findings illustrate some short-comings in the way partial equilibrium models characterise production without the explicit impact of inputs, which may result in over response in price effects. Von Lampe et al. (2014) note this, particularly in regard to short-comings in accounting for change in productivity, within agricultural modelling. Whereas, conversely, CG approaches may have drawbacks in assessing trade and climate change scenarios.

3.6.2 General equilibrium models

A 'computable general equilibrium' model is an economic model which incorporates all sectors of the economy. The term general equilibirum models or 'applied' general equilibrium are also used to describe modern applications of models of these types.

---

[8] The Armington approach to modelling trade is on the basis of differentiation preferences for domestic and imported goods, and is used in CGE modelling, whereas the trade-cost approach simulates bi-lateral trade through minimizing the total cost of trade, including the costs of trade and production price.

Computable General Equilibrium models are often static models, meaning they do not solve for an annual equilibrium over the examined time horizon, but instead solve their base year (the last initial year with real data), and the final year of the examined period. This method simplifies the computing requirements, but has the drawback of not elucidating the pathway towards the outcome in the final year. This form of analysis has limitations, meaning that some CGE models are less suitable for dynamic time-series analysis, which require the analysis of how events change over time, or alternatively research which addresses non-linear change over time, where impacts may be temporary or multi-directional over time. There are some versions of CGE models, such as some versions of GTAP, which are dynamic rather than static (Ianchovichina & McDougall, 2001; Golub, Hertel & Sohngen, 2008).

GTAP

One of the most widely known and used general equilibrium models is the Global Trade Analysis Project (GTAP) model. Developed at Purdue University the GTAP model aimed to create a CGE model with more transpancy in its data and assumptions (CGTA, 2019).

GTAP includes the household budgets and flows to the government, banking, and the private sector, in the form of tax, savings, and income and other expenditure respectively. Spending between different industries of the private sector are also accounted for in the flow of inputs and outputs of various goods and services. The government is also linked to the private sector through subsidies and taxation.

The GE equilibrium central to the solution process in GTAP is met when global savings is equal to global investment. This is alongside other key assumptions, such as global supply equalling global demand; however, the global savings and global investment equilibrium is central to the solver.

Production in GTAP is a function of the availability of land, labour and capital, estimated with Leontif production functions in a constant elasticity of production (CES) form, assuming no substitutability of intermediate inputs ,although these can be readily modified. In its basic form GTAP does not differentiate production parameters by region, outside of cost shares for different inputs based on benchmark data (Britz & Keeney, 2010). The fixed cost-shares can be changed, sometimes for the use in scenario analysis (Keeney & Hertel, 2005).

GTAP continues to develop with additions to the model framework and database. This includes incorporating more detailed accounting of the agricultural sector (Chepeliev & Aguiar, 2018; Keeney & Hertel, 2005) and land-use (Lee et al., 2005; Golub, Hertel & Sohngen, 2008)

3.6.3 Partial equilibrium models

Partial equilibrium (PE) models only simulate part of the total economy (thus the name ‘partial’ equilibrium). This is often limited to a single sector of the economy. This approach is commonly used in modelling agriculture as the agricultural sector is relatively self-contained compared to other sectors, with relatively few linkages to other sectors. These external linkages can then be modelled exogenously (outside of the functioning of the model), but as exogenous variables there is no iterative response in their pricing and supply within the modelling framework. Other than agriculture, PE models have also been used to model the energy and other sectors (Wise & Calvin, 2011).

The scope and complexity of a model is an important consideration, relative to the research objectives. In the case of PE models, by limiting the scope of considered sectors, more detail within that same sector can be considered, at a relatively low-cost. One strength of this approach is if the relevant links to other sectors are not material, and the aims of the modelling task are restricted to the sectors covered in the PE model, this can be an appropriate compromise. Conversely, research aims which require the complete interplay between many different sectors of the economy are not ideally addressed with a PE modelling approach, and would be better suited to CGE models. This includes research which wishes to address changes in whole-economy welfare, total employment, and government spending.

Due to the usually aggregate commodity profiles presented in CGE models, PE models can be more suited to performing trade analysis of tariffs and trade agreements, as they can deal with high specific products in their use of tariff lines, whereas Input Output tables used as the basis for informing cross-sector relationships in CGE models are not available at the sub-sector level, let alone at the single tariff line level (Narayanan, Hertel & Horridge, 2010). The commodity coverage used in PE models generally can focus on disaggregated commodities, and address tariff lines in closer detail.

The links between capital and labour in the production of goods are also weaker in PE models. While some version of exogenous or modelled inputs from capital and labour can be included in a PE framework, by not considering the entire economy the links and flows of capital and labour between sectors will not be accounted for. Thus the price of inputs in a PE framework is often static, rather than being an endogenous factor of the modelling.

Five notable PE models are covered in the following section, with discussions of their uses, structure, limitations, and advantages.

SWOPSIM

The Static World Policy Simulation Model (SWOMPSIM) is an early example of a PE model and the first example of a 'template' style structure (Britz, 2004) which utilised an identical equation structure for different regions or commodities. The distinction between commodities or regions of supply and demand are made using the parameters in the equation framework.

SWOPSIM has been used to measure the effect of yield change in key grain producing regions, and to simulate the impacts of climate change on agriculture (Tobey, Reilly, & Kane, 1992). Although the science behind the scenario development is now out of date, and thus the findings are no longer relevant, the structure of the model and the general approach is of interest to the application of PE modelling approaches for assessing climate effects.

LTEM

The Lincoln Trade and Environmental Model is a multi-commodity, PE model with global coverage (Cagatay & Saunders, 2003), based on the VORSIM modelling platform, a later development of the SWOPSIM framework. The model was adapted to account for greenhouse gases and groundwater nitrates (Cagatay, Saunders & Wreford, 2003), including the integration of forestry as a land-use as commodity market (Saunders, Kaye-Blake & Turner, 2009) and assessing trade liberalisation (Revell, Saunders & Saunders, 2014).

CAPRI

The Common Agricultural Policy Regionalized Impact Analysis (CAPRI) model was developed by a consortium of researchers, centred at the University of Bonn, originally focused on analysing the EU common agricultural policy (CAP). Since its development, it has been used in many different applications including WTO trade outcomes, potential bi-lateral trade agreements, and climate impacts on European agriculture (Weick et al., 2005; Weissleder, Adenäuer & Hecklei, 2008; Shretha et al., 2013). The model is a hybrid approach using regional CGE modules, which are then aggregated under a mathematic programming approach.

CAPRI is a joint model, using two PE sub-modules. The supply module uses exogenous input prices to determine the level of supply by regions in a regional programming model which covers supply for EU member states and some other European nations (Turkey, Norway & Western Balkans) in a high level of detail. The market module is a global spatial multi-commodity model covering 40 agricultural commodities, and 27 trading blocs, determining market prices, through bi-lateral trade between the 27 regions. As the CAPRI model was originally developed as a tool for analysing CAP reforms, there is a focus on the European Union in the model.

Adenäuer (2008) describes the structure and parameterisation of CAPRI. The parameters of CAPRI are synthetic, i.e. taken from the literature, but constructed in a way to ensure symmetry and homogeneity. Exceptions include parameters for input-use by input price, which are estimated using OLS (Britz, 2004). Supply in CAPRI is simulated using Leontif coefficients on a 'per head'/'per hectare' basis (Britz & Keeney, 2010). The model also simulates bi-lateral trade flows using Armington assumptions (Armington, 1969).

CAPRI deals with demand for products for use in biofuels exogenously. The data used for CAPRI is taken from the EUROSTAT REGIO data, FAO, FAPRI, DG Agri, and some internal estimations of trends. However, the base year of CAPRI is calibrated only to the DG-AGRI baseline for model closure, and has no other formal validation.

CAPRI has been used for a number of modelling applications often assessing EU-centric impacts. These have included the impacts of climate change (Shresta et al., 2013), and environmental linkages from agriculture such as nitrogen budgets (Oenema et al., 2009; de Vries et al., 2011; Leip et al., 2011) and GHG emissions (Weiss & Leip, 2012).

Aglink-Cosimo

Aglink-Cosimo is a joint developed model by the Organisation for Economic Co-operation and Development (OECD), and the Food and Agriculture Organization of the United Nations (FAO). The model is a multi-commodity, partial equilibrium model, focused on agricultural products with a global coverage. The model is used primarily for forecasting agricultural commodity prices for the annual OECD-FAO Agricultural Outlook publication (OECD-FAO, 2016; 2017; 2018).

Aglink-Cosimo is a dynamic recursive model, solving year on year, and using the results from the previous year as the initial state for the solver in each year. The model solves for a world equilibrium price which resolves global net trade to zero, for each included commodity, by simulating production and consumption at the regional level.

All commodities in Aglink-Cosimo are considered homogenous, that is products are not differentiated by their origin, and are in essence perfect substitutes in production and consumption. This method of solving does not allow for explicit modelling of bi-lateral trade (OECD, 2015). The base data in Aglink is informed by country specific questionnaires, whereas Cosimo data is updated from previous year's data. The baseline data collection process also incorporates expert validation and review, and model closure is achieved through merging and simulating a baseline between the Aglink and Cosimo modules.

Additionally all behavioural functions in Aglink-Cosimo are calibrated to the basedata, using an error term. As basedata is only collected for countries in the Aglink module, there is a bias towards this data.

SIMPLE

Baldos and Hertel (2012) created the Simplified International Model of Agricultural Prices, Land use and the Environment (SIMPLE), a static partial equilibrium model, in order to test long run prices for agriculture.

The SIMPLE model is named in part due to its high level of aggregation in the included regions and commodity coverage. The model uses the GTAP database, with aggregates combining all agriculture into three demand commodities (un-processed food, processed food, and livestock products). It splits the world into five demand regions (based on income) and seven supply regions (based on geography). The model aims to show the general trends in agriculture, and to test exogenous shocks and their impact on supply and demand.

In terms of model structure, SIMPLE focuses on three key exogenous inputs growth in aggregate demand for agricultural products; change in the availability of global agricultural lands; and change in agricultural yields. The response of agricultural prices to these three shifts is the key function of the model, which solves for an equilibrium global agricultural price and land-use (Baldos & Hertel, 2012). The model also employs a novel endogenous measure of TFP for crops.

One shortcoming of the model is that livestock and processed foods are not traded between regions, instead being assumed to be consumed domestically within their producing income regions.

The model was proposed in Hertel's seminal 'perfect storm' paper (2011) and has since been used in assessing a number of long run issues for agriculture and food security including climate change and agricultural productivity (Baldos & Hertel, 2014a; 2014b; Hertel & Baldos, 2016).

3.6.4 Mixed models

Some modelling frameworks are not exclusive of other approaches. Some have combined modelling approaches, or used complementary frameworks, to surpass the limitations inherent in one approach. For example, the previously mentioned CAPRI uses a duel PE/regional programming model framework.

Grant, Hertel and Rutherford (2007) combined GTAP, a CGE model, with a PE model in the GAMs modelling platform, to assess the Doha round of WTO trade negotiations at the individual tariff line level. Similarly to pure PE analysis this was restricted to a specific sub-set of one sector, focusing on the implications for traded dairy commodities. This approach to incorporating a PE element with GTAP is expanded in other GTAP publications (Hertel, 1997; Narayanan, Hertel & Horridge, 2010). GTAP has also been linked with the CAPRI model to incorporate whole economic effects in CAPRI's detailed analysis of the EU (Jansson, Kuiper & Adenäuer, 2009).

Similar to mixed model approaches, integrated assessment models (IAMs) combine multiple model frameworks, including those outside of economic models, such as bio-physical or climate models. IAMs are used predominantly for long-term projections of the impacts of climate change, Issues where the impacts manifest across many different areas, requiring the expertise of many disciplines and their associated modelling approaches.

GLOBIOM

The Global Biosphere Management Model or GLOBIOM model is a partial equilibrium economic model, however its links with other modelling frameworks (the EPIC model for crops, RUMINANT for most animals, G4M for forestry) place it in the integrated assessment category (Valin et al., 2013). Developed by the International Institute for Applied Systems Analysis (IIASA), the model was designed to quantify land use change in agriculture and forestry, and to assess the economic implications of these changes. The model has global coverage and has a bottom-up approach, in that the core drivers of the model are land-use and crop growth on the supply side of the model. The model solves to maximise producer and consumer surplus.

The GLOBIOM model is integrated with the EPIC crop model (Williams et al., 1989), which maps world crops at a five degree grid level. GLOBIOM considers six types of world land use: cropland; grassland; short rotation plantations; managed forest land; natural forest land; and other miscellaneous natural land. From these six land-types, 27 crops types, 7 animal types, and 5 wood products are considered. The distribution of crops in the gridded space of land-use uses a combination of FAOSTAT and EUROSTAT data allocated in the Spatial Production Allocation Model (SPAM). The GLOBOIM model has different management systems based on the levels of tillage and water used, differentiating between subsistence, rainfed, and irrigated farms. Additionally, through the inputs from the EPIC crop model, different crop yields can be simulated based on the crop rotations used. Input costs are based on input pricing data from the FAOSTAT database. This approach to cropping systems seems sophisticated; however, the logic behind the allocation of different farm systems and the extent of irrigated land is not made clear.

The modelling of livestock in GLOBIOM uses another secondary model, RUMINANT, which maps the inputs and outputs for the four ruminant animal types in the model, showing conversion rates for pasture and feed use. Conversion rates for the remaining animal types and feed conversion rates have been taken from the literature, although the exact sources are not disclosed, and presumably do not provide specific studies for many regions.

Forestry in GLOBIOM is split into short rotation plantations and managed forests. Which parcels of land are suitable for forests is determined by geographic indicators from Geographic Information Systems (GIS) data. The G4M model is used to provide production and processing data for the forestry systems in GLOBIOM. The four primary wood products roundwood (industrial and non-industrial), branches and stumps, and harvest losses, are converted into five products: sawn wood, wood pulp, energy wood, traditional use wood, and other non-energy use wood. The forestry industry in the GLOBIOM model also includes a number of input measures for the processing of wood products.

Shifts in production can occur as farmers change their behaviours in response to price shifts, converting from rainfed to irrigated systems, or by changing the level of inputs in a management system or style of crop rotation. Interestingly each production technology is modelled with its own explicit Leontif production function, implying static ratios of returns to inputs for each technology. The change in production is a function of the change between selections of production technologies.

The demand system for GLOBIOM accounts for food use, feed-use, energy use (wood and oilseeds processed as biofuels), and use of all non-energy wood products. Demand is reactive to changes in population and GDP (income as GDP/population), and changes in the consumer price of goods. This relationship is defined using elasticities from Seale, Regmi and Bernstein (2003). Nelson et al. (2014), in a meta-study describing different model's responses to climate change indicated that GLOBIOM's demand elasticities are higher than comparable models in the study.

Products in GLOBIOM are considered homogenous in international trade, and are exported from the region with the lowest production costs (including transport and tariff measures). The cost of trade does not scale constantly, so trade defers between regions past a certain point. This assumption seems contrary to reality where increased scale often promotes more efficient trade and lower trade costs.

GLOBIOM has been used to assess the impact on land-use from first and second generation bio-fuel mandates (Havlik et al., 2011), analysing impacts on deforestation, and the relative price changes for fuel and crops.

3.7 Conclusion

This chapter has summarised the relevant exisiting literature on modelling trade in global agriculture, including the component factors of global supply and demand, and some of the issues surrounding them. The section on trade modelling presents some of the most prominent and utilised models in this field and their structures, as well as some discussion on the strengths of different modelling approaches.

From this literature review it is apparent that different model types have diffeerent drawbacks and suitabilities. PE models may over-estimate simulate shocks, while CGE using the Armington approach may report lowere prices. In terms of suitability, model selection should be performed relative to the researh questions, with the scope of the study being a key factor. When focusing on one sector, such as agriculture, a PE apporach may allow for more comphrehesive coverage of detail, while the CGE approach may use borader aggregation but cover intra-industry responses and substitutions. IAM are powerful mixed models, and are designed to take a long-term perspective on climate change but are often constructed from a bio-physical or climate perspective first, which can lead to constraints on elements of their economic modules. This can makes IAMs less interesting from an economic perspective. Futhermore the complexity of some models made impede their flexbility for incorporating new elements as they have broad data requirements and high time costs to update, maintain or alter.

The SIMPLE model combines elements of PE and CGE approaches, using a CGE aggregate sector approach, within a single sector in order to reduced uncertainty for long term projections. This allows for a pure economic approach in a simple structure, which while inaapropraite for resolving research questions focused at the commodity level, is useful for broad questions about total agriculture.

The next chapter, Chapter 4, will present the research aim and objectives. Then this discussion of model types will form the grounds for selecting the most suitable methodological approach to address those questions in Chapter 5.

4. Research Aims and Objectives

4.1 Introduction

This brief chapter builds on the information presented in the literature review by identifying gaps in the literature which can be addressed in this thesis. The chapter will also present the research aim and the four research objectives which will be used to meet this aim.

As discussed in the introduction to this thesis (Chapter 1), there is a gap in the literature between short and medium economic models and integrated assessment models or climate models. The short- and medium- term PE and CGE models often do not feature structural elements which support long-term analysis and due to the complexity of their structures may suffer from high levels of uncertainty in long term projections. Integrated assessment models and climate models, while sometimes include economic components, often do not consider all facets which are present in a purely economic model.

Current challenges to agriculture and food security (discussed in Chapter 2), such as the question of structural change potentially leading to higher food prices, resource depletion and climate change, require a longer-term analysis than is offered by many of the economic PE and CGE models.

Furthermore, due to the increasing importance of TFP in the growth in agricultural production, and the long lags in returns on R&D spending in agriculture, an economic model with a longer-term focus appears to be the most appropriate for addressing some of these questions.

Notably, the SIMPLE model has led this approach. However, the SIMPLE model does not include TFP or trade for animal products and is static. Thus, the use of a new model which utilises long lags of R&D spending in their relationship with TFP, dynamic income elasticities to mimic the change in preferences associated with changes in income over the long term and incorporates TFP and trade for animal products would help add to the evidence on long term changes and challenges in agriculture.

4.2 Research aims and objectives

The aim of this research is to develop a novel economic model that capable of addressing four important research objectives:

1. To ascertain the prospects and directionality in real agricultural prices under the medium and long term, given credible projections of key macroeconomic drivers, as an indicator of aggeregate global supply and demand.

2. To test varying levels of total factor productivity in agriculture to determine whether there is sufficient potential for growth in agriculture relative to projections of long term growth in aggregate demand.

3. To assess the impacts on production, yields and world prices for agricultural commodities given the impacts of climate change on global yields.

4. To examine the impacts of long term developments in population and economic growth on the regional distribution of the production and consumption of agricultural commodities, and total greenhouse gases.

Thus, the thesis provides additional perspectives into an area of the literature focused on assessing the world prospects for food prices and global supply and demand over the medium and long term, incorporating a novel endogenous approach on total factor productivity in agriculture (although exogenous TFP factors are used for some scenarios).

4.3 Conclusion

This chapter has outlined the research aims and objectives of the thesis and has highlighted the areas in which a novel contribution to the literature on agricultural trade modelling and productivity will be made.

The next chapter will introduce the structure and component data and parameters of the model which will be used to perform scenario analysis in order to address the research questions and illuminate some of the issues around long-term challenges in global agricultural markets.

5. Methodological approach, model specification and structure

5.1 Introduction

This chapter builds on the review of the literature in Chapter 3, in order to present a suitable methodological approach in order to best address the research questions put forward in Chapter 1.

The proposed research concerns the outcomes of long-term changes and challenges to agriculture. As examined in the literature review, economic modelling is a robust and widely used empirical methodology for assessing long-term changes in agricultural prices and production (Baldos & Hertel, 2014a; von Lampe et al., 2014; Muller & Robertson, 2014; Schmitz et al., 2014; Schneider et al., 2011; Valin et al., 2014). The two main model types used for this type of inquiry, as identified in the literature review, are partial equilibrium and general equilibrium models. Appropriate model selection for assessing the selected research questions is key to the correct application of an economic modelling approach.

Of the examined model types, a partial equilibrium model appears to be the most suitable for this research, as the research questions concern the agricultural sector, with minimal linkages to other sectors of the economy. By focusing solely on one sector of the economy, partial equilibrium models can devote a greater focus to the linkages and workings of that sector. Furthermore, due to the size and scope of general equilibrium models, there is broadly less potential for alteration of an existing model. They are often developed by large consortiums of researchers, so access can be a restrictive issue. Further, the size and scope of the data requirements for populating and managing all sectors of the economy can limit the feasibility of the research. Due to these constraints, the more accessible and flexible nature of partial equilibrium models with allow for further testing and comparison of the key drivers of the model, which will assist in reducing the levels of uncertainty over long-term projections, a key component of the analysis in this thesis.

Extending a short-term model over a 50- to 100- year timeline would require exogenous inputs which cover the same time span. Confidence intervals will expand over these long-term horizons, making the selection of likely outcomes difficult. The suitability of parameters may also need to be assessed, whether parameters specified on short-term data hold over a long-term horizon. Long term elasticities of supply are usually more elastic for example as greater adjustments can be made over a longer time span.

The review of the literature reveals that no appropriate model exists which simultaneously has an economic focus and is suitable for long-term analysis addressing the very long lag in returns to agricultural productivity (up to 100 years). The closest candidate is the SIMPLE model. This model however does not consider productivity for animal products and is a static model. This restricts its ability to understand the gradual change over time and the year-on-year lags on returns from research spending.

Consequently, the approach taken in the thesis is to create a novel dynamic partial equilibrium model using a similar approach as the SIMPLE model, but with an additional focus on the supply of animal products to allow the assessing of productivity change over the long-term, and of climate change related impacts. The LAO model also allows for the interregional trade of crop and livestock products in a net trade approach.

Scenario analysis is often used in economic modelling to compare the relative impact on global markets between potential futures. Scenario analysis can also highlight the relative magnitudes of the impacts of changes in particular key drivers in the model.

The method used to answer the research questions posed in this thesis will therefore be comparative scenario analysis using this specifically designed long-term partial equilibrium model. The model is called the Long-term Agricultural Outlook model or LAO and its structure is modelled in the General Algebraic Modelling Systems (GAMS) mathematical programming platform (version 24.5.4). The CONOPT large non-linear programming solution algorithm is utilised, as it is suitable for use in dynamic non-linear programming such as the LAO model.

5.1.1 Coverage

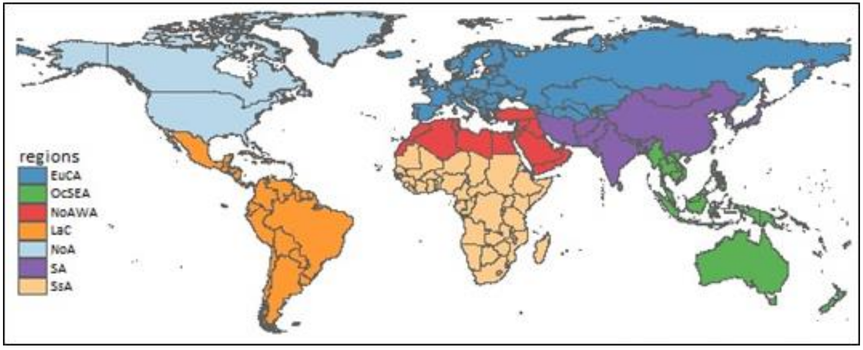
Regions

As with the SIMPLE model, LAO has a global coverage, and uses large regional aggregation. The SIMPLE model uses the income grouping from the World Bank Development Indicators (2003), placing all countries into five regional groups for demand and seven for supply. LAO uses seven regions (Table 2, Figure 6). These regional grouping are based on the regional aggregations used in the FAOSTAT database, to better align the structure of the model with the primary data source. Central Asia has been included in a single region with Europe in order to minimise identification errors for the inclusion or exclusion of post-Soviet states in historic time-series data, used for the parameterisation of the model. The country compositions of these regions are listed in Appendix Table X1)

Table 2: Regions in LAO

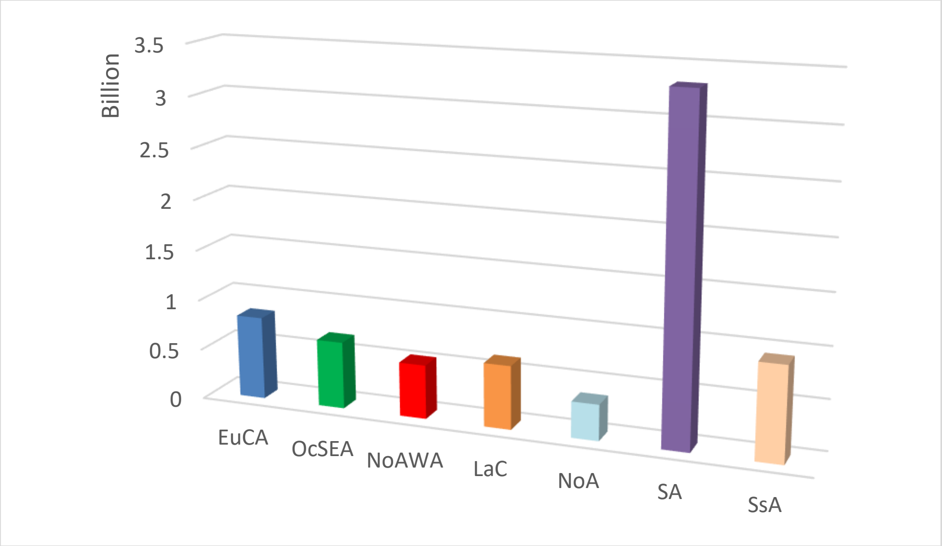
Code	Region
EuCA	Europe & Central Asia
OcSEA	Oceania & South-East Asia
NoAWA	North Africa & West Asia
LaC	Latin America & Caribbean
NoA	North America
SA	South Asia
SsA	Sub-Saharan Africa

Figure 6: Regional coverage in LAO



One limitation of this regional grouping is the relative size of regions. The South Asia (SA) region[9] encompasses China and the Indian subcontinent, two of the most populous regions in the world. The resulting imbalance in terms of the population of respective regions is illustrated in Figure 7. This imbalance may obfuscate specific impacts within subregions of the large South Asia grouping.

Figure 7: Total population by region, 2012



Source: UNDESA (2019a)

---

[9] The 'South Asia' regional grouping includes the East Asia region. This nomenclature of the 'South & East Asia' region was not used in order to avoid confusion with the 'Oceania and South-East Asia' region. Future versions of LAO may utilise the 'South & East Asia' region or split 'East Asia' into a separate region.

5.2 Data

The majority of data used for the model has been taken from the annually updated FAOSTAT database (FAO, 2019c), and supplemented with data from the OECD-FAO Agricultural Outlook database (OECD-FAO, 2019b) and the FAO Fishery databases (FAO, 2019d; 2019e). Macroeconomic data are from the UNDESA population projections (2019a); the IMF world economic outlook (2019); and the IEA energy projections (2019).

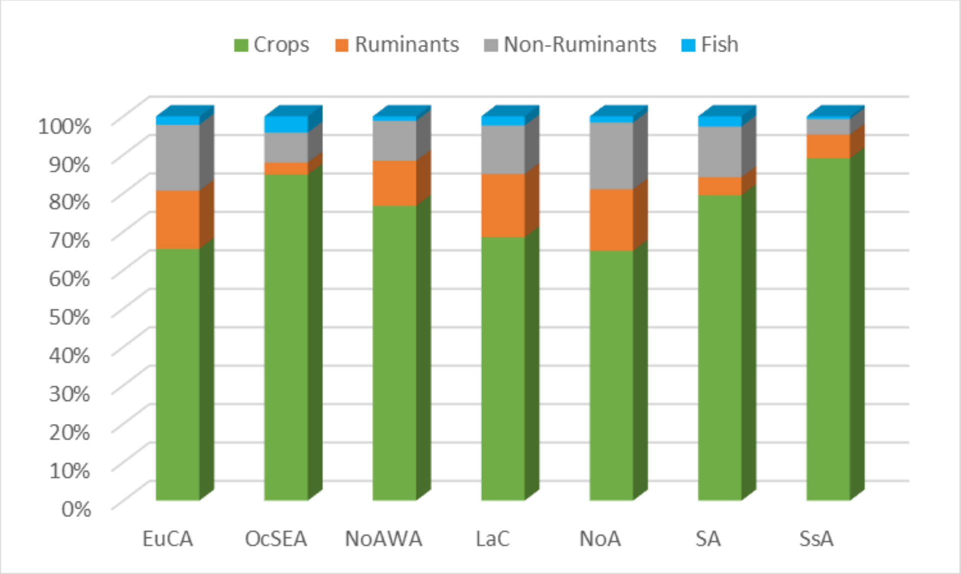
The FAOSTAT database (2019c) provides a standardised database with broad coverage and internal consistency, including quantities of production, processing, trade, stocks, and consumption for 161 crops (Appendix Table X2), 31 primary animal products[10] (Appendix Table X3), and 47 processed goods (21 crops, 26 animal products). The FAO database also provides domestic profiles of commodity balances, which account for the balance between production, different sources of consumption, and changes in ending stock rates. This information also includes the trade balance and imports and exports of agricultural commodities. This data is supplemented with data from the OECD-FAO Agricultural Outlook database (OECD-FAO, 2019b) and the FAO Fishery databases (FAO, 2019d; 2019e).

Figure 8 shows the regional shares of consumption as food for each modelled commodity type. The crops commodity makes up the majority share of food consumption in each region. Oceania & South-East Asia, South Asia, and Sub-Saharan Africa do not have a large share of ruminant animal products in their aggregate diet. Oceania & South-East Asia has the highest proportion of fish in their diet, although it remains a small share comparative to other commodities.

---

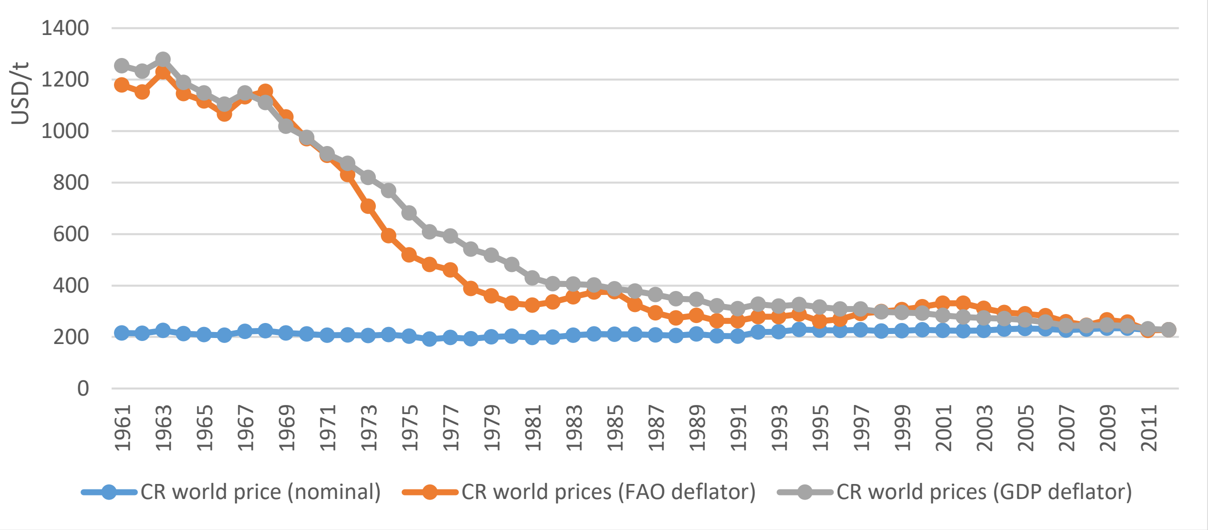
[10] Meat (excluding poultry) is given in dressed carcass weight, minus offal and slaughter fats. Poultry meat is measured as ready-to-cook weight or ready-to-cook weight equivalent

Figure 8: Consumption as food by commodity and region, 2012



Producer price data is also gathered from the FAOSTAT database, which provides data on prices and total value of production. The nominal prices from the FAOSTAT database are then deflated using the FAO food price index (FAO, 2019a). Figure 9 displays the comparative historic pricing for different deflators, including the implied deflator from World Bank GDP data (2020a), and the FAO food price index deflator used in the LAO model.

Figure 9: Real price deflators for the crop commodity, 1961-2012



Source: FAO (2019a); World Bank (2020a)

5.2.1 Macroeconomic data

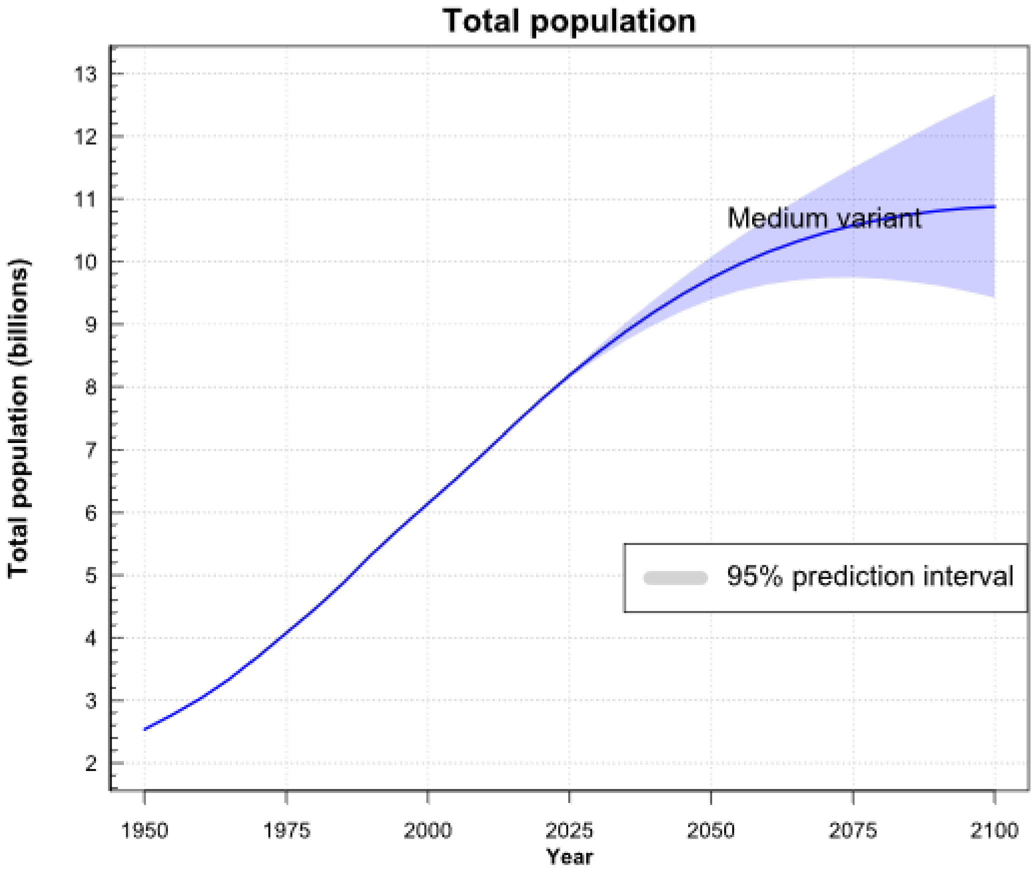
The model utilises some exogenous data to inform the progression of the world economy over the long-run. These projections are taken from international sources, which are listed under the ensuing sub-headings. Any given macro-economic projection also embodies assumptions about the development and likely economic future over the long-run. In this way, even constructing a baseline for the model is similar to scenario analysis in testing the possible macro-economic futures.

Fortunately, the simple framework of the model is designed to allow for changes to the structure and data of the model. This minimises the additional time cost of testing various macro-economic data from other sources, and of performing sensitivity analysis on different sources of macro-economic projections.

Population

The principal source for population data is the UN Department of Economic and Social Affairs, population division's projections (2019a). The UNDESA provides a range of different projections based on different projections of fertility, mortality rates; these projections run out to 2100. The UNDESA relies on national census data, and historic data on mortality and fertility rates in order to estimate global demographics (UNDESA, 2019b). Probabilistic methods are used for projections of fertility, implying a range of possible outcomes. The 'medium-fertility' variant is used as the benchmark population projection for the baseline (Figure 10). The high and low fertility variants are used for framing the outer bounds of possible outcomes.

Figure 10: UNDESA medium variant population



Source: UNDESA (2019a)

The population data taken from the UNDESA projections are aggregated according to the LAO model's regional grouping. The resulting population prospects by LAO's groupings are displayed in Figure 11. In order to better illustrate the majority of regions with regional populations of under one billion people at the beginning of the projections (2012) they are displayed separately in Figure 12.

Figure 11: Total population by region in LAO, 2012-2100

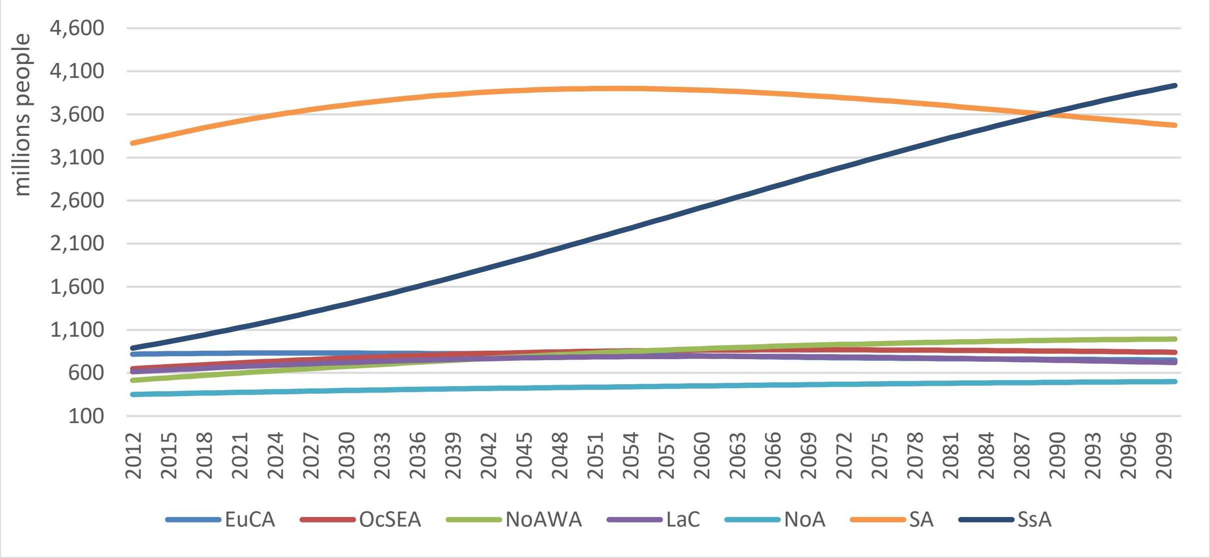
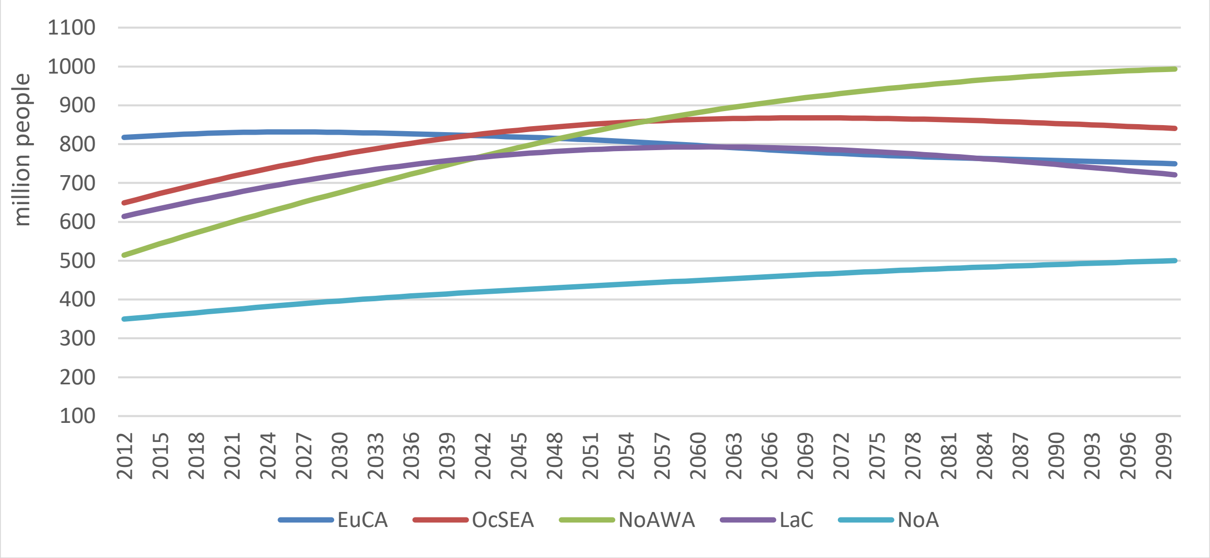
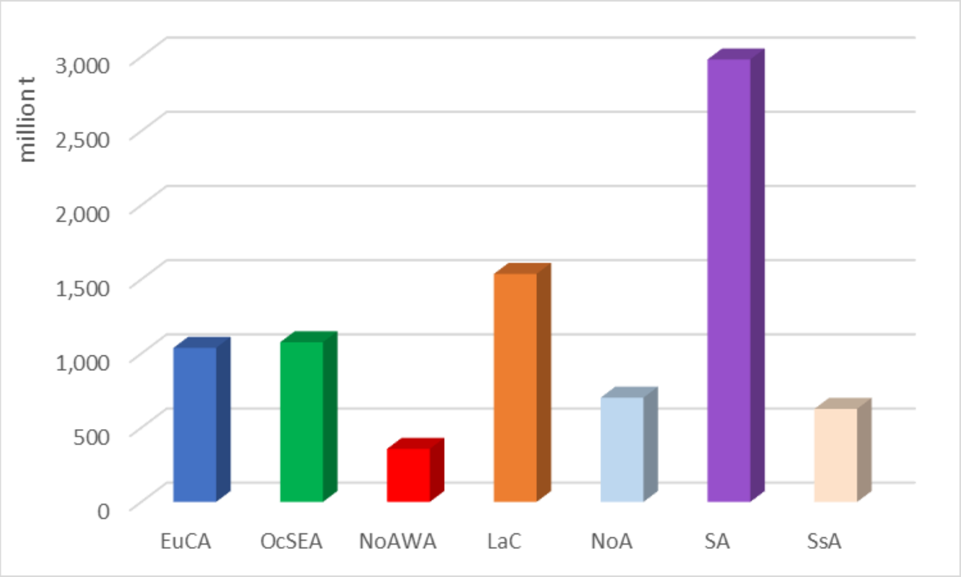


Figure 12: Total population by region in LAO (regions under 1 billion total population), 2012-2100



Recall from Figure 7 that there is a significant discrepancy in the regional distributions of population between 'South Asia' and the rest of the regions in 2012. The projected growth in population for the 'sub-Saharan Africa' region grows significantly between 2012 and the end of the century. The large discrepancy between populations in these regions should not impact upon the functioning of the model, as long as the respective total demand and production are comparable between regions. The disparity between these regions is less pronounced when examining productive capacity (Figure 13). Yet South Asia is the largest producer of the selected regions.

Figure 13: Total production of crops by region, 2012



GDP

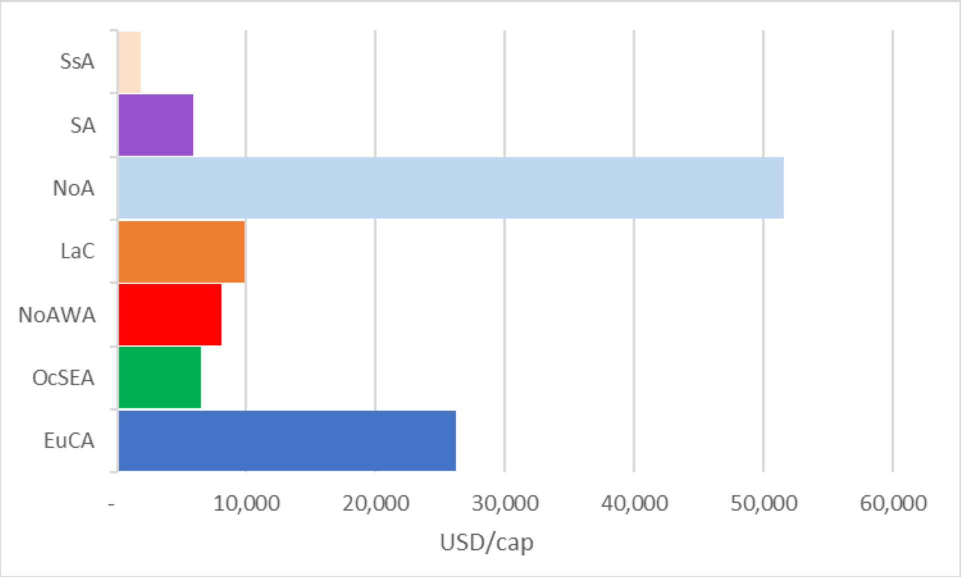
While the UN projections of population are a widely used measure globally for long-term population projections, there is no equivalent predominant source for measures of global GDP, especially one that projects over such a long time horizon as the UNDESA population projections. The economic prospects of nations are much more uncertain, and are reliant on many factors (population among them). Therefore, the reliability of GDP projections must be treated with some caution, and provides a candidate for testing through the use of scenario analysis to frame the potential bounds of the development of GDP into the future.

The GTAP database 10 uses the World Bank Development Indicator database (World Bank, 2020a; Aguiar et al., 2019) for historic GDP data. The World Bank also publishes the Global Economic Prospects report (World Bank, 2020b), a bi-annual dataset with short-term projections of GDP (currently out to 2021). The IMF also provides a projection of GDP to 2024 in the World Economic Outlook Database (IMF, 2020). This is also used for the GDP baseline in the Macroeconometric of the Global Economy (MaGE) model (Fouré, Bénassy-Quéré & Fontagné, 2012; 2013), which is used to project GDP out to 2050, based on capital, energy and labour supply. The EconMap database (CEPII, 2016), which contains the projections from the MaGE model, also provides projections to 2050, under the five SSP scenarios; including key macro-economic factors and total productivity rates by country. Lastly, PWC also published a report on the prospective global economic future in 2050, including PPP GDP projections (2017).

The baseline scenario of the LAO model uses IMF GDP data projected out to 2050 using a country-level linear projection. However, other GDP projections are tested in the modelling framework.

The resulting average income per capita in 2012, the LAO model's base year, from the selected baseline scenario GDP and population projections are shown in Figure 14. North America and Europe & Central Asia are the two wealthiest regions with over 50,000 USD per person, and over 25,000 USD per person respectively. All other regions have less than 10,000 USD per person on average, with Sub-Saharan Africa showing the lowest average income at 1,849 USD per person.

Figure 14: Income per capita by region, 2012



Other macro-economic data

Oil prices are another key exogenous input for the model. Projections of oil price for the model's baseline has been sourced from the IEA energy projections (2019).

5.3 Model Structure

The following section details the structure of the LAO model. This includes the equations central to the model. The assigned subscript notation universal to all equations in the LAO model are as follows:

r – region
c – commodity
cc – crop commodity
ac – animal commodities
t – period

The principal equations in LAO are specified in a log-log form, mirroring those in the structure of Aglink-Cosimo, which uses a similar partial-equilibrium structure (OECD, 2015). The structure of an earlier version of the LAO model is also described in an OCED working paper (Saunders, Adenauer & Brooks, 2019).

5.4 Trade and market clearing

The central equation for the LAO model is the world market clearing equation (Equation 1). This is the target for the solver driving the model. The sum of global net trade for each commodity is driven to zero, ensuring a closed system of world trade. This is performed by solving for a set of world prices in the multi-regional and multi-commodity system which balance aggregate supply with demand for each commodity across the regions. This also allows for individual regions to have non-zero rates of net-trade, while aggregate net trade is zero. As each product is homogenous from different export sources, bi-lateral trade is not tracked in the LAO model. .

Equation 1: world market clearing

$$\sum_r QT_{r,c,t} = 0$$

where:

QT – quantity net trade

Equation 2 shows the composition of quantity traded for each commodity and region. The quantity traded is the remainder from domestic supply, less all forms of demand (feed, food, and use for biofuels) and the change in domestic stocks from the current period to the last. Any deficit or surplus is resolved on the world market. As with all volumetric measures of commodity production and consumption in the LAO model, the units of net trade are million tonnes of commodity.

Equation 2: net trade

$$QT_{r,c,t} = QP_{r,c,t} - QF_{r,c,t} - QC_{r,c,t} - QB_{r,t} + \Delta QS_{r,c,t_{-1}}$$

where:

QT – quantity net trade
QP – quantity produced
QF – quantity consumed as feed
QC – quantity consumed as food
QB – quantity processed for biofuel-use
QS – quantity held as stocks

5.5 Supply

5.5.1 Crops

The quantity of crops produced in the LAO model is simply the yield per hectare multiplied by the total area harvested (shown in Equation 3).

Equation 3: quantity produced (crops)

$$QP_{r,t} = AH_{r,t} \cdot YD_{r,t}$$

Where:

AH – area harvested

YD – yield

QP – quantity produced

Area Harvested

Spatial information is not implicit in the modelling framework. Instead, the regionally aggregated harvested area for different crops is considered. This can allow for trade-offs between different land-uses through price elasticities, but not in explicit trade-offs in particular parcels of land, or utilising land prices for determining their usage, such as those used in GTAP and the SIMPLE model.

Equation 4 shows the equation governing the behaviour of area in LAO. This equation denotes that, changes in area harvested are driven by the own price of the crop, and a rolling average of producer prices. The rolling average of previous prices is included in order to simulate producer's price expectation, based on the last five years of prices. This factor will lead to a partial lag in changes to area harvested from producer prices.

Equation 4: area harvested[11]

$$log(AH_{r,t}) = MIN\left(a + \sum_{cc} \beta_{r,cc}^{ppAH}\, log(pp_{r,cc,t}) + \beta_{r}^{rap}\, log(rap_{r,t}), WATERMAX_{r}\right)$$

Where:

AH – area harvested

WATERMAX – max area allowed by freshwater required

rap – 5-year average producer price

pp – producer price

The *WATERMAX* function is a maxima condition for water usage in each region applied to the standard area harvested equation, a hard limit for the expansion of area harvested. If the projected area harvested (based on changes to producer prices) exceeds *WATERMAX*, total area harvested will be set at the level of *WATERMAX*. This does limit the elasticity of supply for area harvested and the own-price elasticity would be expected to change as the area harvested approached one of these limits. However, this is not reflected in the current structure of the model.

WATERMAX is calculated from the World Bank World Development Indicators database (2020) which provides the annual freshwater withdrawals for agriculture, domestic, and industry by country; as

---

[11] All logarithms in this and other equations are natural logarithms.

well as the renewable internal freshwater resources. The LAO model projects increases in domestic and industrial usage relative to the projected shift in population (for domestic usage) and GDP (for industrial usage). The level *WATERMAX* is set at the remaining renewable freshwater minus domestic and industrial usage in each projected year[12].

Yield (crops)

The other component of production is yield. The yield equation is shown below (Equation 5). This equation includes some of the key novel modelling components, including the use of TFP, which is explained further in Section 5.5.5. Yield in the model is a function of the own-price for crops, and the cross-price elasticities for other land-based agricultural commodities; the cost index, which simulates levels of input pricing; levels of total factor productivity; and the world price of oil. The specification of the cost index and TFP are expanded upon in sections 5.5.6 and 5.5.5 respectively.

Equation 5: yield (crops)

$$\log(YD_{r,t}) = a + \beta_r^{ppYD}\log(pp_{r,cc,t}) + (\beta_r^{ci}\log(ic_{r,t}) + \beta_r^{tfp}\log(tfp_{r,t}) + \beta_r^{op}\log(op_t)$$

Where:
YD – yield
op – world oil price (index)
tfp – total factor productivity (index)
ic – input cost index
pp – producer price

5.5.2 Supply (animal commodities)

The basic structure of production for animal commodities is conceptually similar to that for crop production, except area harvested is replaced by total animal numbers, and yield in this context refers to product per animal head. The general production equation for animal commodities is Equation 6, where production is animal numbers multiplied by yield per animal.

Equation 6: quantity produced (animal)

$$QP_{r,ac,t} = AN_{r,ac,t} \cdot YD_{r,ac,t}$$

Where:
AN – animal numbers
YD – yield
QP – quantity produced

---

[12] This implies that agricultural uses have the lowest priority for growth out of the three uses, merely as a by-product of the exogenous sources of growth used for the two other uses.

Animal numbers

Similar to the specification of area harvested for crop commodities, the equation for animal numbers is a function of own- and cross- price elasticities and a 5-year rolling average of producer price to simulate farmer's medium term price expectation (Equation 7).

Equation 7: animal numbers[13]

$$\log\left(AN_{r,ac,t}\right) = a + \sum_c \beta_{r,ac,c}^{ppAN} \log(pp_{r,ac,t}) + \beta_r^{rap} \log(rap_{r,ac,t})$$

Where:
AN – animal numbers
rap - 5-year average producer price
pp – producer price

Yield (animal products)

In this thesis, the term 'yield' has been used for both the yield of crops, and also to the quantity of product produced from each animal. This is to highlight the similarity in the way in which the two are treated within the modelling framework. The components making up the input factors and TFP for cropping and animal products are of course different, but the specification of production per ha, and production per head is the same. As with yield for crops, the yield equation for animal products (Equation 8) shows that yield is a factor of own- and cross-price elasticities; a cost index; TFP; and the world price of oil. The specification of the cost index and TFP are expanded upon in sections 5.5.6 and 5.5.5 respectively.

Equation 8: yield (animal)

$$\log\left(YD_{r,ac,t}\right) = a + \beta_r^{ppYD}\log\left(pp_{r,ac,t}\right) + \beta_{r,ac}^{ci}\log(ic_{r,ac,t}) + \beta_{r,ac}^{tfp}\log(tfp_{r,ac,t}) + \beta_r^{op}\log(op_t)$$

Where:
YD – yield
op – world oil price (index)
tfp – total factor productivity (index)
ic – input cost index
pp – producer price

5.5.3 Supply (fish)

The supply equations for fish commodities are much less complex than those for the crops and animal products. Fish is divided into two commodities: fish from capture, and fish from aquaculture.

---

[13] Animal numbers are not modelled as having a TFP component, as area harvested does not. Although in both cases technological improvements could be made to increase the viability of cropland or improved birth rates of animals, this is outside the scope of this research, but would constitute valuable research for the future.

These two commodities are perfect substitutes in terms of demand, but are produced in different ways, represented in the modelling with two distinct supply equations.

Equation 9 is the supply equation for fish from aquaculture. Own- and cross-price elasticities are considered, as well as the world price for oil, a key input. As TFP is not considered for fish commodities in the model, a trend variable is used to replicate technological growth and improvements in productivity. The price of fishmeal has not been included in the supply equation for fish from aquaculture. The cross-price effect for the price of fish from capture however has been considered for all regions.

Equation 9: supply (aquaculture)

$$\log\left(QP_{r,t}\right) = \mathrm{a} + \sum_c \beta_{r,c}^{pp} \log(pp_{r,t}) + \beta_r^{op} \log(op_t) + log(\beta_{r,t})$$

Where:
QP – quantity produced
pp – producer price
op – world oil price (index)

Equation 10 is the supply equation for fish from capture. Structurally this equation is identical to the supply equation for fish from aquaculture, with the addition of a maximum. This limit on production is included to simulate the potential limit of fish stocks in the ocean. This limit is based on Ye et al. (2013), which estimated the potential world production given fish stocks were maintained at maximum sustainable yield levels, a target from the world summit on sustainable development in 2002.

Ideally, fish stocks would be specified separately and with a dynamic response to overfishing, where if supply exceeded sustainable levels, overall potential stocks for future period would be reduced. However, this is beyond the scope of the thesis given the relative minor focus on fisheries.

Equation 10: supply (fish from capture)

$$\log\left(QP_{r,t}\right) = MIN(a + \sum_c \beta_{r,c}^{pp} \log(pp_{r,t}) + \beta_r^{op} \log(op_t) + log(\beta_{r,t})\ , maxfs_r)$$

Where:
QP – quantity produced
pp – producer price
op – world oil price (index)
maxfs – maximum regional fish stocks

5.5.4 Producer and consumer price

The prices in the LAO model are based on historic data. Year by year regional prices are defined by the world price, which is set by the world market clearing equation (Section 5.4). The price wedges account for the various tariffs and support measures on either the supply or demand side. Historic world prices have been calculated as an export weighted aggregate of national producer prices, i.e., the more of the world's export share is provided by a country, the more of the world price their producer price accounts for. The wedges *sp* and *cp,* are wholly synthetic, representing the difference between this world price and the regional producer prices in the base period (2008-2012). Therefore, these wedges are not tracking real data on price supports and tariffs, but instead the theoretical distance between regional producer prices and the world price. The consumer and producer price wedges are static. That is, they are held at their initial values unless changed exogenously as part of a scenario. Equation 11 shows the simple price equation for the supply side, whereas Equation 12 shows the similar equation for demand, the only difference being a unique price wedge representing differences in consumer prices.

Equation 11: producer price

$$pp_{r,c,t} = wp_{c,t} \cdot sp_{r,c,t}$$

Where:

pp – producer price

wp – world price

sp – producer price wedge

Equation 12: consumer prices

$$pc_{r,c,t} = wp_{c,t} \cdot cp_{r,c,t}$$

Where:

wp – world price

pc – consumer price

cp – consumer price wedge

5.5.5 Total Factor Productivity

As described in Chapter 3, yield growth can be attributed to the increase in the use of inputs, or the increase in total factor productivity. Growth in agricultural total factor productivity can be thought of as the product of advancements in research and development as they are realised and disseminated. Fuglie's measure of TFP is a value measure rather than a measure of quantity output, and thus has been incorporated in the equation structure as factor of yield, rather than as a multiplicative index of total output above input. The structure of supply in the model takes this lagged response to spending in agricultural research and development, as well as incorporating the elements of Alston's research on spillovers in research and development between regions. By using a long-term horizon in the modelling framework, a longer lag of flow-on effects of investments into research and development can be accounted for over 35 years, in line with the findings of Alston and Pardey (2001).

Two recent proposed lag structures for returns to R&D spending are explored in Alston et al. (2011), and Fuglie (2017); the two methods are shown below in Equation 13 and Equation 14.

Equation 13: Gamma lag distribution (Alston method)

$$b_k = \frac{(k-g+1)^{(\delta/1-\delta)}\lambda^{(k-g)}}{\sum_{k=0}^{L_R}[(k-g+1)^{(\delta/1-\delta)}\lambda^{(k-g)}]}$$
$$\text{for } L_R \geq k > g;\ \text{otherwise } b_k = 0$$

Source: Alston et al. (2011)

Where:
k – period
g – gestation lag
L_R – Total lag length
δ – defines lag shape
λ – defines lag shape

Equation 14: Gamma lag distribution (Fuglie method)

$$b_k = \frac{(k-g-1)^{\left(\varphi/1-\varphi\right)}\theta^{(k-g)}}{max\left[(k-g-1)^{\left(\varphi/1-\varphi\right)}\theta^{(k-g)}\right]}$$

Source: Fuglie, 2017

Where:
k – period
g – gestation lag
L_R – Total lag length
θ – defines lag shape
ϕ – defines lag shape

Both methods rely on estimating the best fit for lag parameters. Alston et al. (2011) used feasible generalised least squares to assign values to the lag shape, then a grid search to find best fit for the length of period and gestation lag. The LAO model uses this method for lag length and shape. The time-series for R&D spending was constructed from UNESCO GERD (2019) database on spending on Agricultural Science, and OECD agricultural science domestic R&D spending (OECD, 2014). The estimate best fit for the UNESCO and OECD data found the following parameters for returns to R&D spending[14]:

g = 0

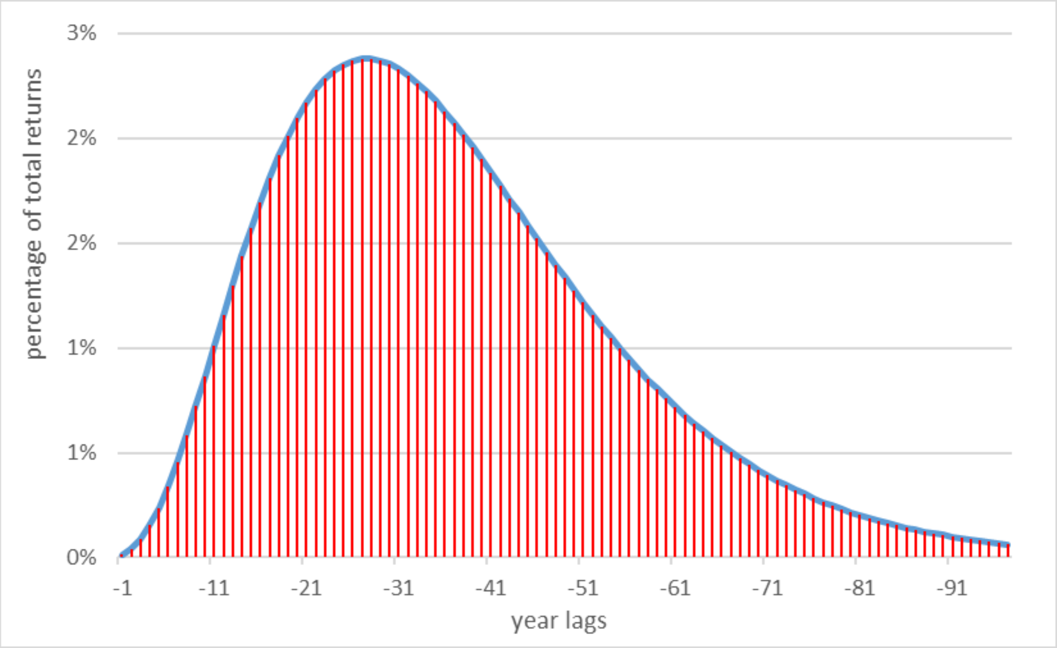
δ = 0.9

λ = 0.75

$\sum bk$ =1

These parameters set for the LAO model result in the lag shape shown in Figure 15. This lag shape has its peak of returns in the 25th year after the research spending and lasts for 97 years until all returns are realised[15].

Figure 15: Lag on research and development spending in agriculture in LAO model



Spillover

Alston's method from the 2002 paper is used for the relation and spill-over of research from different regions. The comparative similarity of agriculture outputs between regions is used to judge the relevance and applicability of research investments in other regions, as shown in Equation 15[16]. The

---

[14] Best fit was estimated using a linear equation using TFP as the dependant variable and total global lagged spending and total global spillover spending as the independent variables. The resulting SSE and Adj. R^2 are shown in Appendix Table X4. No gestation lag was assumed as in Alston et al., 2011.

[15] As a result of this lag structure, historic prices will be influencing future TFP for 97 years past the base year.

[16] The spillover weighting is symmetrical, merely showing the compatibility of the region's agriculture production by commodity. Spillovers only occur in proportion to the extent of each region's research and are parameterised. In this way, they are regionally distinct; greater spillovers will occur from regions performing more research; and regions for which spillovers are a minor factor will be reflected through the estimation of the spillover elasticity.

resulting spill-overs between regions are shown in Appendix Table X5, Table X6 and Table X7, for crops, ruminant animal products, and non-ruminant animal products, respectively.

Equation 15: Spill-over weighting in LAO model

$$rds_{r,c,t} = \sum_{r1 \neq r2}^{nr-1} rd_{r,c,t-yl} \cdot \left(\frac{\sum_{m=1} f_{r1m} f_{r2m}}{\left(\sum_{m=1} f_{r1m}^{2}\right)^{1/2} \left(\sum_{m=1} f_{r2m}^{2}\right)^{1/2}} \right)$$

Subject to:

$$0 \leq f_{rnm} \leq 1\,; \sum_{m=1} f_{rnm} = 1$$

Where:

rds – Ag. R&D investment spill-over
rd– Ag. R&D investment (% of GDP)
f – value of output (% of total Ag. Output)
m – different agricultural commodities
yl – gamma lag

Periods of high prices

The final component of the total factor productivity equation is a measure of periods of relative high prices. This measure is intended to simulate the ability of producers to re-invest in new technologies. If the current period is one of relative high returns, there is more opportunity for reinvestment. The uptake of new technologies is an important component in the development of new technologies and practices. Equation 16 shows this specification of the periods of high prices, the period of high prices is only active if the average price in the last 3 years is higher than the average producer price of the last ten years. If this is the case then *hp* is set as this proportion, whereas if the average price of the last 3 years is less than the average of the last ten years, the *hp* variable is set to 1. The potential size of this proportional modifier was set at 1.03.

Equation 16: periods of high prices

$$hp_{r,c,t} = hp_{r,c,t-1} MIN\left(1.03, MAX\left(1, pp_{r,c,t-2,-4}^{AV3} / pp_{r,c,t-5,-15}^{AV10}\right)\right)$$

where:

pp^{AV3} – Average producer price in past 3 years

pp^{AV10} – average producer price in past 10 years

hp – period of high prices

The resulting specification for TFP, incorporating all the previously discussed elements, is presented below in Equation 17 in a log-log specification.

Equation 17: total factor productivity

$$\log(tfp_{r,c,t}) = a + \beta_{r,c}\log(rd_{r,c,t-\gamma l}) + \beta_r^{rds}\log(rds_{r,c,t-\gamma l}) + \beta_r^{hp}\log(hp_{r,c,t-2})$$

where:

tfp – total factor productivity (index)
yl – gamma lag distribution
rd – Ag. R&D investment (as proportion of GDP)
rds – Ag. R&D investment spillover
hp – period of high prices

5.5.6 Inputs

Input prices are a strong driver of agricultural product prices, and the distribution of costs between inputs can heavily influence the production methods used, and the viability of different crops. For example, the relative prices of land and non-land input factors can determine whether the intensification of farming methods increases (Hertel & Baldos, 2016).

In the context of constructing a global model with wide commodity inclusion, input prices pose a challenge. There is, of course, a strong influence from the change in input prices upon farmers' behaviour and thus final production. However, there are few, if any, sources of global data for input prices. Furthermore, the lack of comparability in factor prices between different methods of farming, or regions, is limited at best. The necessary data gathering and standardisation between regions required to adequately derive production responses to input prices for the majority of primary products and regions is far beyond the scope of this research inquiry, and likely the research community, for the near future.

It is possible to gather data for some inputs. Fuel is a key agricultural input, and oil price is a readily available metric. Labour prices are also available, with ILOSTAT providing country level data for labour costs per worker (ILO, 2020). However, this labour price has limited global coverage, especially as a time-series, which is necessary for assessing the rate of change in wages.

An alternative to using explicit input prices is the use of a combined index of input pricing. This can assess changes in total input costs, and the relative cost-shares of different inputs, without the need for comprehensive annual data.

Aglink-Cosimo utilises this index approach with an index of input costs as a key component of the supply specification for domestic agriculture production (OECD, 2015). The Aglink-Cosimo cost index incorporates relative cost shares for different factors: non-tradeable inputs, energy, fertilisers, seeds, and lastly other tradeable inputs. The change in these shares is motivated by changes in GDP, GDP deflation rates, and the price of crude oil (adjusted for local exchange rates).

An index of input costs is utilised in the LAO model structure to account for the relative shifts in input costs (Equation 18). This method is taken from Peterson (1988), where an index of input costs is constructed from the relative weightings of factor shares of individual inputs (Equation 19). For the LAO model the relative shares of inputs are taken from Fuglie (2012), which in turn aggregates the inputs from the FAOSTAT database (FAO, 2019c).

Equation 18: input cost index

$$ic_{r,c,t} = \sum_{i=1}^{n} \omega_{i,r}\, P_{i,r,t}$$

Equation 19: factor shares of inputs

$$\omega_{r,i1} = a \cdot X_{r,i1} \cdot \bar{X}_{i2} \cdot \ldots \bar{X}_{in}$$

subject to:

$$\sum_{i=1}^{n} \omega_{r,i} = 1$$

where:

ic – input cost index
ω – factor share of input
i – input (1,2…n)
P – index of input/output price ratio
X – observed level of input
Ẍ – mean observed level of input

5.5.7 Demand

The structure of the demand equations is explained below. The parameters governing the elasticities in the equations is expanded in section 5.6.1. This section includes intermediate input demand for agricultural products as well as final demand for food.

Consumption as food

Consumption as food is a factor of own consumer prices, relevant cross-prices for substitute and complimentary commodities, then the demographic factors of income and population. Equation 20 shows this demand specification, and Equation 21 breaks down the income elasticity, as it is specified separately preceding Equation 20. The specification of the income elasticities is expanded upon in section 5.6.1.

Equation 20: demand (product consumed as food)

$$\log\left(QC_{r,c,t}\right) = a + \sum_c \beta^{pc}_{r,c,c} \log(pc_{r,c,t}) + \beta in_{r,c,t} \log(GDP_{r,t}/pop_{r,t}) + \log(pop_{r,t})$$

Equation 21: income elasticity

$$\beta in_{r,c,t} = a + \beta^{in}_{r,c} \log(GDP_{r,t}/pop_{r,t})$$

where:

QC – quantity consumed as food

pc – consumer price

GDP – gross domestic product

βin – income elasticity

in -income

pop – population

Consumption as feed

Feed consumption is a factor of consumption prices and the production of animal commodities. A trend variable is also included in the specification in order to track general changes in the use of feed relative to the quantity produced of animal products. Equation 22 shows the demand for feed as it is applied in the model.

Equation 22: demand (product consumed as feed)

$$\log\left(QF_{r,c,t}\right) = a + \beta^{pc}_{r,c} \log\left(pc_{r,c,t}\right) + \sum_c \beta^{qp}_{r,c,c} \log\left(QP_{r,ac,t}\right) + log(\beta_{r,t})$$

where:

QF – quantity consumed as feed

pc – consumer price

QP – quantity produced

Biofuels

Demand for crops for use in first generation biofuels is a factor of the own price of crops and the price of oil. As the use of crops in biofuel production is also dictated by government mandates, a minimum consumption is assumed, in an attempt to mimic the mandated levels of production. This minimum consumption of crop commodities for use in creating bio-fuels is set as an exogenous variable. In the model baseline this variable is set at the level of biofuel consumption in the base year, as taken from the FAO database (FAO, 2019c). This level can be shifted in the future years of model's projections, but these levels are not endogenously calculated as part of the model's solving process. Equation 23 shows this formalised, as it is expressed in the modelling framework.

Equation 23: demand (products consumed in biofuel production)

$$\log\left(QB_{r,t}\right) = \text{MAX}\left(a + \beta_r^{pc}\ \log\left(pc_{r,t}\right)\ + \beta_r^{op}\log(op_t), Minbio_r\right)$$

where:

QB – quantity processed for biofuel-use

pc – consumer price

op – world oil price (index)

Minbio – policy defined minimum biofuel-use

Waste

Food consumption as wastage is treated in the model in a similar manner as 'consumption as food', using the same own-price elasticities, however with no cross-price relationships assumed. One alternate approach would be to set waste as a proportion of total consumption; however, the historic data does not suggest a consistent proportionate relationship with total demand (FAO, 2019c). This demand category also includes other uses such as seed, and demand not specified elsewhere[17].

Equation 24: waste (product consumed as wastage & other uses)

$$\log\left(QW_{r,c,t}\right) = a + \beta_{r,c}^{pc}\log(pc_{r,c,t}) + \beta in_{r,c,t}\log(GDP_{r,t}/pop_{r,t}) + \log(pop_{r,t})$$

where:

QW – quantity consumed as wastage & other uses

pc – consumer price

GDP – gross domestic product

βin – income elasticity

pop – population

5.5.8 Stocks

The equation for ending stocks is taken from the LTEM modelling structure (Saunders, Cagatay & Moxey; 2004). The change in stocks is a function of a stock shifter, the consumer price of commodities and production. This specification allows for the stock levels to react to changes in price and quantity consumed.

The stocks equation (Equation 25), unlike most of the other equations in LAO (which are log-log), is a linear specification.

---

[17] Further research could examine the inclusion of a trend variable in the specification of waste and other uses.

Equation 25: ending stocks

$$QS_{r,c,t} = a \cdot pc_{r,c,t}{}^{\beta_{r,c}^{pcQS}} \cdot (QP_{r,c,t} + QC_{r,c,t})^{\beta_{r,c}^{stock}}$$

where:

QS – quantity held as stocks

pc – consumer price

QP – quantity produced

QC – quantity consumed as food

5.6 Parameters

5.6.1 Demand elasticities

Own-price elasticities of demand elasticities for the model are taken from the USDA ERS food elasticities and weighted to the LAO regional groupings (Seale, Regmi & Bernstein, 2003; Muhammed et al., 2011). This data source provides uncompensated elasticities for different commodity groups. Cross-price demand elasticities were estimated using a log-linear structure with an ordinary least squares regression. Data were based on the price and commodity data from FAOSTAT (FAO, 2019c). The resulting own- and cross- price elasticities are shown in Appendix Table X8 and Table X9.

Income elasticities have also been taken from the USDA ERS food elasticities publication (Seale, Regmi & Bernstein, 2003; Muhammed et al., 2011), weighted and aggregated to the regional grouping used in the LAO model. In order to suit long-term projections a dynamic income elasticity has been included, in order to account for changes in income elasticity depending on the relative income growth in each region. Estimating Engel elasticities would require primary data on expenditure for each product which is infeasible for the broad regional and commodity coverage of the basic model. Instead, a hierarchy of unconditional expenditure elasticities estimated from Muhammed et al. (2011) was constructed based on the relative per capita income in each country, broadly mimicking the findings from the literature (Anker, 2011; Seale & Regmi, 2006). The unconditional expenditure elasticities are the conditional expenditure elasticities from the conditional Florida Slutsky model, multiplied by the income elasticity for the entire food and beverage grouping taken from the Florida-Pi model (also estimated in Muhammed et al., 2011).

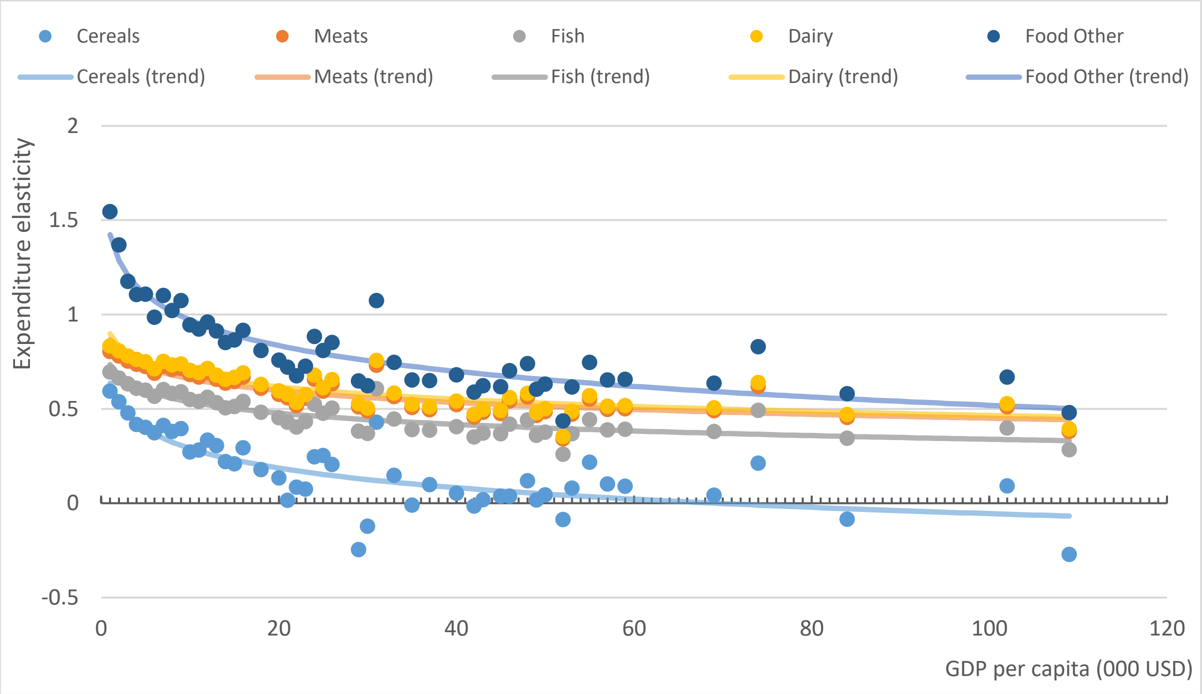
This was used for each commodity group to construct a logarithmic trend between countries. The income elasticities for each region begin at their initial stated value (Appendix Table X10), but then proceeded at the rates defined by the logarithmic trend[18], as their per-capita income rose through the timeline of the model. This imperfect method aims to utilise the available data on income

---

[18] Log. trend follows: $\beta in = \alpha + \beta \cdot \log(GDP/pop)$. Estimated parameters are presented in Appendix Table X11.

elasticities to replicate a shift in consumption patterns in line with the relative elasticity of spending on foods of countries with similar per capita income levels. Figure 16 shows the resulting relationship between individual country's income elasticities for different categories of food, and the respective trends. In the LAO model the paring of commodities to expenditure groups was as follows: crops to cereals; ruminant animals to dairy; non-ruminant animals to meats; and fish (from both sources) to fish.

Figure 16: Expenditure elasticities trends



NB: each point represents one country's expenditure elasticity from Muhammed et al. (2011).
Projections are author own calculations

Own-price elasticities of demand were also taken from Muhammed et al. (2011). The Frisch own-price elasticities for sub-categories of food were demand weighted and aggregated to the regions used in the current model. This is the same approach as used in the SIMPLE model (Baldos, Hertel, 2012). Ideally, given the model structure, Cournot own-price elasticities for individual products would be used as they account for the demand response to marginal price shifts, given nominal incomes held constant (where Frisch elasticities of demand are estimated holding marginal utility of income constant). Conversely Frisch own-price elasticises are considered a good measure of average own-price elasticities for general food sub-categories (Muhammed et al., 2011), and thus may better suit the aggregate commodity groups used in the model.

Additionally, Clements and Chen (1996) make the point that the differences in food consumption patterns between regions can largely be explained by income and price effects, and that between regions consumption preferences are largely aligned. This reinforces the coherence of an aggregate commodity and regional demand functions for the model, if cross-country differences in preferences are aligned.

5.6.2 Supply elasticities

Own- and cross- price elasticities of supply for the animal numbers and area harvested equations (Equation 4 & Equation 7) used in the model have been estimated using a log-linear structure with an ordinary least squares regression[19]. Data were based on the price and commodity data from FAOSTAT (FAO, 2019c). These supply side elasticities are shown in Appendix Table X12, Table X13 and Table X14.

5.6.3 Emissions Factors

GHG emissions for each commodity are calculated from FAOSTAT data (FAO, 2019c). The resulting emissions factors (Appendix Table X15) are emissions per head for animal commodities, and per hectare of harvested area for crops. Fish from capture has emissions factors tracking emissions per mil. tonne of production.

5.6.4 Other elasticities

Yield own-price elasticity

Goodwin et al. (2012) provides a discussion on the price response of crop yields to movements in price, then analyses data for U.S. cropping between 1977 and 2007, finding a long-run elasticity of 0.25, and a short-run intra-seasonal elasticity of 0.0085. Choi and Helmberger (1993) found yield responses of 0.27 (for corn), 0.03 (for wheat), and 0.13 (for soybeans). Huang and Khanna (2010), performed a similar analysis, controlling for fertiliser price technology, land quality, and weather impacts on US panel data and found crop yield elasticities of 0.15 (for corn), 0.43 (wheat), and 0.06 (for soybeans).

Compared with the above research, the LAO model uses a modest elasticity of yield response of 0.1 for all commodities and region. This ensures a positive relationship between own-price and yield growth. Due to the aggregated nature of the commodity and country coverage, and the sparseness of available research into the issue, this is a very crude measure of the relationship, which is shown to differ between crops (Choi & Helmberger, 1993; Huang & Khanna, 2010), and to be potentially significantly larger in long-run estimations (Goodwin et al., 2012).

---

[19] There is some evidence of positive serial correlation in some yield specifications. Durbin-Watson tests for yield equations ranged between 0.7-1.7.

Rolling average price elasticity

The equation for area and animal numbers include own- and cross-price elasticities, showing the influence of current pricing on the extent of area planted and animal stocks. However, decisions on adjustments to crop area and livestock numbers are based on expectations about price changes over a longer run horizon. In LAO, responses to price-expectations are modelled as a response to a rolling average of the previous five year’s prices. This is similar to the approach used in Aglink-Cosimo, where own-price elasticities for several lagged years are used in the supply equations for beef and veal, milk, and annual crops. Single year lag estimations are also used for other meat products (OECD, 2015).

The elasticity governing this behaviour is set at 0.02, below the own-price elasticity found in the literature.

5.7 Conclusion

This chapter has described the structure, data, and parameterisation of the LAO model. The LAO model covers global agricultural trade in seven regions and five commodities and is largely populated by FAO data (2019c). The LAO model is structurally similar to PE models like Aglink-Cosimo and the LTEM, focusing on agriculture and using a similar net trade approach, yet uses an aggregate commodity and region approach found in the SIMPLE model. Special attention has been paid to the treatment of TFP and income elasticities in the model, in order to make the model appropriate for long-term analysis. This approach to dynamic income elasticities, and the use of long lags to R&D spending contributing to the growth of TFP (especially for animal products) are elements in which LAO’s approach is novel and can contribute to the wider literature on economic modelling.

The following chapter describes the range of scenarios selected to be run using the LAO model in order to answer the research questions posed in Chapter 4.

6. Scenario Based Approaches to Projection

6.1 Introduction

This chapter broadly describes the range of possible underlying changes in exogenous variable that will form the basis for framing a number of scenarios exploring both the impact of individual key variables in the model (described in Chapter 5) and of more complex sets of assumptions regarding a combination of variables. In particular this includes setting he foundation for the baseline, which can be compared with the individual scenarios explored in Chapter 7.

This includes comparing key exogenous macro-economic data and projections taken from other sources; testing key model parameters; and analysing scenarios designed to address the four research questions central to this thesis:

1. To ascertain the prospects and directionality in real agricultural prices under the medium and long term, given credible projections of key macroeconomic drivers, as an indicator of aggeregate global supply and demand.
2. To test varying levels of total factor productivity in agriculture to determine whether there is sufficient potential for growth in agriculture relative to projections of long term growth in aggregate demand.
3. To assess the impacts on production, yields and world prices for agricultural commodities given the impacts of climate change on global yields.
4. To examine the impacts of long term developments in population and economic growth on the regional distribution of the production and consumption of agricultural commodities, and total greenhouse gases.

6.2 Scenario Selection

An economic model is a hypothetical simplified representation of economic processes. This abstraction of economic reality is structured as such that economic relationships and linkages may be quantified or specified, creating a simulacrum of real-world relationships and linkages. Once this is defined, simulations testing the effect of changes in variables and parameters, can be performed. By designing these simulations to mirror proposed policy changes or projected outcomes for macro-economic variables, the economic model can simulate the anticipated reaction of markets and economic agents, as implied through the model's specification and representation of economic theory, and importantly, unintended consequences of implementing these decisions. This form of analysis can be described as 'scenario analysis'.

Scenarios can ask hypothetical questions regarding the future, and a model can shed light through the application of constraints and relationships to that future. A scenario may factor a change in a singular variable or policy, or entire bundles of different production rates/economic variables/et cetera may be tested. For example, the Shared Socioeconomic Pathways (SSP) scenarios (Riahi et al., 2017) test complex, multi-faceted and inter-linked bundles of social, economic, and political changes.

In terms of the scenario analysis with the LAO model, both styles of scenario analysis are performed. Testing the change implied when single key macro-economic variables are changed (population, GDP, TFP), and changes from bundles of variables of which represent more complex futures (SSP, RCP Scenarios). The importance in assessing different futures for key macroeconomic variables is key for policymakers and researchers, as it helps untangle the component pressures in global markets, allowing for targeted analysis on the key drivers of market change, and the prioritisation of resources. Additionally due to the expanding confidence intervals in projections of macro-economic variables over the long-run, testing various futures helps inform the widening range of possible outcomes. In the context of this thesis, if we can further elucidate the contributions to increased demand over the long-run, and to what degree investment into agricultural research and development impacts on supply, we may be able to assess the global likelihood of maintaining low real food-prices. Furthermore, we may be able to identify the levels of productivity, global incomes, land-use or input-use, which would entail maintaining this current era of affordable food, without causing additional damage to the global environment.

The design of these simulations is important in utilising an economic model in a meaningful and valuable way. Durance & Godet (2010), describe key conditions of making a useful scenario: pertinence, coherency, likelihood, importance, and transparency. The analysis in this thesis will meet those five criteria by designing scenarios which are pertinent to the research objectives, coherent in utilising simple logical structures, likely as they will focus on framing macro-economic projections from credible organisations or from trends taken from historic data[20], important as they relate to serious challenges for global agriculture, and transparent in that the sources and projections used to form these scenarios is provided.

Model outcomes will be presented as changes over time compared to the 'baseline' scenario, which represents business as usual with no specific policy changes and median growth in macroeconomic

---

[20] These projections and sourced projections will also inform credible bounds on scenario changes i.e., the range of simulated projections.

variables. Outcomes will focus on changes in world price as an indicator of the balance of aggregate global supply and demand, quantity changes in regional production and consumption, and other key input when appropriate.

6.2.1 Baseline

The analysis begins with constructing a baseline scenario for the LAO model. The baseline is a scenario representing 'business as usual', with no shocks applied to the model, and serves as the basis for comparison for all other scenarios presented. In terms of the exogenous variables needed to inform this scenario, the baseline scenario utilises the medium variant population projection from the UN (UNDESA, 2019a) and a linear projection extending the IMF's Global Economic Outlook projections of GDP by country (IMF, 2019; author's own calculations). No exogenous TFP variable is required, since the endogenous TFP equation is used for the baseline scenario.

6.3 Exogeneous Macro-economic Variables

The scenario analysis examines two key macro-economic variables used in the LAO model: population, GDP, and productivity. By selecting different potential pathways of development for these macro-economic variables, we can use the LAO model to assess how markets would react to these pathways, and examine the implications for greenhouse gases, food security, and agricultural prices if these macro-economic projections were realised.

The following section discusses the key macro-economic drivers used in the LAO model for this set of scenario results. The projections used are either various scenarios taken from one key source (as is the case for population scenarios), scenarios taken from various international sources (as is the case for GDP projections) or representative pathways for growth from the author's own calculations (for the TFP scenarios).

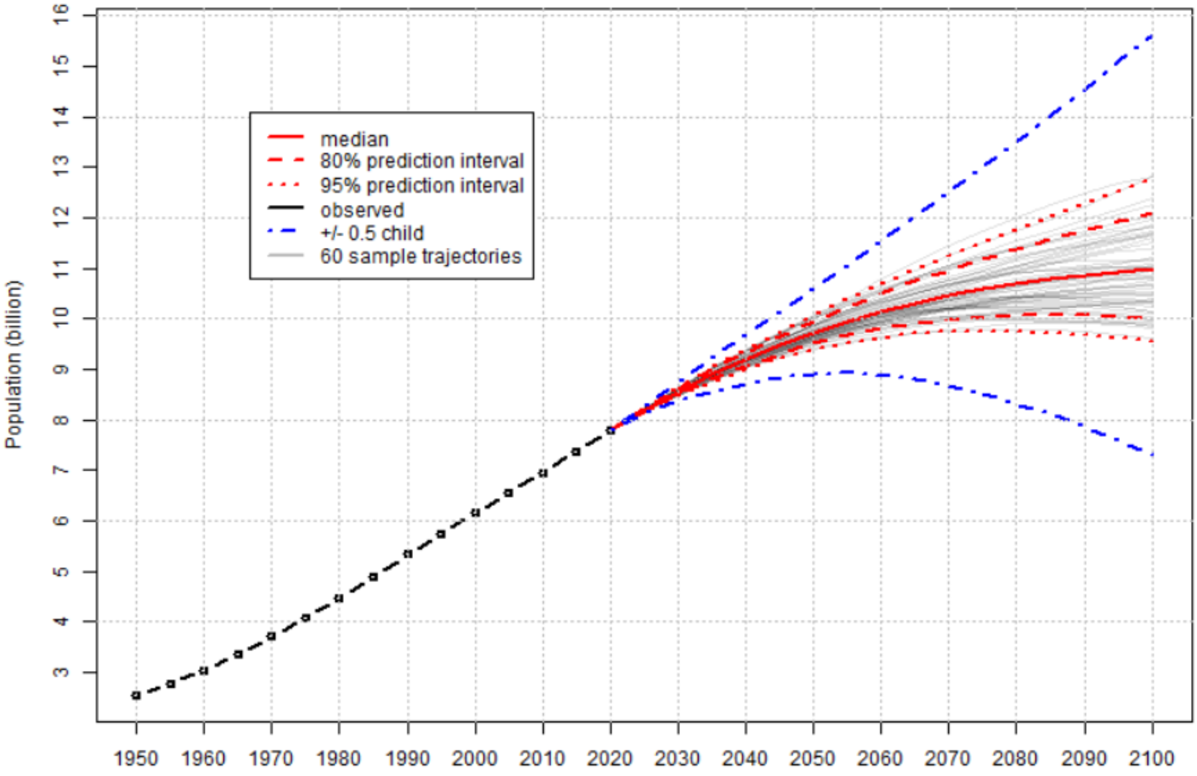
6.3.1 Population

This section of the analysis focuses on testing different population projections in the modelling framework. As there is a consensus within the modelling community on the use of the UNDESA population projections, the LAO model only considers different projections from the UNDESA.

Figure 17 shows the UNDESA population projections (2019a) with the confidence intervals and difference from a 0.5 live births per woman change in projected average fertility rates. These changes in projected fertility rate make up the high and low fertility estimates from the UNDESA, shown alongside the constant mortality, constant fertility and constant replacement scenarios in

Figure 18. The median, high, and low scenarios are used in the LAO scenario analysis to represent a broad range of potential outcomes for population growth[21].

Figure 17: UNDESA total population probabilistic projections, to 2100

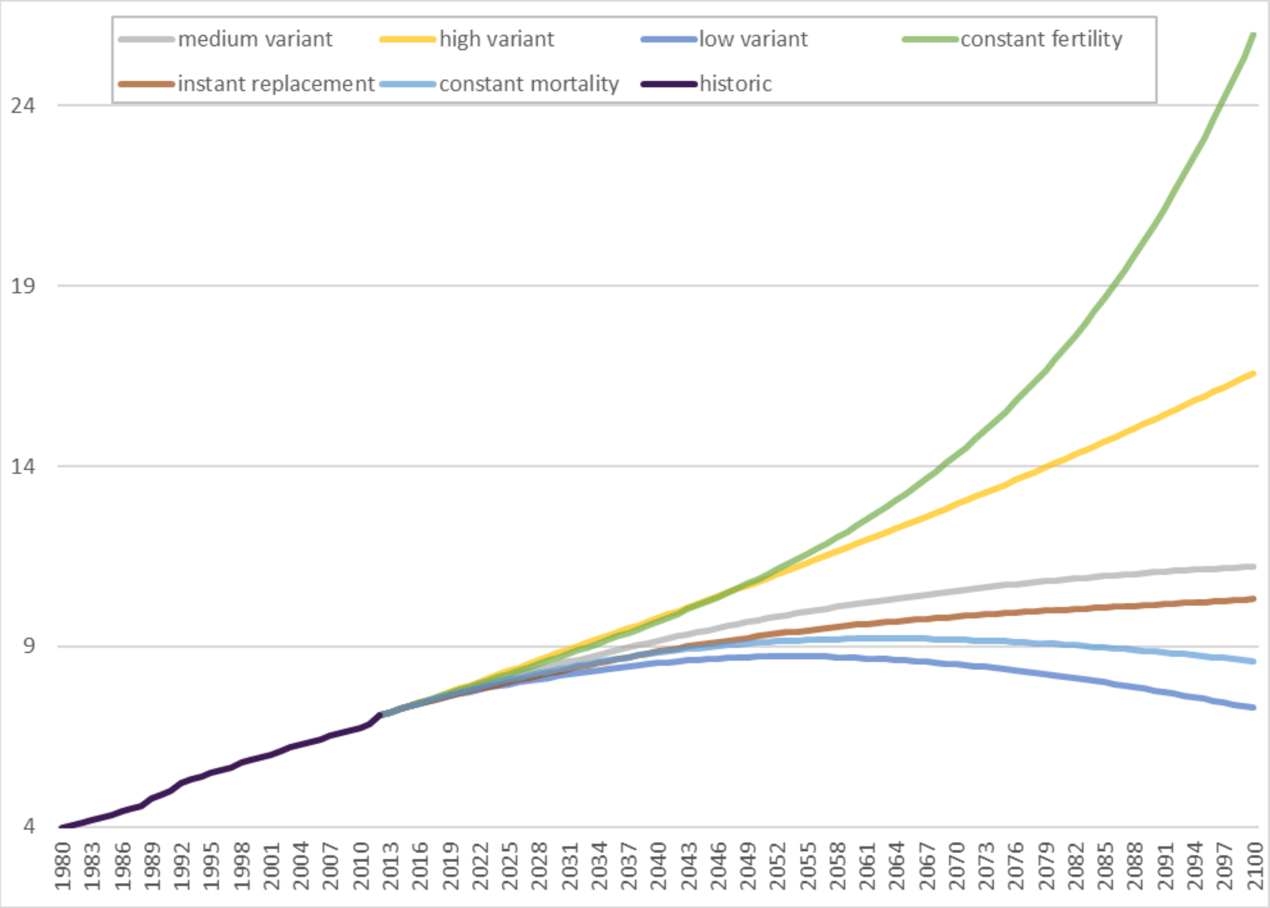


© 2019 United Nations, DESA, Population Division. Licensed under Creative Commons license CC BY 3.0 IGO.
United Nations, DESA, Population Division. *World Population Prospects 2019*. http://population.un.org/wpp/

---

[21] The UNDESA (2019a) also provides their projections of 95% confidence intervals on their population projection. These projections would also have served as informative population outcomes but have not been included in this analysis.

Figure 18: UNDESA total population projection scenarios, to 2100



Source: UNDESA, 2019a

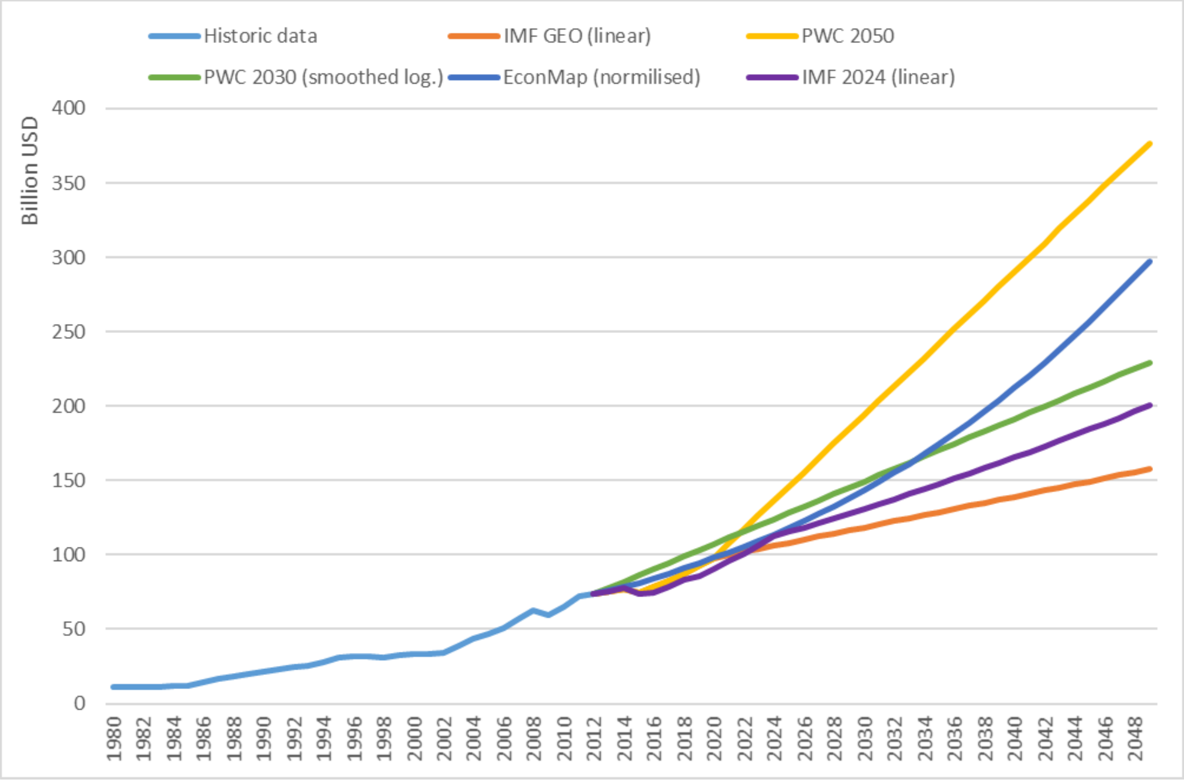
6.3.2 GDP

This section of the analysis focuses on the GDP for the different regions represented in the LAO model. GDP per capita is a key exogenous driver in the model and defines the purchasing power for demand for food in the model's projections.

Figure 19 shows the key GDP projections used in the LAO model. Some of these projections have been extended beyond their original time horizon, these include the World Bank projections (which originally cover 2012-2021), the PWC 2030 projections (2012-2030), and the IMF Global economic outlook projections (2012-2024). Similarly, all data have been fitted and normalised to the same initial point as the historic data in 2012, LAO's base year. This historic data series shown is taken from the World Bank.

Population and GDP are interlinked, thus where possible any given GDP projection which has an accompanying projection of population growth are utilised together.

Figure 19: GDP projections in the LAO model, 2012-2050



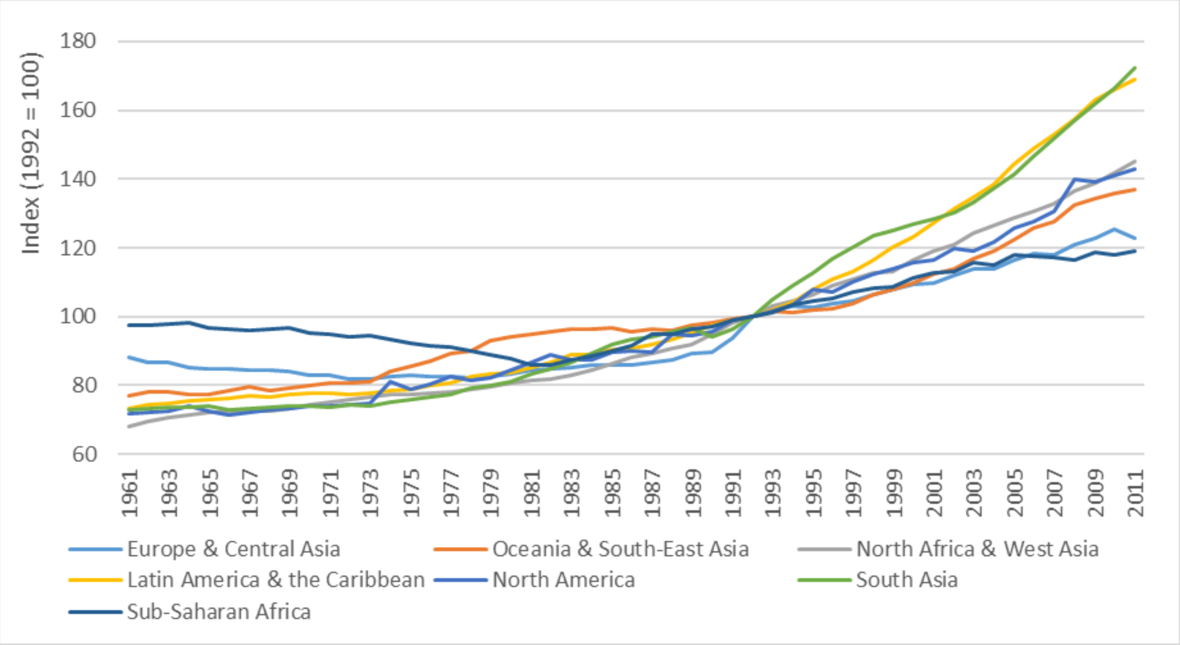
6.3.3 Total Factor Productivity

This section of analysis focuses on the prospects for global agricultural prices dependant on the level of Total Factor Productivity (TFP).

The LAO model has an endogenous total factor productivity function (as described in section 5.5.5), which calculates total factor productivity year-by-year as the model solves. This endogenous TFP measure is based on three main drivers: a lagged estimate of the level of investment into agricultural research and development; the spill-over effect from applicable agricultural research and development in other regions; and the ability of producers to invest in new technologies and practices (measured by periods of relative high product prices).

However, in order to test the general responsiveness of the model’s outcomes to different levels of TFP and to test exogenous projections or scenarios of higher or lower TFP, an exogenous measure of TFP can be utilised in the model. For the exogenous specification of TFP, different projections extending the historic TFP data taken from the Fuglie (2012; 2015a) dataset on global agricultural TFP have been constructed (Figure 20).

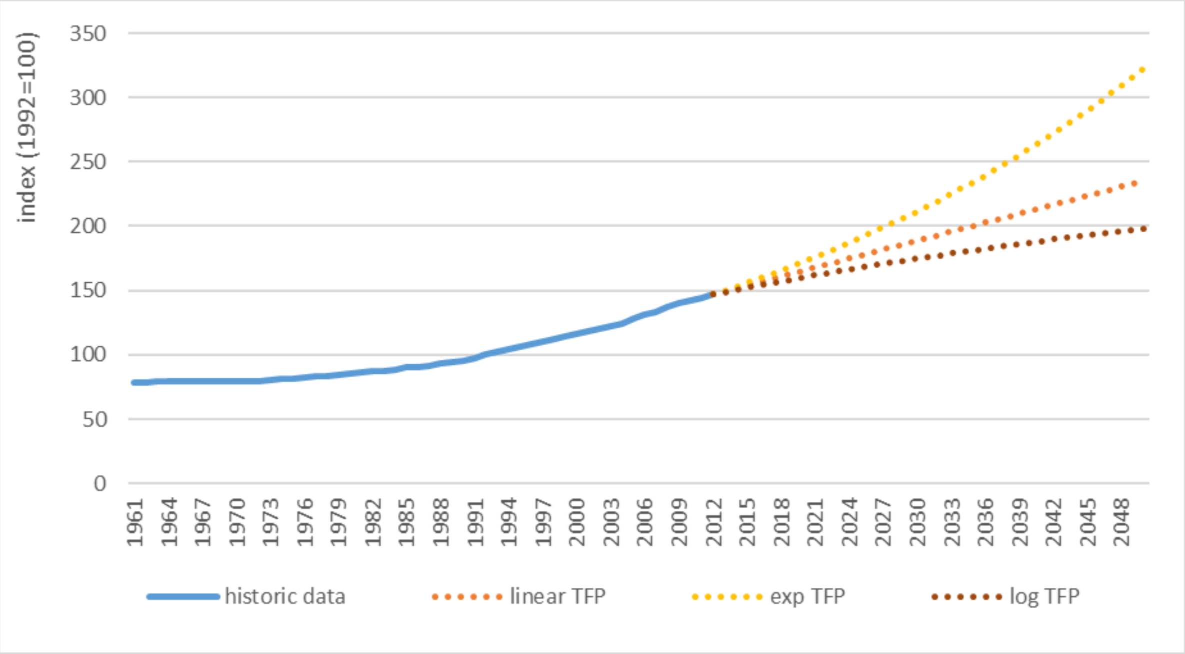
Figure 20: Historic agricultural TFP by region, 1961-2012



Source: Fuglie, 2015b

The global average of the regional TFP projections is shown in Figure 21. Three simple types of projection are used: linear; exponential; and logarithmic. These extensions beyond the base year are extrapolated from the data from 1992 to 2012. The average annual TFP growth rates for the historic (1992-2012) and those resulting from the three projections (2012-2050) are shown in Table 3.

Figure 21: Global average of TFP index, and various growth projections to 2050



Source: author’s own calculation

Table 3: Historic and projected TFP annual average growth rates by region and commodity

		1992-2012	2012-2050		
		historic	linear	log	expo.
Crops	EuCA	0.012	0.008	0.006	0.010
	OcSEA	0.018	0.011	0.007	0.019
	NoAWA	0.019	0.013	0.008	0.020
	LaC	0.028	0.015	0.010	0.028
	NoA	0.019	0.012	0.008	0.019
	SA	0.026	0.016	0.009	0.029
	SsA	0.009	0.007	0.005	0.006
Animal products (RA & AN)	EuCA	0.008	0.006	0.004	0.010
	OcSEA	0.024	0.014	0.009	0.024
	NoAWA	0.021	0.013	0.008	0.022
	LaC	0.028	0.016	0.011	0.030
	NoA	0.021	0.013	0.008	0.021
	SA	0.032	0.016	0.010	0.031
	SsA	0.017	0.011	0.007	0.015

These various methods of projecting future TFP allow for the testing of a suite of potential TFP outcomes and can serve as the bounds of likely outcomes. For the purposes of the TFP scenarios the linear projected TFP based on post 1992 data has been utilised as an intermediate projection comparative to the more conservative logarithmic projection and the higher exponential growth projections.

6.4 Combined Variable Scenarios

This section explores some scenarios put forward by other organisations as possible social and economic futures. Unlike the previous section, which focused on the changes brought on by isolating and altering single model parameters one at a time, these scenarios consider bundles of exogenous variables, simulating more complex global socio-economic states.

6.4.1 SSP/RCP scenarios

The Shared Socio-economic Pathways (SSP) and the Representative Concentration Pathways (RCP), were developed as a shared scenario framework for research on climate change, linking assumption on climate policies with future radiative forcing and socioeconomic development until 2100 (O’Neill et al., 2014; van Vuuren et al., 2013). They will be modelled as a set of bundled macroeconomic scenarios.

The LAO model is not a biophysical model. Thus, changes in yields must be taken from a secondary source that accounts for the bio-physical impacts on crops. In this case, the projections by the PBL IMAGE model, a global IAM, which has been used to assess the millennium ecosystem assessment, and the SRES and SSP scenarios have been used (Stehfest et al., 2014). In particular, the yield implications from the SSP scenarios under various RCPs are taken from the IMAGE model and used in place of the LAO model's TFP equation, this is performed by removing the TFP equation from the model structure and from the yield equation. The percentage yield change from the IMAGE scenarios is implemented through a supply shifter in the yield equation. Average annual growth rates for these exogenous yield changes are shown in Appendix Table X16. The LAO endogenous TFP response is disabled, as the IMAGE model has an exogenous growth function, taken from its linkages with the MAGNET model, which is also transmitted through the yield changes.

The SSP scenarios from the IMAGE model also embodied different macro-economic projections for GDP and population. These will also be used in the LAO model to replicate the SSP scenarios. Growth rates for these GDP, population, and the implied GDP per income are shown in Appendix Table X17.

6.5 Conclusion

This chapter has discussed some of the motivations for economic modelling and how well performed scenario analysis can provide meaningful insights for research and policymakers.

Detailed descriptions of the scenarios selected to address the research objectives of this thesis have been provided, along with their sources and constituent data or projections. These scenarios aim to addresses the research objectives by providing descriptions of economic outcomes for agricultural markets given changes to three key drivers of agricultural supply (TFP) and demand (GDP and population). These scenarios will be shown comparative to a baseline scenario, to demonstrate the most likely business as usual scenario, constructed using projections from UNDESA and the IMF, and utilising the endogenous TFP growth in the LAO model. Lastly, scenarios of global socio-economic futures from the SSP and RCP scenarios will be used to simulate the impacts of climate change and global policy change in LAO.

Taken together, there are 19 scenarios implied by the discussions in sections 6.2 to 6.4 (excluding 3 instances of the baseline under different scenario groupings). These scenarios are analysed in Chapter 7 but are listed in Table 4 for ease of reference.

Table 4: List of scenarios and assumptions

Grouping	Scenario name	GDP	population	TFP/yield growth
1) Baseline	Baseline	IMF GEO	medium variant	endogenous
2) Population	i. high variant	IMF GEO	high variant	endogenous
	ii. medium variant	IMF GEO	medium variant	endogenous
	iii. low variant	IMF GEO	low variant	endogenous
3) GDP	i. IMF GEO	IMF GEO	medium variant	endogenous
	ii. PWC 30	PWC 30	medium variant	endogenous
	iii. EconMap	EconMap	medium variant	endogenous
	iv. PWC 50	PWC 50	medium variant	endogenous
4)TFP	i. linear TFP	IMF GEO	medium variant	linear
	ii. exp. TFP	IMF GEO	medium variant	exponential
	iii. log. TFP	IMF GEO	medium variant	logarithmic
	iv. flat TFP	IMF GEO	medium variant	none
	v. endo. TFP	IMF GEO	medium variant	endogenous
5) SSP	i. SSP1	SSP1	SSP1	endogenous
	ii. SSP2	SSP2	SSP2	endogenous
	iii. SSP3	SSP3	SSP3	endogenous
	iv. SSP4	SSP4	SSP4	endogenous
	v. SSP5	SSP5	SSP5	endogenous
6) RCP	i. RCP 1.9	IMF GEO	medium variant	RCP 1.9 yield Δ
	ii. RCP 2.6	IMF GEO	medium variant	RCP 2.6 yield Δ
	iii. RCP 3.4	IMF GEO	medium variant	RCP 3.4 yield Δ
	iv. RCP 6.0	IMF GEO	medium variant	RCP 6.0 yield Δ

NB: colour indicates baseline assumptions

7. Results: Model Outcomes from Scenario Analysis

7.1 Introduction

This chapter presents the modelling results from the LAO model using the scenario analysis described in Chapter 6. The scenarios have been designed in order to address the four research questions put forward in Chapter 4. This chapter begins by presenting a comprehensive description of the changes in the baseline scenario (1), including showing changes in price, quantity produced, quantity consumed (by usage), and the drivers of those changes (population, GDP, yield, area, animal numbers, and TFP).

The chapter then follows by presenting scenarios 2-4 which test variations in the key exogenous variables (population, GDP and TFP), in comparison with the baseline scenario demonstrating the impacts these key drivers have on the global balance of supply and demand. The impact from scenarios 1-4 on greenhouse gases will also be presented in a specific subsection.

Lastly scenarios 5-6, which show the implications agricultural futures given different political futures, under the Shared Socioeconomic Pathways and under different levels of climate impact, under the Representative Concentration Pathways.[22]

The presentation of results in this chapter will focus largely on describing the outcomes from the model in straightforward terms. The discussion and analysis of these outcomes and how they fit into the broader global socioeconomic context will be presented in the following chapter. All presented scenarios found locally optimal, feasible solutions for each year of the model's time horizon for projections. There was one exception of a single year in the 'PWC 50' scenario (3-iv.), where in 2049 no feasible solution was obtained.

---

[22] In the presentation of the results, the regions in the model will sometimes be referred to in their abbreviated form in order to assist with the visual presentation in some figures and tables. The abbreviations used are as follows: Europe & Central Asia (EuCA); Oceania & South-East Asia (OcSEA); North Africa & West Asia (NoAWA); Latin America & Caribbean (Lac); North America (NoA); South Asia (SA); and Sub-Saharan Africa (SsA).

7.2 Baseline Outcomes

As described in Chapter 6, the baseline is the scenario with macroeconomic indicators and inputs best representing the 'business as usual' case (shown in Table 5). The baseline aims to present a reasonable estimate of the continuation of current policies and trends to serve as a fixed estimate with which to compare other scenarios with changes in modelling parameters, macroeconomic inputs, and policy. In these scenarios, every parameter not being explicitly tested will be set at baseline levels, in order to foster a clear-cut comparison, isolating only those parameters, data or assumptions being examined.

Table 5: Baseline Scenario assumptions

Grouping	Scenario name	GDP	population	TFP/yield growth
1) Baseline	Baseline	IMF GEO	medium variant	endogenous

This business-as-usual scenario could be used to infer the likely state of agricultural markets in the future. However, due to the long-term nature of this research, the ability to make any definitive statements about the future states of markets is severely constrained. There may be some potential for limited comments on the directionality of the baseline, but these comments should be couched within an understanding of the limitations of this style of long-run analysis. The value of the analysis comes primarily from the comparative shifts in the progression of these markets, first between their position in the initial dataset (as of 2012) and in 2050; and secondly, between the presented scenarios and relative to the baseline scenario. Here the scenario analysis may be able to offer insight on general trends in agricultural markets implied by the economic theory, data, and relationships between variables, which unpin the model. To put it another way, the model is not able to predict the price of oil in 2050. Rather, the model will provide a better understanding of the consequences that changes in the price of oil would have for global agriculture and food prices. Being cognisant of these relationships will allow for more informed policy decisions in order to avoid undesirable market outcomes over the long-run.

Even with a simple style of economic modelling like the LAO model, there is a broad range of variables and data outputs from any scenario. This large amount of data is valuable as it covers many different areas, but it also can be overwhelming, and obfuscate the key segments required for explaining and analysing the relevant areas of inquiry. To this end, a few key variables will form the centre of analysis and discussion for each scenario. Most important to the research questions posed in this thesis are the movements of: world prices for each commodity; quantity produced and consumed of each commodity; the yield for crop and animal commodities; and the total greenhouse gas emissions from agriculture.

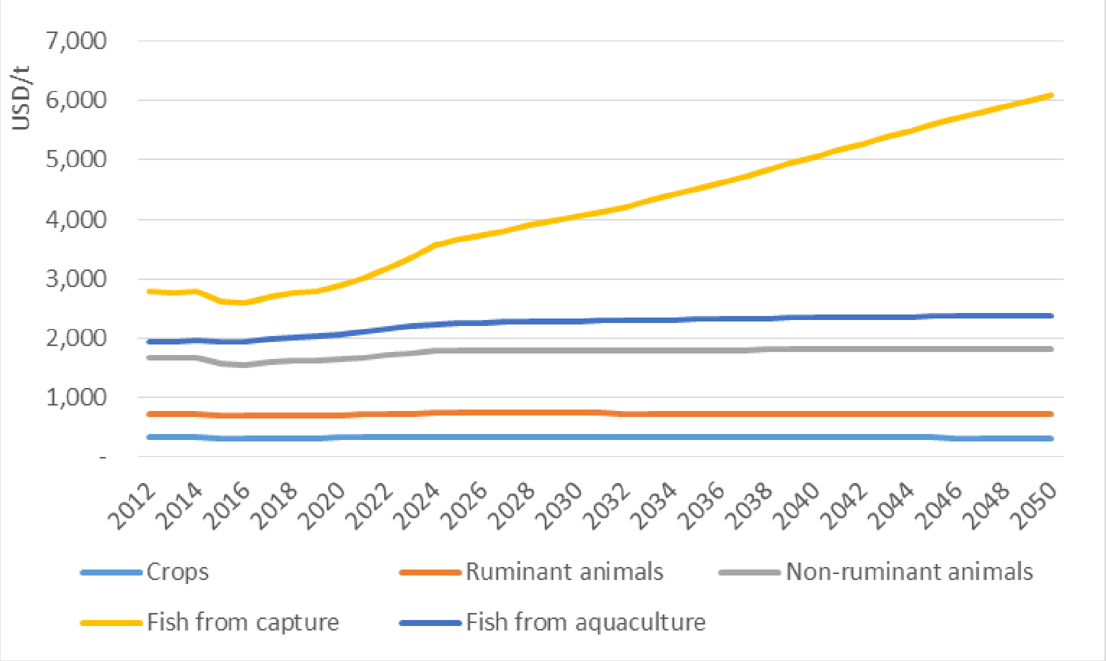
7.2.1 World prices

World prices serve as the main indicator of changes in global agricultural markets under different scenarios. World price represents the equilibrium point between total global supply and total global demand for each commodity, and is the key variable for solving the model, as the model seeks to identify a world price at which global supply and demand are equal.

Changes in world prices can be indicative of whether the availability of agricultural commodities is able to meet total demand, and if not, then to constrain that demand. The world price also influences regional producer prices[23], so world price is also a measure of the general affordability of agricultural commodities and therefore food prices. Rising world prices for agricultural commodities indicate either a relative drop in supply compared to demand, or alternatively a relative increase in demand compared to supply. This is not to suggest that both supply and demand cannot both be rising under high world prices, just that the relative shift in supply and demand is not commensurate.

To further illustrate this point, both supply and demand could increase at exponential rates but not cause a change in world price, if the rates of change were equal. Due to this, whilst world price is an excellent overall measure, it is also important to examine the production and consumption shifts underlying these prices in order to fully understand their implications.

Figure 22: World prices for each commodity in baseline (USD/t), 2012-2050



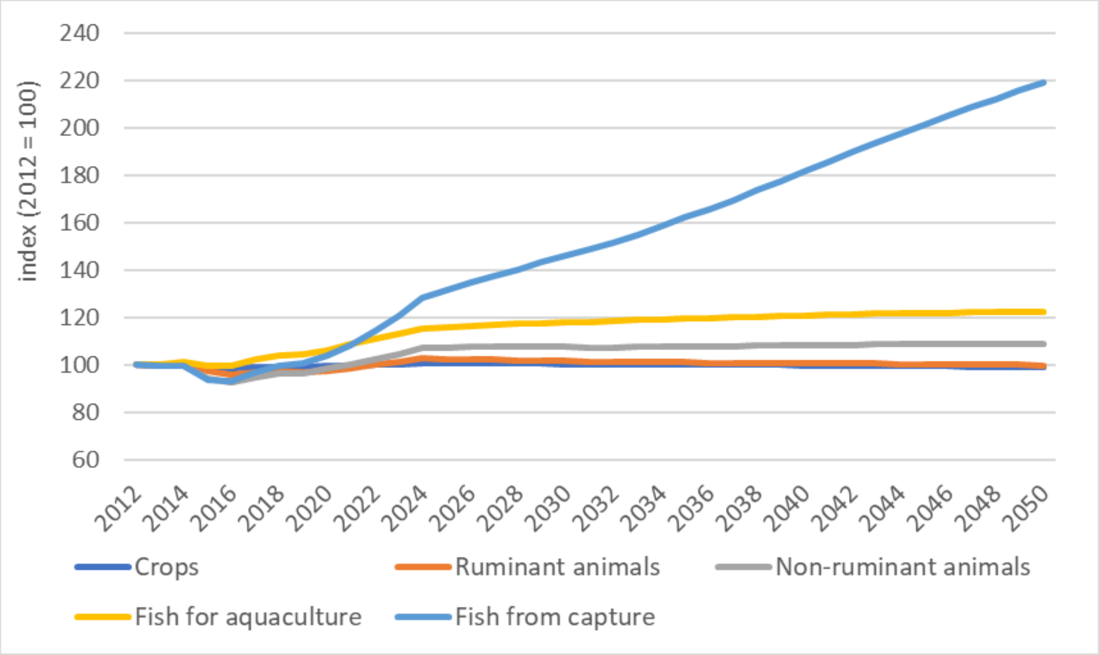
---

[23] Regional producer prices in the base year (2012) are provided in Appendix Table X18.

Figure 22 and Figure 23 display the changes in real world prices produced in the baseline scenario[24], first in real dollar terms (Figure 22) and then as an index of the base year (Figure 23). As can be seen in these figures, with the exception of the fish commodities, the world prices for most commodities are relatively stable in the baseline.

The increase in captured fish prices is not surprising, due to the constraints placed on the supply of fish for capture. As population growth causes demand to outstrip the constrained production of fish from capture, the relative price increases. Demand for fish from aquaculture is also expected to increase as a perfect substitute, servicing additional demand for fish. This increase in fish prices would also be expected to put upwards pressure on prices for animal products as additional demand from the substitution of fish with animal products grows.

Figure 23: World prices for each commodity in baseline (index 2012 = 100), 2012-2050



World prices for animal commodities (ruminant and non-ruminant animal commodities), decline in the first few years of the model simulation. This is in part due to relatively high prices in the base year (2012). The price of ruminant animal products corrects downwards until 2016, where they increase again until 2024. From 2024 the world price of ruminant animals decreases, and reaches the initial price level from the base year at the conclusion of the model run, finishing in 2050 at 0.99 of the 2012 index. Non-ruminant animal prices, however, continue to increase gradually after 2024, ending the projection at 1.09 of their 2012 index price. The increase in prices for non-ruminant animals is indicative of the growing demand from South Asia associated with strong income growth in that region.

---

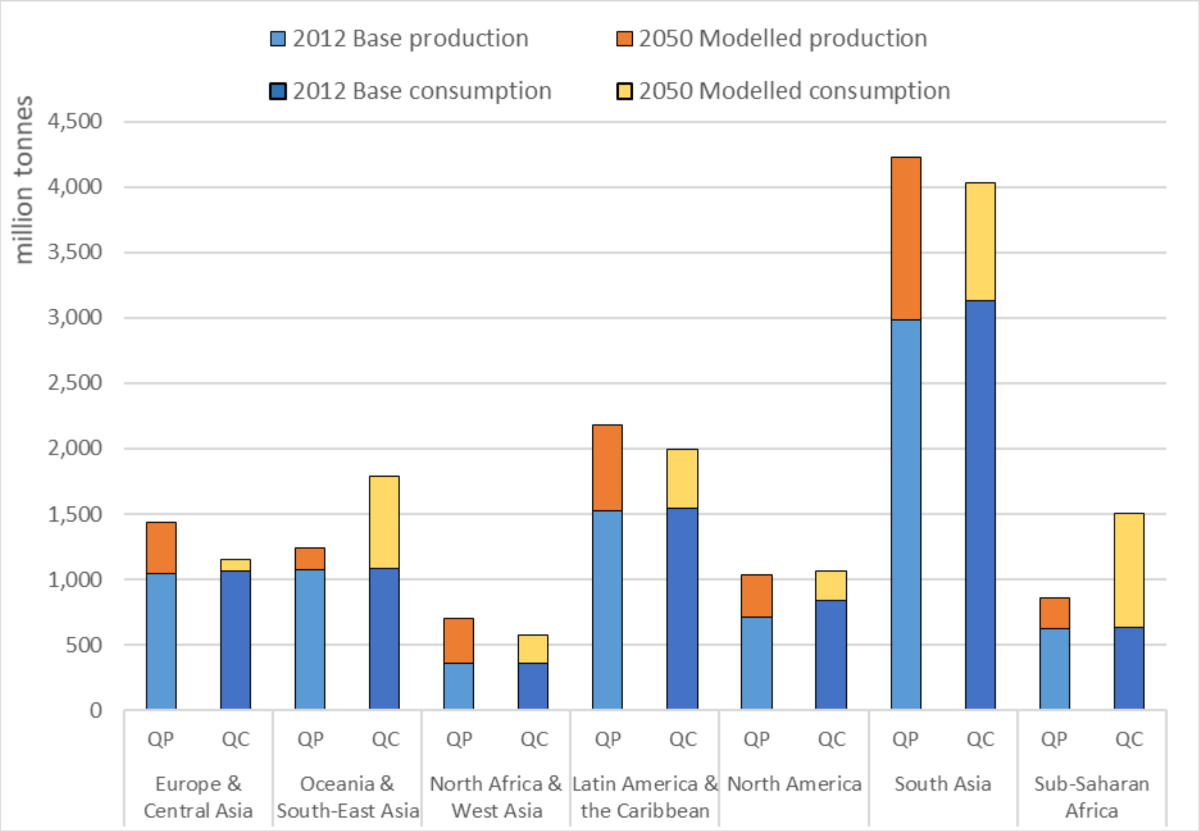
[24] World prices for 'ruminant animals' and 'non-ruminant animals' refer to the prices of the products from those animals, not the price of live animals.

In the case of the crops commodity, the world price in the baseline stays relatively unaffected. Crop prices trend downwards very gradually over the time horizon of the model's projection. The initial correction from the high prices experienced in the base year (2012) is much less severe than that experienced by the two animal commodities. Overall, the world price for crops exceeds the levels from the base year between 2022 and 2039, but declining prices near the end of the simulation lead to a total decrease around 1 per cent from 2012 to 2050.

7.2.2 Crops

Figure 24 shows the state of consumption and production of crops in the base year (2012), and the relative addition to each category by 2050. Of all the figures showing these results, this figure is the most important, as it clearly illustrates the main influences on changes in world prices, and in which regions these changes occur. The figure shows the level of consumption compared to production in each region, and the scale of each region's production and consumption next to other regions, then how these relativities have changed over time.

Figure 24: Comparative regional growth in the production and consumption of crop products, 2012 and 2050



In Figure 24, production and consumption in the base year are closely matched in most regions (shown in blue bars), with North America and South Asia having a slight discrepancy towards consumption. This indicates an original state of low inter-regional net trade. At the end of the model's projections to 2050, the intra-regional balance between production and consumption has shifted in most cases. Most notably, Sub-Saharan Africa, and Oceania & South East Asia, have large increases in the quantity consumed of crops. In the case of Sub-Saharan Africa, this is driven by increases in population and income. In Oceania & South East Asia, this increase in consumption is largely due to increased feed associated with higher production of animal commodities. In both regions, these consumption increases are not matched by significant increase in production, leading to a shortfall in intra-regional supply, and increased inter-regional trade to service this demand.

Growth in production outpaces growth in consumption in many regions, with Latin America & the Caribbean, Europe & Central Asia, North Africa & West Asia, and South Asia all turning from net import regions (in the base year) to net export regions by 2050.

Crop Production

Figure 25: Crop production by region in the baseline scenario, 1961-2050

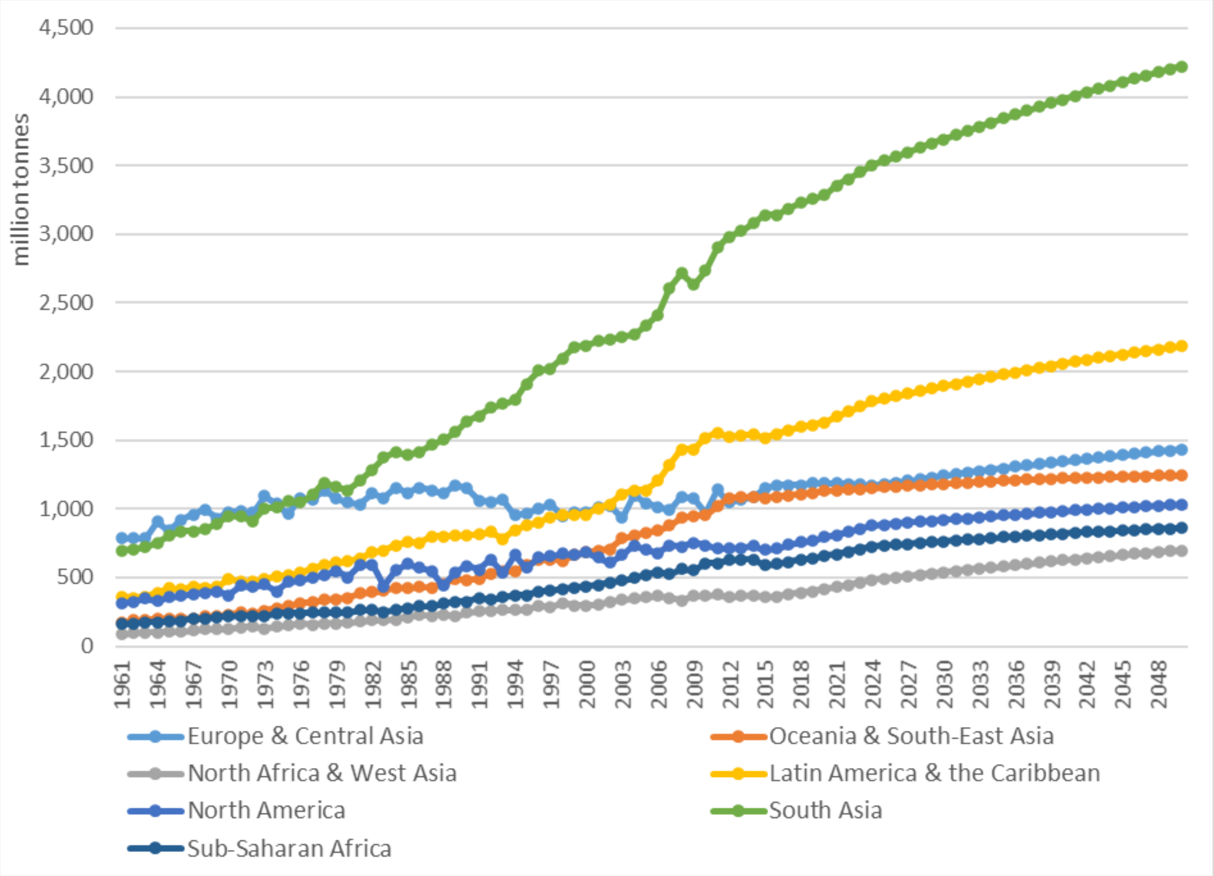


Figure 25 shows the development of crop production in each region including the historic data (1961-2012), followed by the projected path from the LAO model baseline (2013-2050). There is a period of relative volatility from 2013 to 2024 until a more stable equilibrium occurs between the examined regions. This is due to the GDP projections used in the model, which includes real data until 2017, followed by IMF projections until 2024. The period of real data has greater fluctuations in GDP, which transfers to some variance in demand and thus the production responses in the model. Figure 25 also shows general growth in crops over the modelled period, with strong initial growth in South Asia and

Latin America. Conversely North America, North Africa & West Asia, Latin America, and Sub-Saharan Africa, all experience decreases in production in the initial phase of the modelling projections. In terms of production growth, South Asia, and Latin America and the Caribbean have strong initial growth. Conversely North America, North Africa & West Asia, Latin America, and Sub-Saharan Africa all experience decreases initially. Oceania and South-East Asia, North America, and Sub-Saharan Africa show a flat growth by the end of the modelled period.

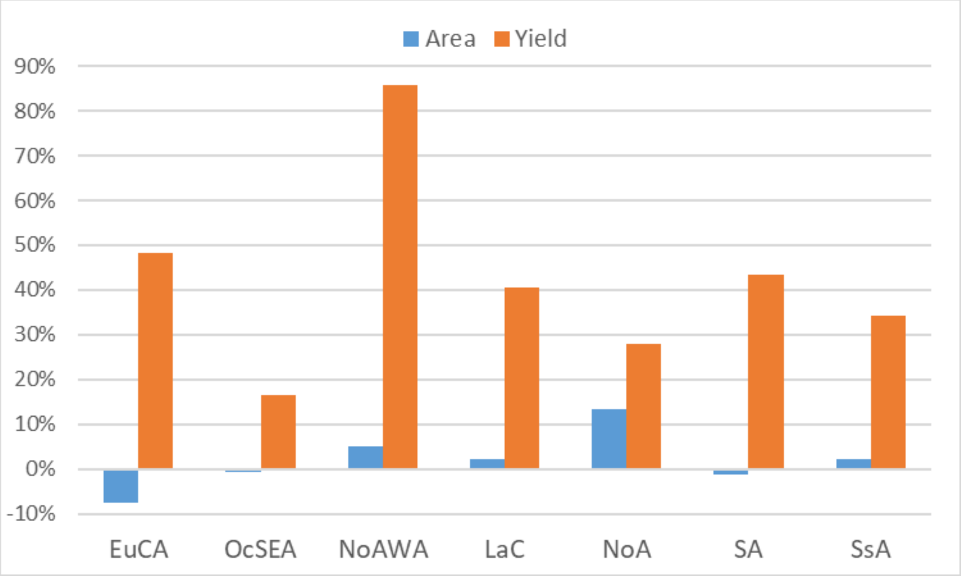
Table 6 presents crop production by region. By percentage, the North Africa & West Asia region has the highest increase in crop production over the examined period. However, by volume South Asia experiences the highest increase in crop production with a change of 1,240 mil.t, which is almost double the next highest increase in Latin America and Caribbean, with a change of 662 mil.t. Overall, global crop production grows by over 3.3 billion tonnes, or 40 per cent between the base year and 2050.

Table 6: Crop production by region in baseline scenario, 2020, 2030, 2040 and 2050

	Million tonnes					**% change from base**			
	Base (2012)	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Europe & Cent. Asia	1,046	1,188	1,241	1,345	1,436	13.6%	18.6%	28.6%	37.3%
Oceania & SE Asia	1,077	1,132	1,183	1,222	1,245	5.1%	9.9%	13.5%	15.6%
N Africa & W Asia	358	417	538	625	699	16.5%	50.2%	74.7%	95.3%
Lat. America & Caribbean	1,522	1,630	1,894	2,057	2,184	7.1%	24.4%	35.1%	43.5%
North America	712	793	920	984	1,033	11.5%	29.3%	38.2%	45.1%
South Asia	2,983	3,286	3,692	3,981	4,223	10.1%	23.8%	33.5%	41.6%
Sub-Saharan Africa	628	662	765	821	860	5.5%	21.8%	30.8%	37.1%
Total	8,325	9,107	10,232	11,036	11,679	9.4%	22.9%	32.6%	40.3%

Figure 26 shows the change in the component factors of crop production: area and yield. As can be seen, the composition of crop growth in each region is strongly influenced by growth in yields rather than by growth in area. In fact, three regions, Europe & Central Asia, Oceania & South-East Asia, and South Asia, have a decrease in harvested area over the modelling period. Yield growth is positive in all regions, but weakest in Oceania & South-East Asia with less than 20 per cent growth over the 38 years modelled period. North Africa and West-Africa has the largest increase in yields by far, with an over 80 per cent increase in yields. In terms of area, North America has the largest percentage increase.

Figure 26: Percentage change in crop area and yield by region, 2012-2050



Crop Consumption

The composition of total consumption is shown in Table 7. Total consumption in the LAO model is split between five uses (consumption as food, consumption as feed, other uses, waste, and bio-fuel use). Beyond the base year (2012), the relative proportion of consumption sources remain stable throughout the modelled range (2013-2050), with a minor proportional increase for feed-use (16% to 18%), while ‘other uses’ has the greatest decrease (30% to 27%).

Table 7: Global consumption for crops by each usage, 2012 and 2050

	Million tonnes			% Δ from 1961/2012	
	1961/2012	2012	2050	2012	2050
Consumption as food	2,297	3,684	5,308	60%	131%
Consumption as feed	905	1,340	2,091	48%	131%
Other uses	1,507	2,424	3,139	61%	108%
Waste	222	474	660	113%	197%
Bio-fuel use	69	402	480	479%	591%
	% of total consumption				
Consumption as food	46%	44%	45%		
Consumption as feed	18%	16%	18%		
Other uses	30%	29%	27%		
Waste	4%	6%	6%		
Bio-fuel use	1%	5%	4%		

The consumption of commodities as food is a critical element in the general analysis, as it corresponds to the ability to feed the global populace. When we again consider the Malthusian proposal at the beginning of this thesis, this is often the question central to fears about food security and the performance of agricultural markets: ‘how does the demand for food compare with the mechanisms for growth of agriculture production?’ Due to this importance of consumption as food to answering the research aims of this thesis. Table 8 presents the development of demand for crops for human consumption.

Table 8: Quantity crops consumed as food, by region, 2020, 2030, 2040 and 2050

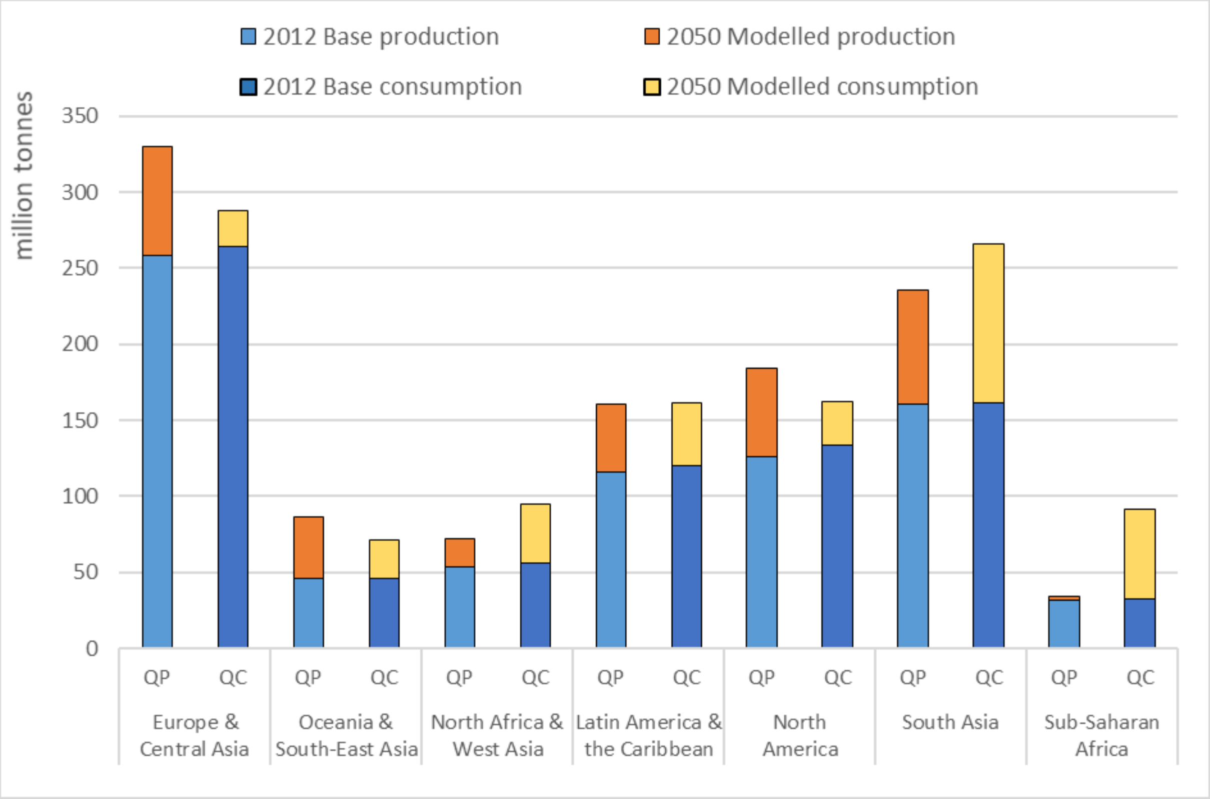
	Million tonnes					% change from base			
	Base (2012)	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Europe & Cent. Asia	392	398	386	367	346	1.5%	-1.6%	-6.4%	-11.7%
Oceania & SE Asia	457	515	626	699	754	12.7%	37.0%	53.0%	65.0%
N Africa & W Asia	204	230	270	302	330	12.7%	32.2%	47.7%	61.8%
Lat. America & Caribbean	331	349	392	417	431	5.4%	18.5%	25.9%	30.2%
North America	236	226	219	214	209	-4.5%	-7.5%	-9.4%	-11.7%
South Asia	1,699	1,909	2,140	2,226	2,257	12.3%	25.9%	31.0%	32.8%
Sub-Saharan Africa	364	442	651	812	981	21.3%	78.6%	122.9%	169.1%
Total	3,684	4,069	4,683	5,037	5,308	10.4%	27.1%	36.7%	44.1%

The two most significant results in Table 8, are: firstly, the large almost three-fold increase in demand in Sub-Saharan Arica over the modelled period; and secondly, the decrease in consumption below their 2012 levels in Europe & Central Asia, and North America. The key drivers of consumption as food are the world price of crops, the income of peoples in each region, and the population in each region. The significant growth in demand in Sub-Saharan Africa is mainly a factor of significant population growth in the region (as shown later in Figure 37). In the cases of declining consumption in Europe & Central Asia, and North America, this is attributed to higher incomes implying very low or even negative income elasticities for crops, and declining or slowing population growth in these regions.

7.2.3 Ruminant animals

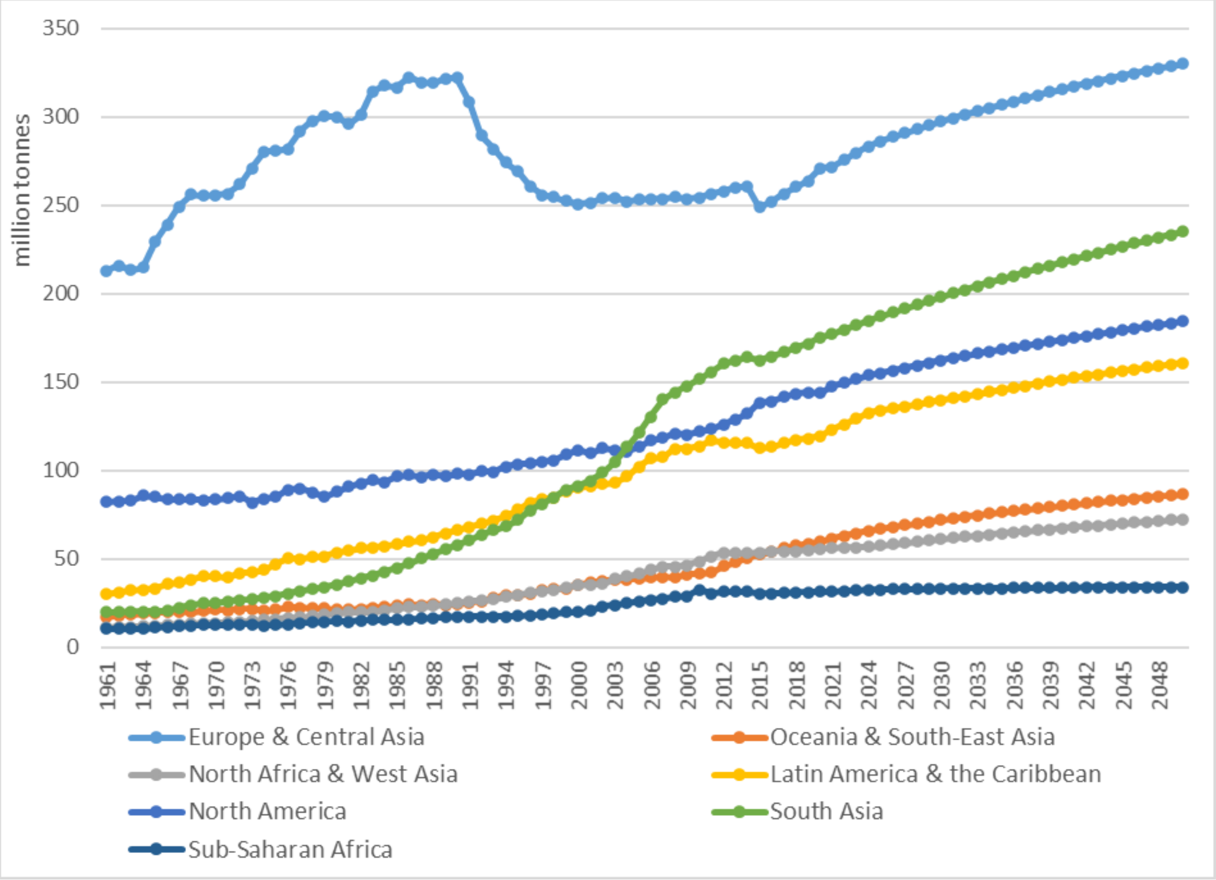
As with the similar figure for crop commodities (Figure 24), Figure 27 is the most important set of results for understanding the development of the ruminant animal sector over the modelled period. The most significant changes shown in this figure are the large increase in consumption in the South Asia region and the large increase in production in the Europe & Central Asia region. The large increases in consumption in South Asia can be attributed to the large increases in per capita income (described further in Section 7.2.7, and Figure 37), given the relatively high income elasticity for ruminant animal commodities (described in section 5.6.1). The modelling implies a higher level of inter-regional trade from the base year, as additional demand in South Asia, and Sub-Saharan Africa is serviced from Europe & Central Asia, Oceania & South-East Asia and North America.

Figure 27: Comparative regional growth in the production and consumption of ruminant products, 2012 and 2050



Ruminant Production

Figure 28: Ruminant animal production by region in the baseline scenario, 1961-2050



The full series of historic data and the model's projections from 2013 to 2050 for ruminant animals are presented in Figure 28. Notably the Oceania & South-East Asia and the North America regions experience significant increases in the early stages of the model's projections. These changes are driven in a large part by the initial dip in the world price for non-ruminant animals. When the world prices for ruminant and non-ruminant animals are simultaneously dropping, the relative size of the decreases and the sensitivity to price changes between the own-price or ruminant animal and the cross price of non-ruminant animals determines whether producers will prioritise land use and inputs for the production of either commodity.

Ruminant production by region is shown in Table 9. In percentage terms, the Oceania & South-East Asia region has the highest growth in ruminant animals (+88%), whereas South Asia has the largest increase in absolute terms, with 75 mil. t additional production by 2050. Globally there is strong growth in ruminant animal production with about 40 per cent, or 312 mil. t, over the modelled series. Most of this growth occurs earlier in the model's projections, partly due to the initial decline in the world price for non-ruminants between 2012 and 2016.

Table 9: Ruminant animal production by region in baseline scenario, 2020, 2030, 2040 & 2050

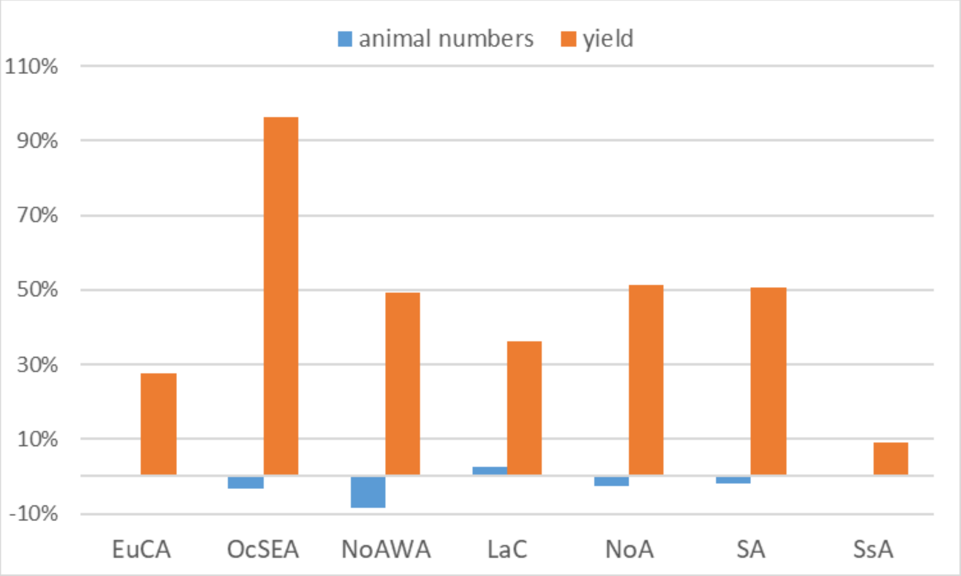
	Million tonnes					% change from base			
	Base (2012)	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Europe & Cent. Asia	258	271	297	316	330	5.1%	15.3%	22.4%	27.9%
Oceania & SE Asia	46	60	72	80	86	29.9%	56.5%	74.1%	87.9%
N Africa & W Asia	53	56	61	67	72	4.1%	14.3%	26.0%	35.5%
Lat. America & Caribbean	116	119	140	151	161	3.1%	20.6%	30.6%	38.8%
North America	126	144	162	174	184	14.2%	29.0%	38.3%	46.4%
South Asia	160	175	198	218	235	9.4%	23.6%	35.9%	46.7%
Sub-Saharan Africa	31	31	33	34	34	0.1%	5.5%	7.5%	8.9%
Total	791	856	964	1,040	1,103	8.3%	21.9%	31.5%	39.5%

As shown in Table 9, the baseline results involve large increases in ruminant animal production in all regions over the modelled period, with an additional 1.1 billion tonnes produced. Figure 29 divides this growth between growth in animal numbers and growth in yields. Similarly to crops, most growth comes from improvements in yield per unit. In fact, the majority of regions have an overall decrease of ruminant animal numbers over the examined period. This growth in yields is most pronounced in the Oceania and South-Asia region with an over 90 per cent increase in yield by 2050. Yield growth in

Sub-Saharan Africa is the lowest of all regions, which suggests a worrying trend since the region already had the lowest yields of any region in the base year.

Europe & Central Asia have the highest rates of production for ruminant animal products, increasing almost 28 per cent over the modelled period. In actuality, the expansion of production may be difficult given the EU's policy objectives for achieving climate neutrality, including action in its non-ETS sectors, which include agriculture[25] (EPRS, 2020). However as shown in Figure 29, the increase in production is coming from improvements in yield per animal, rather than an increase in animal stocks. This would align with goals on increasing emissions efficiency in agriculture, as long as meeting these climate goals would not imply reducing animal numbers.

Figure 29: Percentage change in ruminant animal numbers and yield by region, between 2012-2050



Consumption of Ruminant Animal Products

The consumption of ruminant animal products in the baseline is projected to grow. Table 10 shows the development of global demand by source. The majority of growth comes from increases in consumption as food, although there is also a relatively high change in the demand for ruminant animal products for feed (mostly milk used as inputs into other animal products. In the context of ruminant animals, this is mostly in the form of milk and milk-solids, rather than meat. In terms of shares of total consumption, the share of consumption as food increases from the base year (51% to 58%), while all other shares decrease. Other uses has the highest decrease from 34 per cent in the base year, to 29 per cent in 2050.

---

[25] The LAO model assumes no constraints based on climate policy.

Table 10: Global consumption for ruminant animal products from each usage

	Million tonnes			% Δ from 1961/2012	
	1961/2012	2012	2050	2012	2050
Consumption as food	269	402	634	50%	136%
Consumption as feed	95	105	134	11%	42%
Other uses	197	271	318	38%	62%
Waste	8	12	16	49%	96%
	% of total consumption				
Consumption as food	47%	51%	58%		
Consumption as feed	17%	13%	12%		
Other uses	35%	34%	29%		
Waste	1%	2%	1%		

The breakdown of the results for consumption by region is shown in Table 11 with both absolute and relative change. In absolute terms, global total consumption of ruminant products grows by 322 mil.t, with 104 mil.t of this coming from South Asia. The next highest increase is from Sub-Saharan Africa (59 mil.t), which is the highest change relative to the base year, a change of over 180 per cent. Sub-Saharan Africa experiences such a large increase in consumption due to a relatively small increase in incomes combined with a rapidly increasing population.

Table 11: Quantity ruminant animal products consumed as food, by region, 2020, 2030, 2040 and 2050

	Million tonnes					% change from base			
	Base (2012)	2020	2030	2040	2050	2020	2030	2040	2050
Europe & Cent. Asia	90	91	98	102	104	0.5%	8.8%	12.3%	14.5%
Oceania & SE Asia	17	19	27	30	34	12.1%	56.5%	80.0%	100.8%
N Africa & W Asia	31	35	43	50	56	12.1%	38.7%	60.7%	81.0%
Lat. America & Caribbean	79	79	92	101	107	-1.1%	16.1%	26.7%	34.6%
North America	58	61	63	64	65	5.2%	7.8%	9.9%	11.0%
South Asia	101	127	160	178	191	26.4%	58.5%	76.6%	89.8%
Sub-Saharan Africa	25	30	48	62	77	17.8%	89.2%	145.6%	206.6%
Total	402	442	531	587	634	9.8%	31.9%	45.8%	57.7%

7.2.4 Non-ruminant production

Figure 30: Comparative regional growth in the production and consumption of non-ruminant products 2012 and 2050

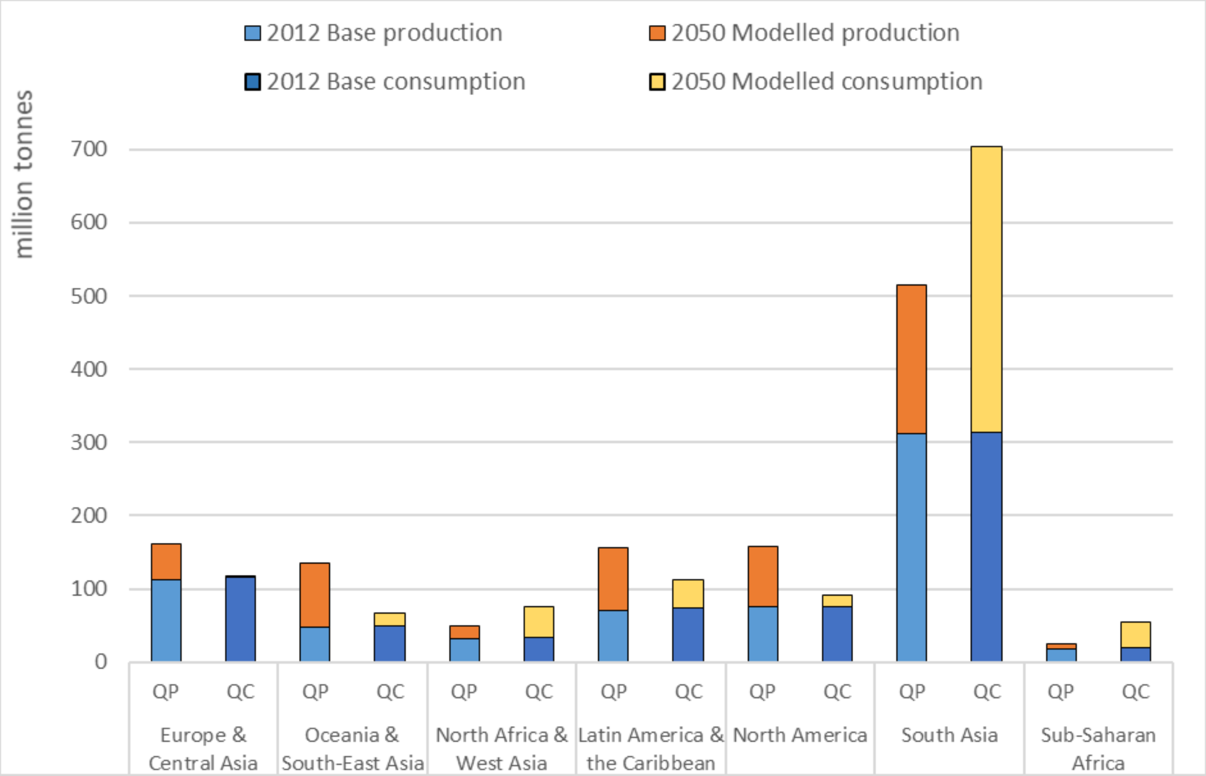


Figure 30 shows the relative state of production and consumption of non-ruminant animals, in the base year and in the final year of the modelling projections. This figure serves as a quick reference to the development of non-ruminant markets. The most obvious change over the modelled period is the sharp increase in both production and consumption in South Asia. In the base year, South Asia has by far the largest production and consumption of non-ruminants, with minimal net trade outside the region. This situation has changed significantly by 2050 with the growth of demand for non-ruminant animal products in South Asia outstripping the growth of production in the region. This imbalance leads to increased production in other regions to help service the demand in South Asia, with many regions becoming net exporters.

The Sub-Saharan region also experiences a large proportionate increase in consumption, in excess of the projected increase in production. The largest of any region, with a 170 per cent increase. Regional imports from other regions are required to service this deficit. North Africa & West Asia also becomes a net importer of non-ruminant animals.

Non-ruminant Production

Figure 31: Production of non-ruminant animal products by region in the baseline scenario, 1961-2050

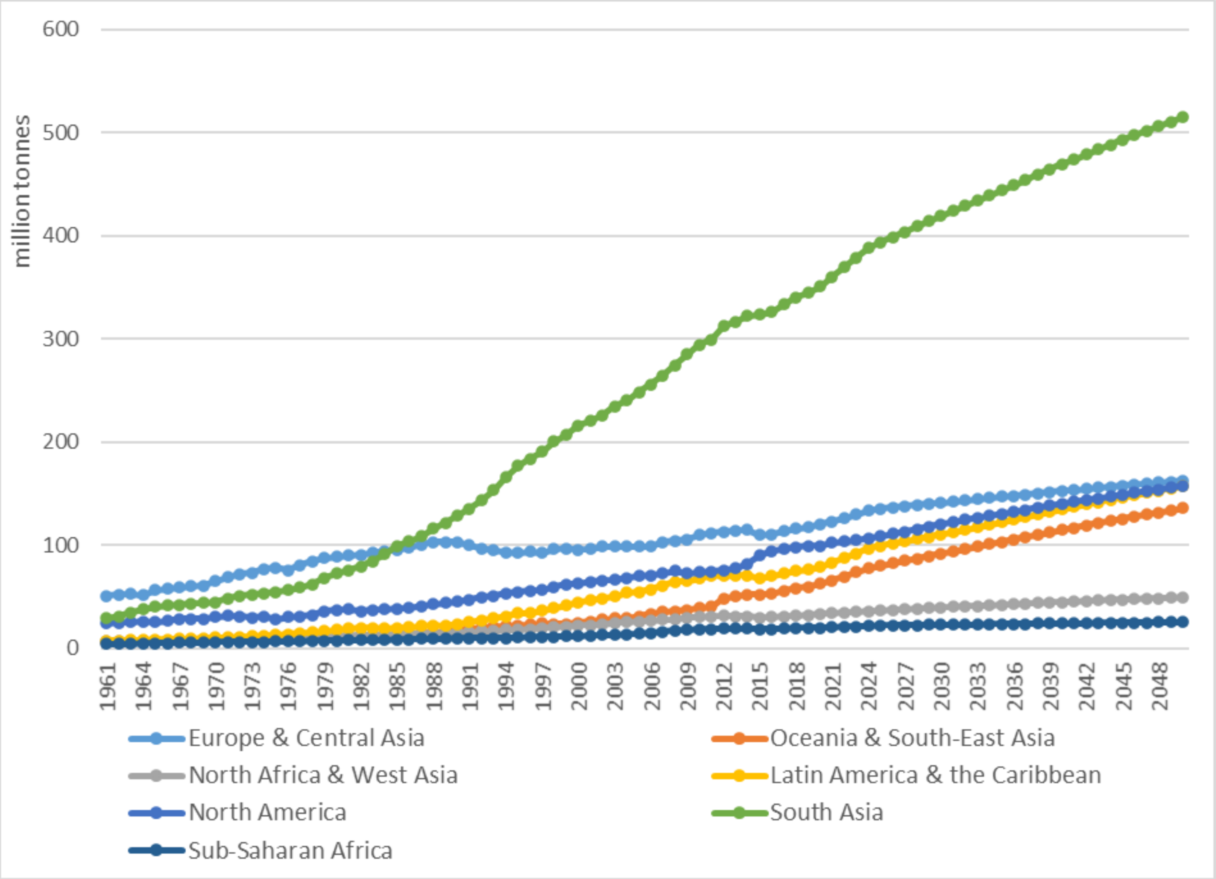


Figure 31 give a visual representation of the development of the production of non-ruminant animals between the different regions in the LAO model. The discrepancy in the extent of production of non-ruminant animals in the South Asia region compared to all other regions is apparent. This gap in production between South Asia and the next highest producing region (EuCA) grows over the modelled period from 199 to 353 mil.t in the initial modelling period, a decrease in the world price for non-ruminant animals is reflected in a drop in production in some regions (EuCA, LaC, & OcSEA). The strong increases in production in South Asia and North America after the base year are therefore counter intuitive, as they occur in the face of depressed world prices. In North America, this is in part due to the cross-price elasticities for ruminant animals which are also experiencing decreasing world prices in this period. This would drive producers to shift production from ruminant to non-ruminants depending on relative prices.

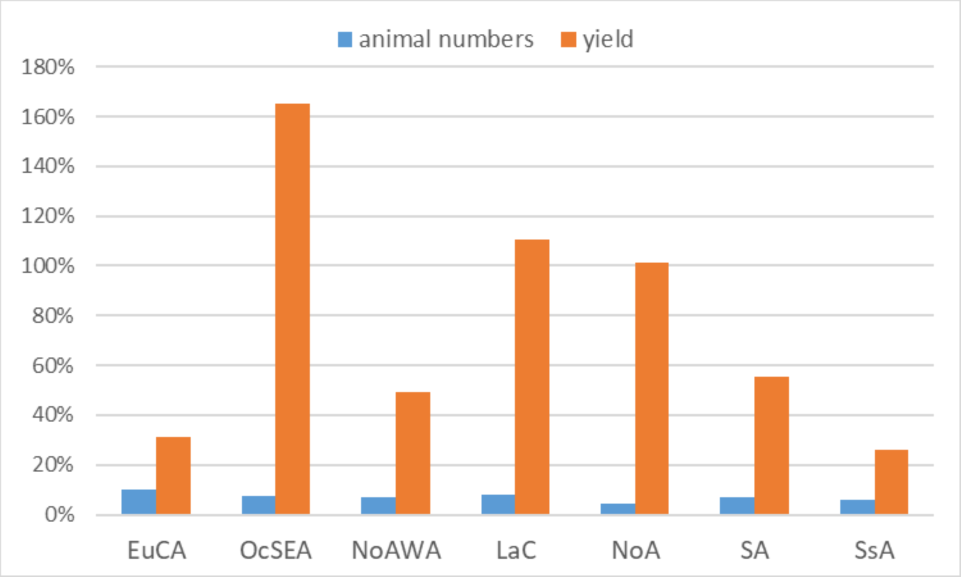
Table 12 presents the regional production of non-ruminant animals, and their changes from the base year, in the baseline scenario. Oceania & South-East Asia has the greatest increase in non-ruminant animal production, with an increase of 180 per cent in 2050. The highest absolute increases in ruminant animal production are in the South Asia region, which also has the highest production rates in the base year (312 mil. t), growing to 515 mil. t by 2050. Absolute and relative growth in Sub-Saharan Africa is weak, growing only 4 mil.t by 2050. In total, global non-ruminant animal production in the baseline scenario is projected to almost double, with an increase of 532 mil.t by 2050 or 180 per cent of the baseline values.

Table 12: Non-ruminant animal production by region in baseline scenario, 2020, 2030, 2040 and 2050

	Million tonnes					% change from base			
	Base (2012)	2020	2030	2040	2050	2020	2030	2040	2050
Europe & Cent. Asia	113	120	141	152	162	6.5%	24.9%	34.9%	43.7%
Oceania & SE Asia	48	62	91	115	136	28.7%	89.2%	136.9%	180.3%
N Africa & W Asia	31	33	39	45	49	6.7%	26.4%	43.7%	58.1%
Lat. America & Caribbean	70	79	110	135	157	12.2%	57.4%	92.1%	124.2%
North America	76	99	120	140	157	30.8%	58.4%	84.6%	107.7%
South Asia	312	351	419	469	515	12.4%	34.3%	50.3%	64.9%
Sub-Saharan Africa	19	20	23	24	25	5.5%	20.0%	27.4%	33.4%
Total	669	764	944	1,080	1,202	14.2%	41.0%	61.3%	79.5%

The division of changes in production by growth in animal numbers and the yield per animal is shown in Figure 32. Non-ruminants show a growth in total animal numbers in all regions. This is different from ruminant animals where yield per ha/unit exclusively accounted for overall growth in most regions. Notably Oceania and South-East Asia has very high growth in yields; Latin America and the Caribbean, and North America both see yields doubling.

Figure 32: Percentage change in non-ruminant animal numbers and yield by region, 2012-2050



Non-ruminant Consumption

The consumption of non-ruminant products increases strongly over the modelled period, mostly driven by increased demand for food in South Asia. Table 13 shows the division of consumption by use, and that the large majority of non-ruminants are consumed as food, rather than other modelled uses. Consumption as food's share of total consumption increases seven percent from the base year (2012) to the final year of the modelling (2050). Similarly to ruminant animal products, other uses' share of total consumption decreases from the base year to the final year (34% to 29%).

Table 13: Global consumption for non-ruminant animal products by each usage, 2012 and 2050

	Million tonnes			% Δ from 1961/2012	
	1961/2012	**2012**	**2050**	**2012**	**2050**
Consumption as food	269	402	634	50%	136%
Consumption as feed	95	105	134	11%	42%
Other uses	197	271	318	38%	62%
Waste	8	12	16	49%	96%
	% of total consumption				
Consumption as food	47%	51%	58%		
Consumption as feed	17%	13%	12%		
Other uses	35%	34%	29%		
Waste	1%	2%	1%		

Table 14 shows the detailed development of non-ruminant animal commodity consumed as food. Total global consumption as food increases nearly two-fold over the modelled period, from 594 mil.t to 1,106 mil.t. Around three quarters of this increase is in South Asia, accounting for 384 mil.t additional consumption between 2012 and 2050. This increase is largely driven by the projected increases in incomes in the region. Conversely, the downwards trend in Engel elasticities causes consumption of non-ruminant products in Europe & Central Asia to decrease below 2012 levels as incomes in the region rise.

Table 14: Quantity Non-ruminant animals consumed as food, by region, 2020, 2030, 2040 and 2050

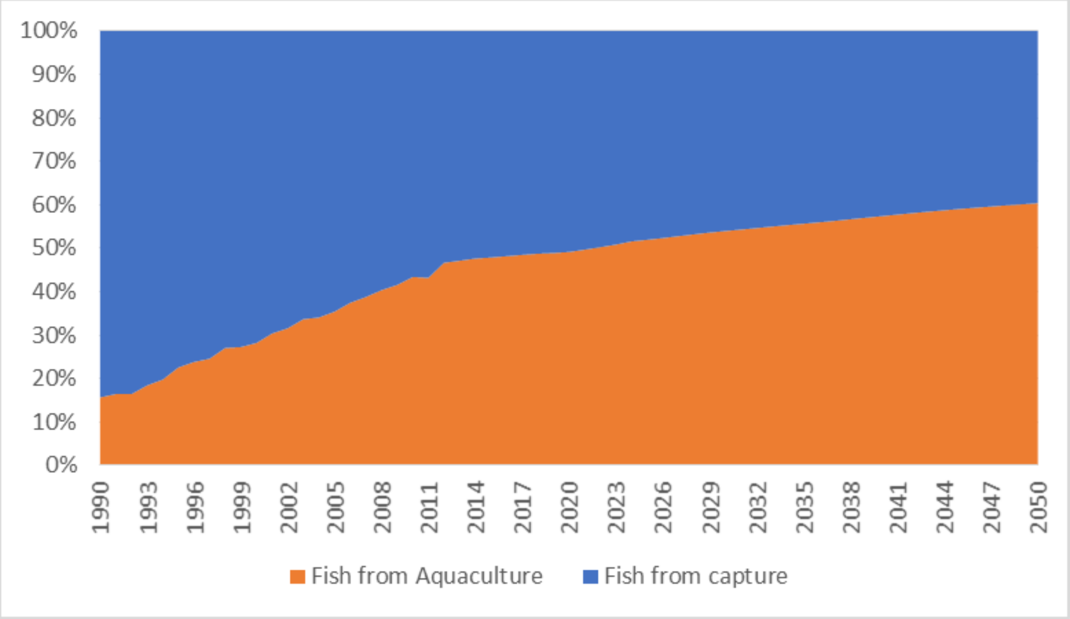
	Million tonnes					% change from base			
	Base (2012)	2020	2030	2040	2050	2020	2030	2040	2050
Europe & Cent. Asia	102	103	105	104	102	0.9%	2.1%	1.0%	-0.8%
Oceania & SE Asia	42	43	49	53	56	3.2%	18.1%	26.9%	34.5%
N Africa & W Asia	28	32	44	56	67	15.8%	60.8%	100.7%	140.9%
Lat. America & Caribbean	61	61	75	87	97	-0.7%	23.9%	42.5%	58.7%
North America	63	66	69	71	73	5.4%	9.7%	13.5%	16.1%
South Asia	281	357	485	580	665	26.8%	72.4%	106.2%	136.6%
Sub-Saharan Africa	16	19	30	38	46	16.9%	79.5%	129.1%	182.1%
Total	594	681	857	988	1,106	14.8%	44.5%	66.4%	86.4%

7.2.5 Fish production

This section explores the development of fish production in the baseline scenario. In particular, the balance between fish production from capture versus fish from aquaculture.

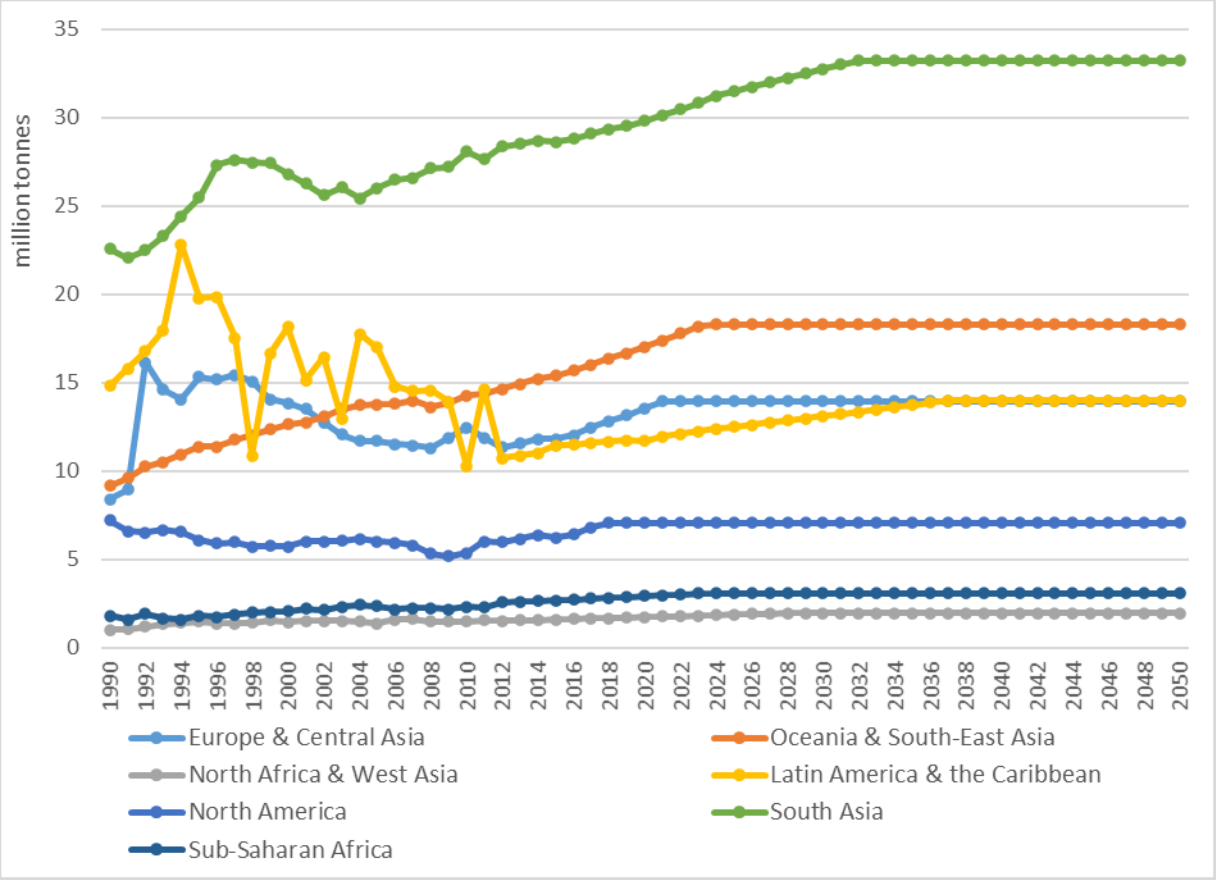
With the limitations placed on the expansion of captured fish in the model, the proportion of total fish from capture should decrease over the modelled period, with an increase in aquaculture offsetting the consumption deficit. These constraints were discussed in section 5.5.3, with the model aiming to simulate the expected maintainable maximum global fish stocks by region. Figure 33 shows the proportion of fish production from the two sources (capture and aquaculture) over the modelled period. The results are as expected with the contribution of aquaculture growing from under half of all fish production in the base year (2012) to over 60 per cent in the final year of the baseline modelling exercise.

Figure 33: Percentage of global fish production from capture versus aquaculture, 1990-2050



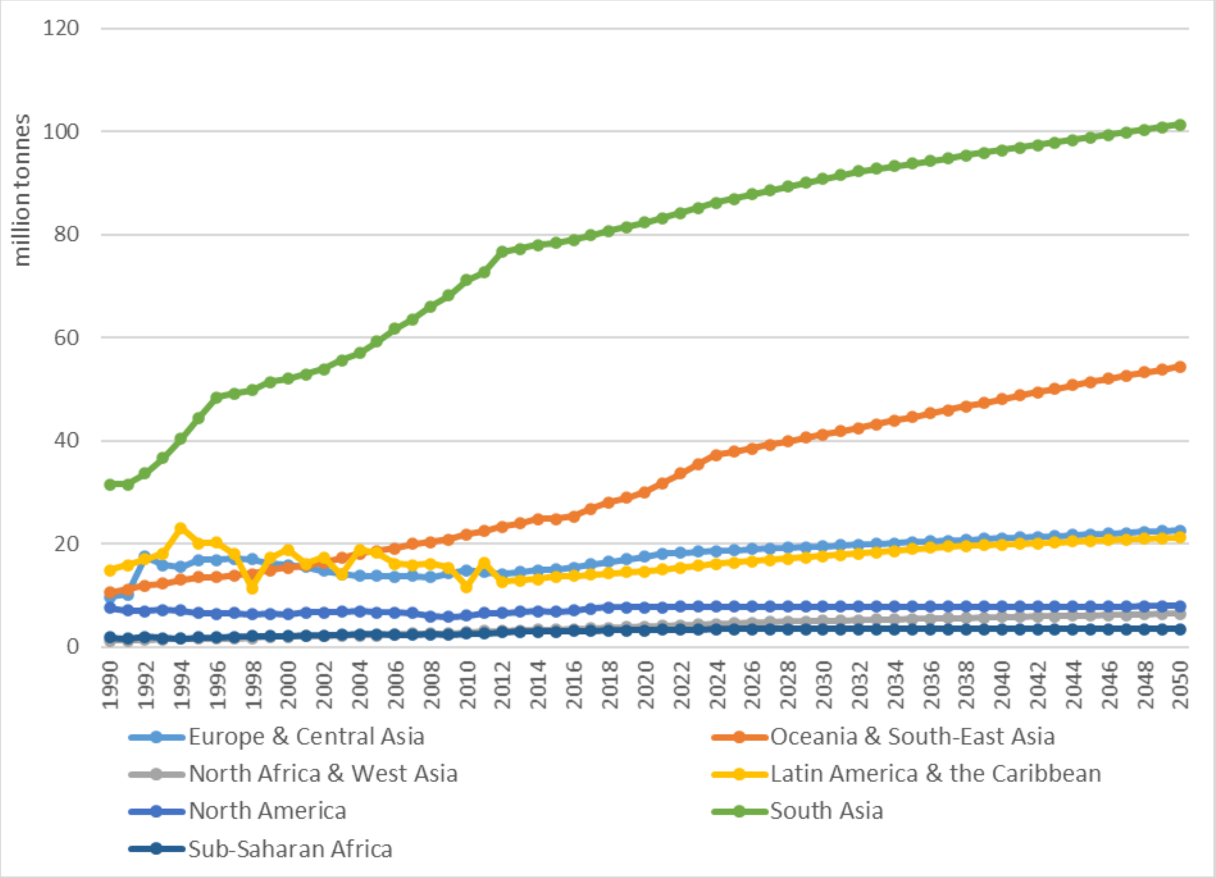
The constraints on fish from capture are shown in Figure 33 as the production in each region reaches their upper limit given regional fish-stocks. This occurs at different points during the model run for different regions in the base scenario. North America and the Europe & Central Asia regions are the first to reach their hypothetical limits, before 2020. The Latin America & the Caribbean, and South Asia regions have the highest caps relative to their starting positions in the base year, but, by 2035, all regions have reached their maximum projected fish production from capture sources.

Figure 34: Regional quantity produced from fish from capture, 1991-2050



Expanding on the limitations of production and the switch from fish from capture to aquaculture, the total fish production from both sources is presented in Figure 35. The major developments in fish production come from Oceania & South-East Asia, and from South Asia, with respective increases of 31 mil.t and 24 mil.t respectively. Overall, the change in fish production is much smaller than the change in production from the other commodities considered in the model. Thus, while the change between aquaculture and fish from culture is an interesting development, the total contribution of fish towards global production and consumption is relatively minor.

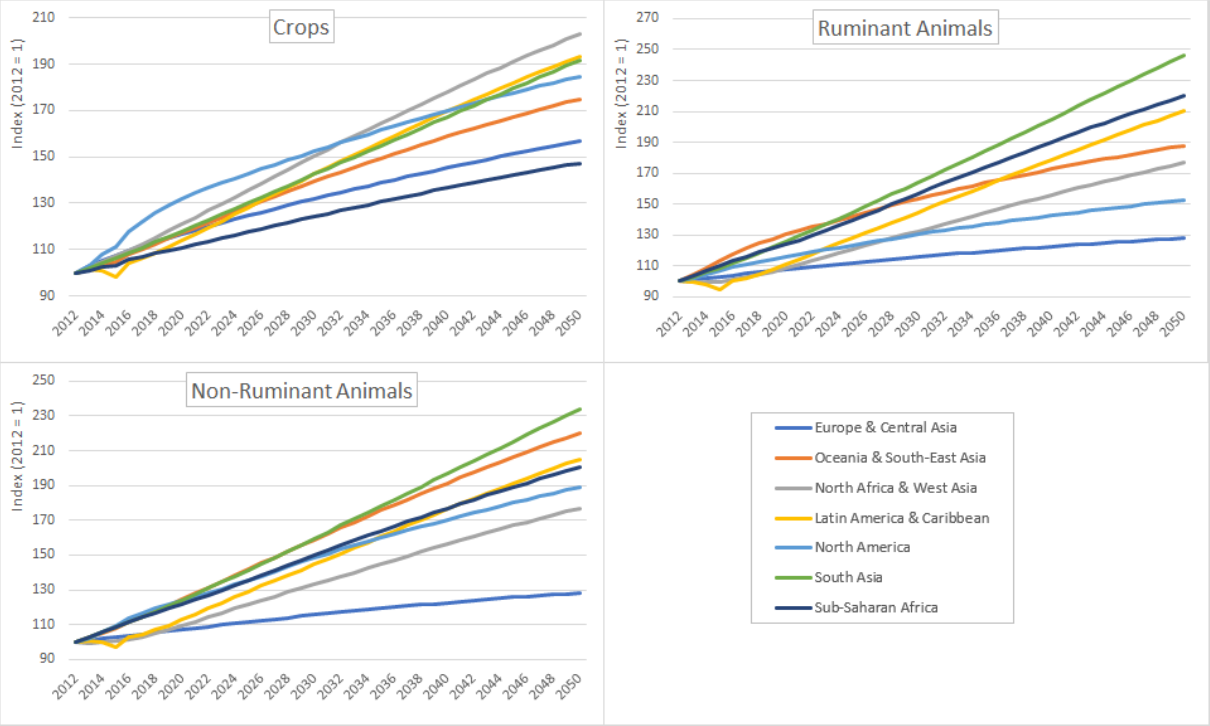
Figure 35: Total fish production by region in baseline scenario, 1990-2050



7.2.6 Endogenous TFP

The baseline scenario also implies a development of TFP from the endogenous TFP component, governed by Equation 17. The development of TFP over the modelled period, for the three commodities with an endogenous TFP specification in the model (crops, ruminant animals and non-ruminant animals) is shown in Figure 36.

Figure 36: Baseline endogenous TFP by region and commodity, 2012-2050



TFP growth for crops is lowest for Sub-Saharan Africa, this may be in part due to low levels of investment into historic agricultural R&D, but also due to low spill-over rates with other regions for in the crop commodity[26]. North Africa & West Asia, Latin America & the Caribbean, and South Asia show the highest TFP growth for crops over the modelled period. Conversely, Sub-Saharan Africa has strong TFP growth in ruminant and non-ruminant animal products.

South Asia has the highest TFP growth for the two animal commodities, followed by Sub-Saharan Africa for ruminant animals, and Oceania & South-East Asia for non-ruminant animals. The strength of South Asia's TFP growth is in part from a high spill-over elasticity (Appendix Table X7).

Interestingly Europe & Central Asia have the lowest growth in TFP for both ruminant and non-ruminant animal products[27]. It is possible in the case of ruminant animals this is due to a higher level of TFP, thus implying a higher level of absolute growth as Europe & Central Asia has the second highest yield rate for ruminant animals, which grows 28 per cent over the modelled period in the baseline scenario. This is less likely the case for non-ruminant animals where Europe & Central Asia has the third lowest yield of all regions.

---

[26] Sub-Saharan Africa has the lowest average spill-over weighting for crops at 0.3112.

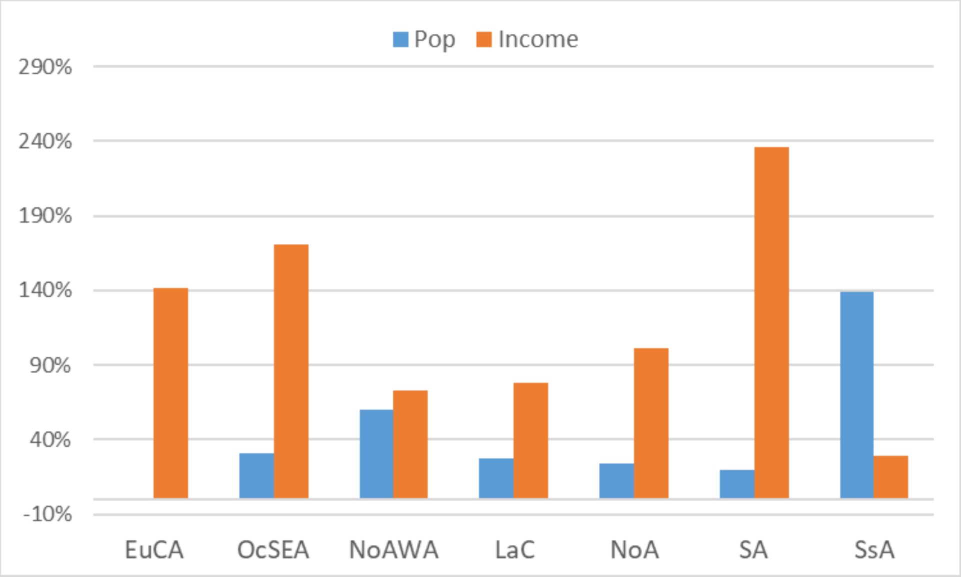
[27] This low-level of TFP growth in Europe and Central Asia is also notable in the historical data of agricultural TFP (Table 3).

7.2.7 Total Food Consumption

This section explores the demand side of results for the baseline scenario in greater detail. The key two exogenous variables driving changes to demand as food for all commodities are population and GDP per capita (described as ‘income’ in this thesis). Thus, understanding the relative development of these two variables can shed more light on changes to the consumption-side of the modelling projections. Growth in consumption reflects more consumers (increases in population), the growth of regional incomes (higher GDP per capita) or changes in income elasticities (relative demand at different income levels).

Figure 37 shows the comparative growth between these two key parameters for each region. This figure identifies the key element of demand growth in each region. For example, population in Europe & Central Asia has slightly negative growth, thus growth in incomes is the primary driver for growth in demand in this region. Figure 37 also shows that all regions other than Sub-Saharan Africa and North Africa & West Asia have significantly more income growth than population growth over the modelled period. The North Africa & West Asia region has almost equal growth in population and incomes, while population growth is by far the largest element in demand growth for Sub-Saharan Africa. The largest regional changes are the income growth in South Asia (followed by Europe & Central Asia, and Oceania and South-East Asia), and the population growth in Sub-Saharan Africa. The magnitude of these increases drive many of the changes in the modelling scenarios.

Figure 37: Percentage growth of demand-side variables, 2012-2050



The key consumptive use for the research questions posed in this thesis is consumption as food. Table 15 displays the changes in consumption as food for all commodities over the 38 years of the model’s projections. The most significant change is the large relative increase in the consumption of non-ruminant animals, which almost doubles between 2012 and 2050. This increase is largely driven by growing incomes in the South Asia region, which accounted for 75 per cent of the global increase in consumption by 2050.

Table 15: Change in consumption as food in baseline scenario, 2020, 2030, 2040 and 2050

	Million tonnes					% of base			
	Base (2012)	2020	2030	2040	2050	2020	2030	2040	2050
Crops	3,684	4,069	4,683	5,037	5,308	10.4%	27.1%	36.7%	44.1%
Ruminant animals	402	442	531	587	634	9.8%	31.9%	45.8%	57.7%
Non-ruminant animals	594	681	857	988	1,106	14.8%	44.5%	66.4%	86.4%
Fish from capture	72	81	87	89	89	11.9%	20.9%	22.9%	23.0%
Fish from aquaculture	43	48	56	61	64	12.5%	29.7%	40.5%	48.8%
Total	4,795	5,321	6,214	6,761	7,201	11.0%	29.6%	41.0%	50.2%

In absolute amounts, crops consumption increases the most of all commodities. The increase in consumption of crops is unevenly spread between regions, with over a third (36%) of the additional consumption occurring in Sub-Saharan Africa, driven by population growth, coupled with relatively low incomes resulting in a higher sensitivity of the consumption of staple foods associated with income growth. Another third of increases in crop consumption comes from South Asia, with an 11 per cent increase in crop consumption per capita, combined with a 19 per cent increase in population.

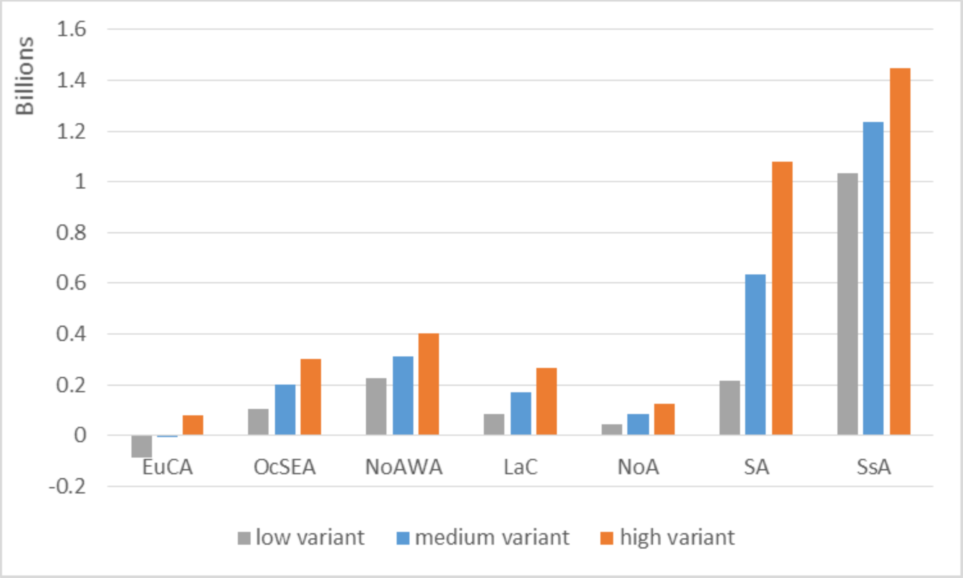
7.3 Population Scenarios

Table 16: Population scenarios assumptions

Grouping	Scenario name	GDP	population	TFP/yield growth
2) Population	i. high variant	IMF GEO	high variant	endogenous
	ii. medium variant	IMF GEO	medium variant	endogenous
	iii. low variant	IMF GEO	low variant	endogenous

This section describes the three population scenarios (2.i-iii) run using the LAO model, one of which being the baseline (described in Table 16). Population is one of the most influential exogenous inputs to the model. The population scenarios are based on the UNDESA population prospects (2019a), expanded on in section 6.3.1. The change in population influences the demand equation in the model, changing total domestic demand in each region. The baseline scenario used the ‘medium variant’ population scenario, which is therefore the basis for comparison in this section’s two alternative population scenarios.

Figure 38: Regional change in population between 2012-2050



Source: UNDESA, 2019

The change in population over the modelled projection period (2012-2050) is shown in Figure 38. Of the regions in the model, the Sub-Saharan region experiences the largest growth of population from the base year to the end of the projection, with between 1.0 and 1.4 billion additional people by 2050. While Sub-Saharan Africa has the highest increase in population from the base year, South Asia has the largest variance between the high and low variant scenarios with a difference of 860 million people between the two scenarios. This implies the South Asia region has the highest uncertainty in the development of its population.

All regions other than Europe and Central Asia have increases in population over the projected period. The low and medium variant scenarios project a decrease in the population of Europe and Central Asia from 2012 to 2050.

Table 17: Comparison of consumption as food between population scenarios, 2050

	Million tonnes				% change from medium variant			
	Crops	Ruminant animals	Non-ruminant animals	Fish from all sources	Crops	Ruminant animals	Non-ruminant animals	Fish from all sources
medium variant[28]	5,308	634	1,106	153	-	-	-	-
high variant	6,010	678	1,214	159	13.23%	6.84%	9.76%	3.57%
low variant	4,619	591	1,003	148	-12.97%	-6.87%	-9.34%	-3.18%
	% of total consumption as food							
medium variant	61%	18%	18%	2%				
high variant	63%	18%	17%	2%				
low variant	59%	19%	19%	2%				

The most significant impact of changes to the projected population is the change to the quantity of agricultural commodities consumed as food. This increase of demand across all commodities is shown in Table 17. In terms of absolute change, the crop commodity shows the greatest variance between scenarios of 1,391 mil.t. The location of the increases in population is also significant, due to the regional specificity of the demand profiles. Thus, the relatively large changes in the consumption of non-ruminant animals are driven by the large variation between scenarios in South Asia, which also has one of the highest per-capita consumptions of non-ruminant animals.

In terms of the shares of consumption between the food commodities there is between a two and four percentage point shift between the high and low variant scenarios (except for fish). In the high variant scenario, a greater proportion of crops is consumed. This is due to the largest absolute population changes coming from South Asia[29] which has the highest average per capita consumption of crops. Inversely the same effect, of population change in South Asia, is responsible for the proportional decrease of crops in the low variant scenario.

The consumption of fish is not significantly affected by the different population scenarios either in absolute or proportional terms.

The modelled impacts of the examined population scenarios are presented below. The key result is the impact on world prices, as this is a good proxy for the relative pressures from changing production and consumption globally. It is also an important indicator for the affordability of food, a key consideration for answering the research aim of this thesis.

---

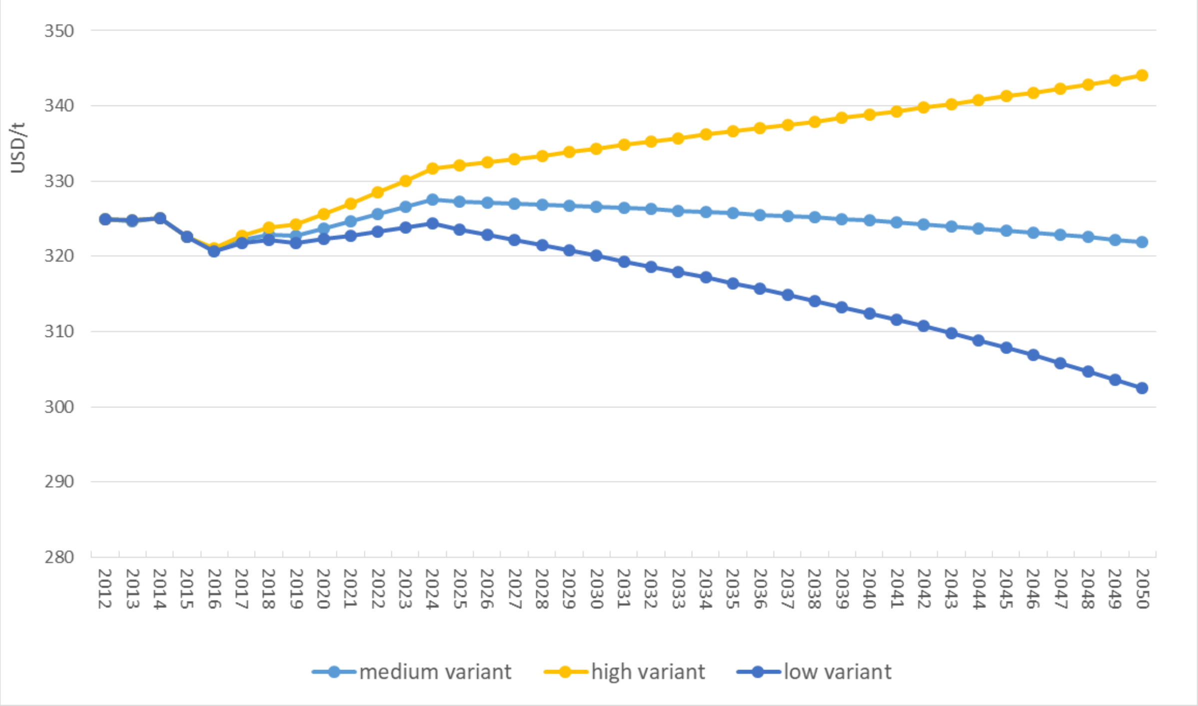
[28] Baseline scenario.

[29] Sub-Saharan Africa had the second largest variation in population but has the lowest average per capita consumption of all commodities except crops.

Figure 39 displays the different results for world prices for crops across the different population scenarios examined. All scenarios show the initial decrease in the world price for crops, as markets correct for the relatively high food prices in the base period. As described in the baseline scenario, the real prices in the medium variant population scenario shows a steady decline after 2024 across the modelled period, with a slight decline of half a per cent from 2027 to 2050.

With upwards pressure on prices in the high population variant, the outlook for world price is very different. After the divergence between scenarios in 2016, the world price for the high variant scenario trends upwards, resulting in higher crop prices in 2050 than in 2012, the base year. By 2050, the world price for cops have increased 7.3 per cent above their lowest point in 2016.

Figure 39: Population scenarios 1-3, world price for crops, 2012-2050



Considering the other extreme in terms of population, the low variant scenario leads to a decline in world prices for crops. The decrease in final consumption demand for crops of 12.95 per cent brought on by a lower global population, results in almost a seven per cent drop in price from the base year, and six per cent difference from the medium variant scenario, in 2050.

Table 18 presents the regional demand changes driving the changes in world crop prices from the different population scenarios. In absolute terms the greatest change in consumption as food is in South Asia, which has a variance of 631 million tonnes between the high and low population scenarios. This is more than double the variance in Oceania and South Asia, which shows a 249 million tonne difference in crop consumption between the high and low population scenarios. In fact, the difference in consumption seen in South Asia is almost as large as that for all other regions combined (759 million tonnes). Thus, the question of changes in crop consumption (2050) largely concerns the development of South Asia. This is unsurprising, given it is the region with the second largest population growth between 2012-2050 in both the high and medium scenarios, and the highest variance in population between scenarios.

Looking to Sub-Saharan Africa, the region with the largest increase in population between 2012 and 2050 in all population scenarios, and the second highest variance between scenarios, the impact on crop consumption is much lower than in South Asia, with a variance of only 141 mil.t. This is due to the low consumption per capita in Sub-Saharan Africa.

Table 18: Regional comparison of crops consumed as food between population scenarios, 2050

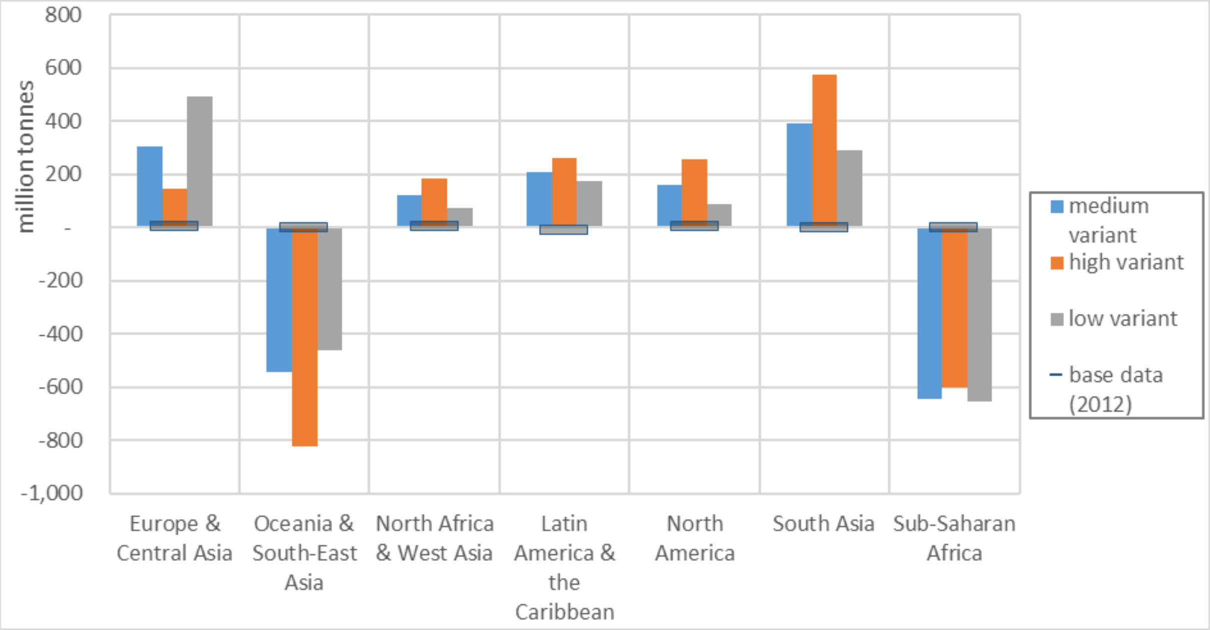
	Million tonnes			**% change from medium variant**	
	medium variant	**high variant**	**low variant**	**high variant**	**low variant**
Europe & C. Asia	346	399	295	15.4%	-14.7%
Oceania & SE Asia	754	881	632	16.8%	-16.2%
N Africa & W Asia	330	370	291	12.1%	-11.9%
Lat. America & Caribbean	431	490	375	13.6%	-13.1%
North America	209	246	175	17.8%	-16.4%
South Asia	2,257	2,578	1,947	14.2%	-13.7%
Sub-Saharan Africa	981	1,045	905	6.6%	-7.8%
Total	5,308	6,010	4,619	13.2%	-13.0%

Another key measure of the scenario results is the trade balance for each region. The trade balance gives a succinct measure of the deficit or surplus of regional production compared to regional consumption. Figure 40 gives the trade balance for the medium, high and low variant scenarios, in comparison with the trade balance in the base year. The relative regional consumption and production for the baseline scenario has already been discussed in the previous section.

In terms of regional shares of consumption, South Asia is the largest consumer of crop products accounting for over 40 per cent of global consumption as food. This share increases in the high population variant as South Asia experiences the highest absolute increase in crop consumption, and conversely decreases in the low population variant.

The trade balances for crops in the base year are low compared to those shown in 2050, this indicates a lack of inter-regional trade in the base period.

Figure 40: Regional crop trade balance between population scenarios, 2050



Sub-Saharan Africa and Oceania & South-East Asia both have large deficits in trade in all population scenarios, whereas South Asia and Europe & Central Asia service the majority of this deficit, both becoming net exporters in all scenarios. Addressing the variation between the population scenarios, one of the most interesting changes is in Europe & Central Asia, where the extent of crop exports varies heavily under different population projections. This is in part due to Europe & Central Asia having the second lowest change in consumption between population scenarios, and a high responsiveness to non-ruminant animal prices, causing productive capacity in Europe & Central Asia to divert from crop production (even given higher crop prices), because changes in non-ruminant prices are higher still.

Oceania & South-East Asia remain a net importer of crops, this is due to their having the highest increase per capita of crop consumption from the base year, and the smallest increase in crop production over the same period. This high per capita consumption rate is also responsible for the high level of change in consumption in Oceania & South-East Asia between the population scenarios.

Ruminant Animals

Figure 41 shows the world prices over the modelled period for ruminant animals given the different population scenarios. By 2050, world prices for ruminant animal for the medium population scenario end up very close to their levels in 2012. This is after some fluctuation in the early years of the simulation. At the end of the projected period, they are trending gradually downwards, implying lower that base level prices over the long-term. In the low population scenario, world prices are steadily decreasing reaching 12 per cent under their base year levels by the end of the projected timeline. The high variants entail upwards trending prices in the final years of the projections, with prices in 2050 exceeding initial prices in the base year by 12.7 per cent.

Figure 41: Population scenarios 1-3, world price for ruminant animal products, 2012-2050

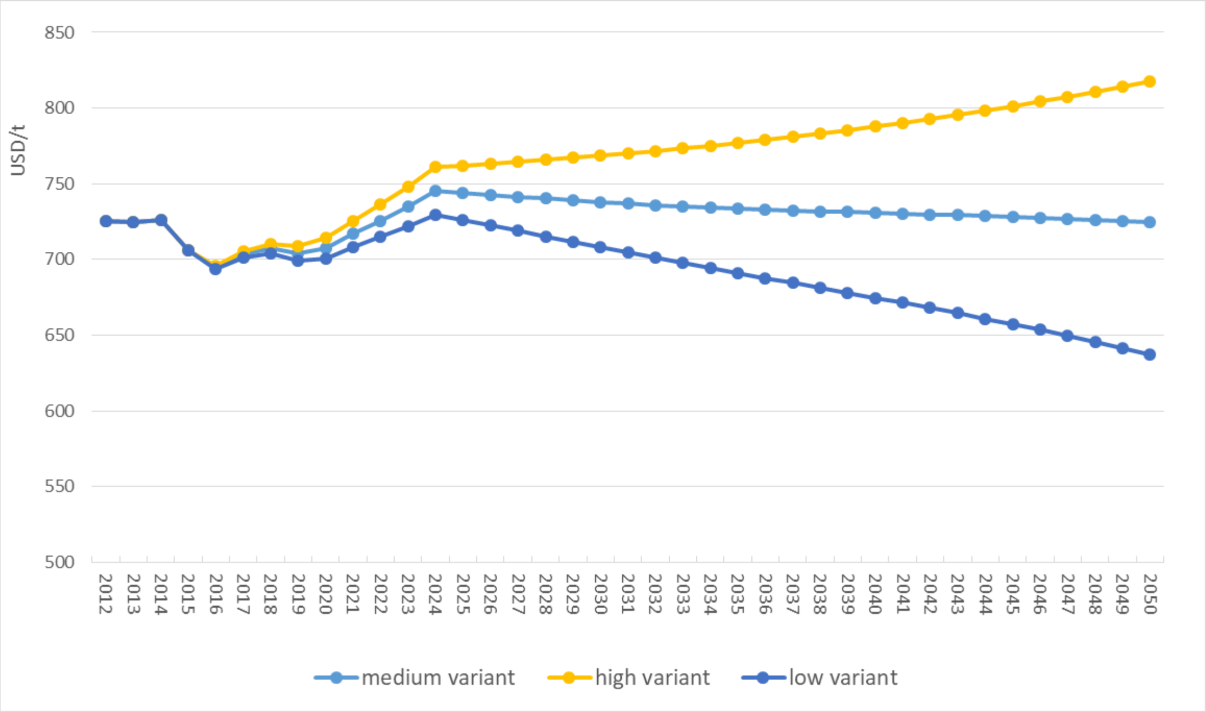


Table 19 shows the consumption of ruminant animal commodities as food in each population scenario. Overall, between the scenarios, there is about a seven per cent variance in global consumption above and below the medium variant population scenario.

Table 19: Regional comparison of ruminant products consumed as food between population scenarios, 2050

	Million tonnes			% change from medium variant	
	medium variant	**high variant**	**low variant**	**high variant**	**low variant**
Europe & C. Asia	104	113	94	9.5%	-9.0%
Oceania & SE Asia	34	40	28	17.4%	-17.2%
N Africa & W Asia	56	58	55	3.4%	-3.2%
Lat. America & Caribbean	107	110	104	3.1%	-3.1%
North America	65	70	59	8.9%	-8.5%
South Asia	191	202	179	5.7%	-6.1%
Sub-Saharan Africa	77	83	71	7.4%	-7.7%
Total	634	678	591	6.8%	-6.9%

The consumption of ruminant animals is most sensitive to population growth in South Asia, with an increase of almost 11 mil.t of additional consumption in the high variant, and a 12 mil.t decline in the low variant scenario. Proportionally, the increase in South Asia is comparable with the changes in other regions. Due to their higher initial consumption, however, the absolute change in South Asia is the greatest.

In terms of regional shares of consumption, South Asia is the largest regional consumer of ruminant animal products, accounting for roughly thirty per cent of consumption. This changes about 0.06 percentage points, decreasing in the high population variant and growth in other regions is higher than growth in South Asia and conversely increasing in the low variant. Europe & Central Asia and Latin America and the Caribbean are the next biggest consumers of ruminant animal products, with around 16 per cent of total global share each.

With respect to the level of consumption in the medium variant scenario, the Oceania & South-East Asia region has the highest proportionate changes of all regions. Consumption of ruminant animals as food increases over 17 per cent in the high variant scenario, compared with the medium variant scenario.

Non-Ruminant Animals

Figure 42 shows the price impacts for non-ruminant animal products for the three population scenarios. Similarly to the world price prospects for ruminant animal commodities, the medium variant scenario is the only one with relatively stable world prices at the end of the projection period. However, unlike the ruminant animal commodities, prices for non-ruminant animals trend much higher in comparison to their initial state in the base year. In 2050, both the medium and high population scenarios have higher world prices than in the base year (9% higher in the medium variant; 26% higher in the high variant). It is only in the final years of the low population scenario that world prices dip below their 2012 levels. This points to the likelihood of higher prices for non-ruminant animal products into the future regardless of the population outcome (within the UNDESA projections).

Figure 42: Population scenarios 1-3, world price for non-ruminant animals

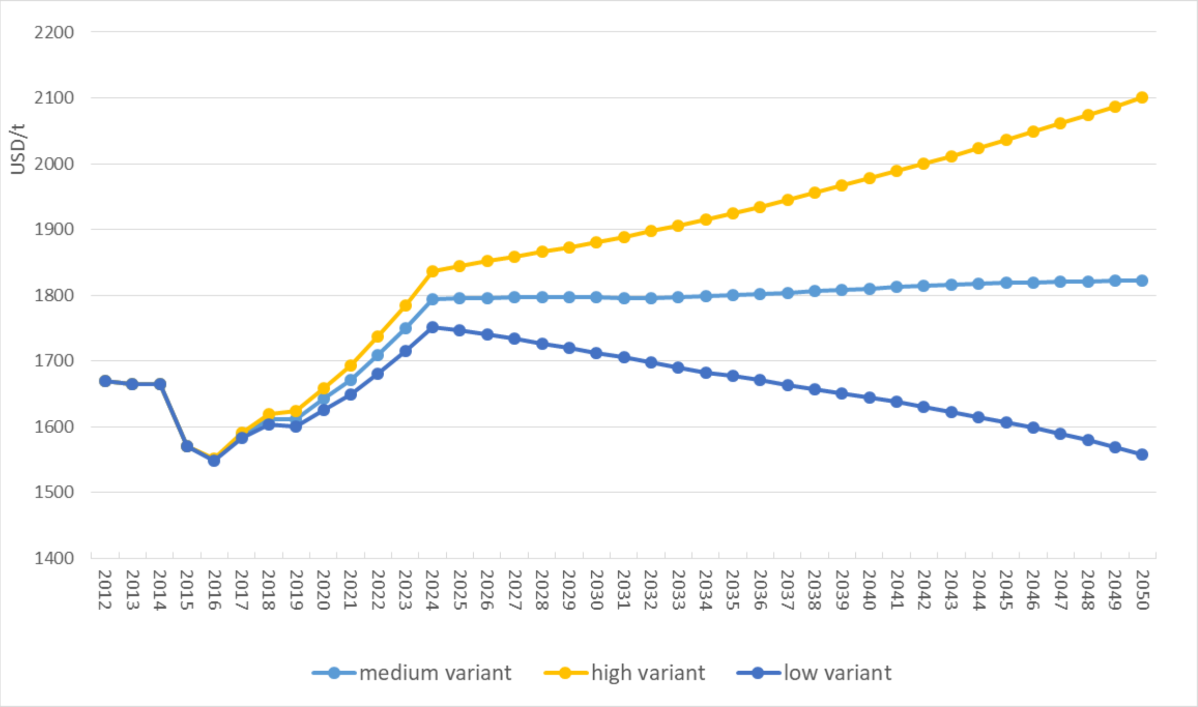


Table 20 shows the comparative regional impact on food consumption for non-ruminant commodities. The high population variant scenario implies an almost 10 per cent increase in global consumption of non-ruminant products above the medium variant. The difference in consumption between scenarios is most pronounced in South Asia by far, with a 73 mil.t increase in consumption as food in the high variant scenario. In comparison, the combined increase in all other regions is only 35 mil.t. Thus the change in consumption is South Asia is the primary driving factor of price change of non-ruminant animals in these scenarios.

Table 20: Regional comparison of non-ruminant products consumed as food between population scenarios, 2050

	Million tonnes			% change from medium variant	
	medium variant	high variant	low variant	high variant	low variant
Europe & C. Asia	102	107	97	4.8%	-4.7%
Oceania & SE Asia	56	61	52	8.2%	-6.7%
N Africa & W Asia	67	74	59	11.0%	-11.3%
Lat. America & Caribbean	97	104	89	7.9%	-7.8%
North America	73	81	66	10.7%	-10.3%
South Asia	665	739	596	11.0%	-10.5%
Sub-Saharan Africa	46	49	44	5.3%	-5.4%
Total	1,106	1,214	1,003	9.8%	-9.3%

In terms of regional shares, South Asia is responsible for the majority of global consumption of non-ruminant animal products, accounting for roughly 60 per cent of global consumption in 2050 for all population scenarios, although his share drops slightly in the low variant scenario. Europe & Central Asia are the next largest consumer with roughly 9 per cent of the global share in the medium variant scenario, although this increases to almost 10 per cent in the low variant scenario as South Asia consumes fewer non-ruminant animal products.

The prospects for the low variant compared to the medium variant are of the same order of magnitude as the difference between the medium and high variants. Here again we see that the vast majority of change comes from South Asia, where a 10.5 per cent drop in consumption could result in 70 mil.t less consumption of non-ruminants. This change in consumption is not surprising due to South Asia having the largest absolute change in population between the medium variant and other scenarios, and South Asia having the largest per capita consumption of non-ruminant animal products.

7.4 GDP Scenarios

Table 21: GDP scenarios assumptions

Grouping	Scenario name		GDP	population	TFP/yield growth
3) GDP	i.	IMF GEO	IMF GEO	medium variant	endogenous
	ii.	PWC 30	PWC 30	medium variant	endogenous
	iii.	EconMap	EconMap	medium variant	endogenous
	iv.	PWC 50	PWC 50	medium variant	endogenous

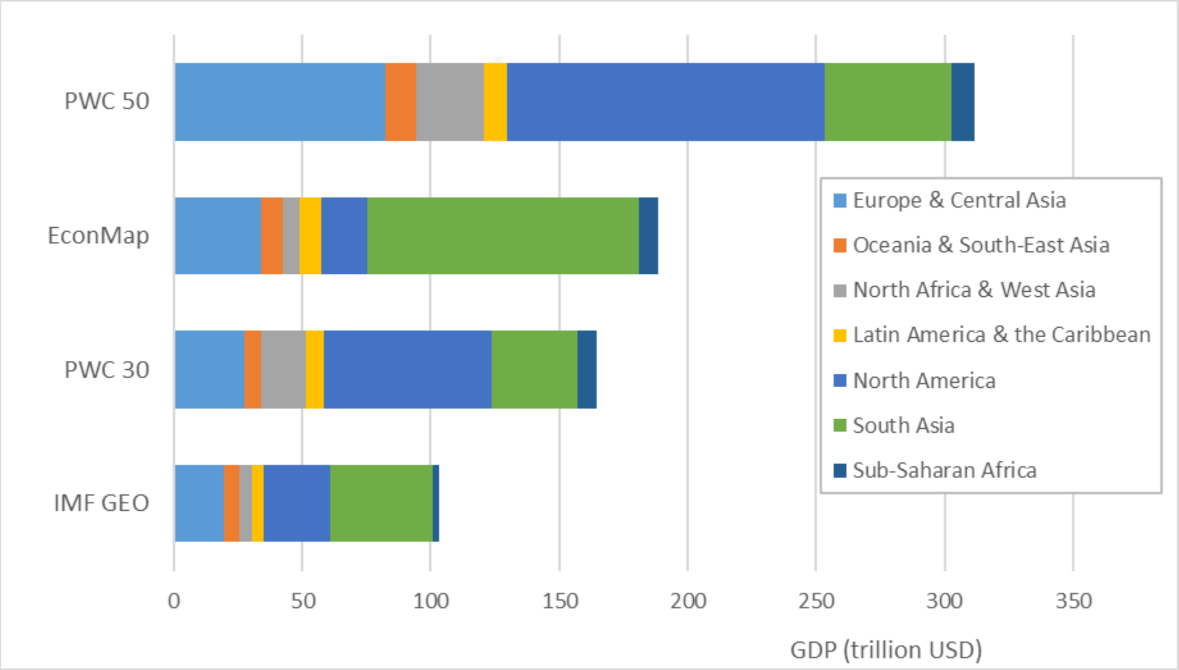
Along with changes in population, income change is a key driver of consumption in the LAO model. Income is measured as GDP per capita, and this section examines results from using GDP projections from different sources (shown in Table 21). The presented GDP scenarios use the same exogenous population projection (UNDESA medium projection), so conclusions on the change in income should be considered with some caution. In actuality, the development of GDP over time is interlinked with growth in population.

The various regional and total GDP increases are shown in Figure 43[30]. Discussing the magnitude of GDP change between scenarios, the 'IMF GEO' projection (which serves as the GDP projection for the model baseline) is the most conservative of those examined, showing the smallest global increase in GDP by the final year of the model's projections. The 'PWC 50' scenario has the largest global increase of the examined scenarios, with over three times the increase of the 'IMF GEO' scenario.

---

[30] Regional growth rates for the various GDP projections are shown in Appendix Table X19.

Figure 43: Regional GDP increase between 2012 and 2050



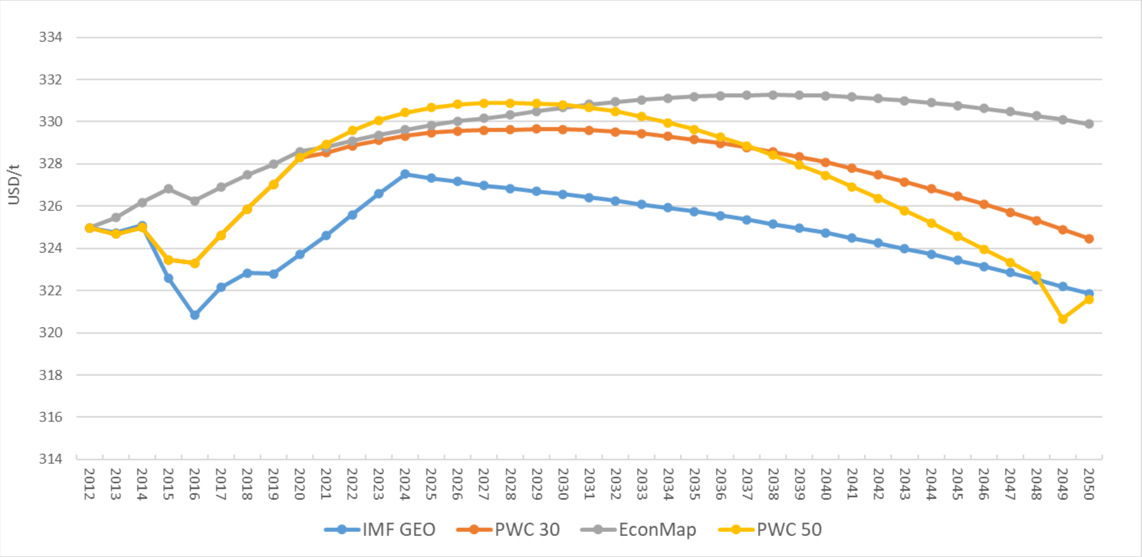
Further complicating the analysis of GDP scenarios is the regional disparities in total GDP growth. For example, while the 'PWC 50' scenario has the highest overall increase in world GDP, the main increases are in developed regions (EuCA and NoA), leading to very different impacts on global consumption, and thus prices, than in the 'EconMap' GDP scenario.

Indeed, the key driving factor in changes in world prices is not overall GDP or world income growth, but the growth of incomes in relatively low-income regions. Most notable is the 'EconMap' projection, which predict the largest increase in incomes in SA of all examined scenarios.

The implications of GDP projections in general, are illustrated in Figure 43. The Sub-Saharan region has the lowest increase in GDP in two of the four GDP projections ('IMF GEO' & 'PWC 50'), yet simultaneously has the largest increase in population over the same period. Even with the smaller increases in GDP and a significant growth in population, all scenarios imply an increase in average incomes in Sub-Saharan Africa; from between a 5 per cent increase (IMF GEO) to a 270 per cent increase (PWC 50) from the baseline in 2012 to 2050.

While Sub-Saharan Africa has the lowest GDP increase per capita over the modelled period (2012-2050) in all examined scenarios, North America and Europe & Central Asia (the two regions with the highest GDP per capita in the base year) consistently have the two highest increases across all scenarios. This indicates that according to the utilised exogenous measures of GDP and population, global wealth inequality is likely to increase over the next thirty years, rather than improve. This will have consequences for the affordability of food, and global poverty, especially in Sub-Saharan Africa, if not addressed through policy means.

Figure 44: World price for crops between GDP scenarios, 2012-2050

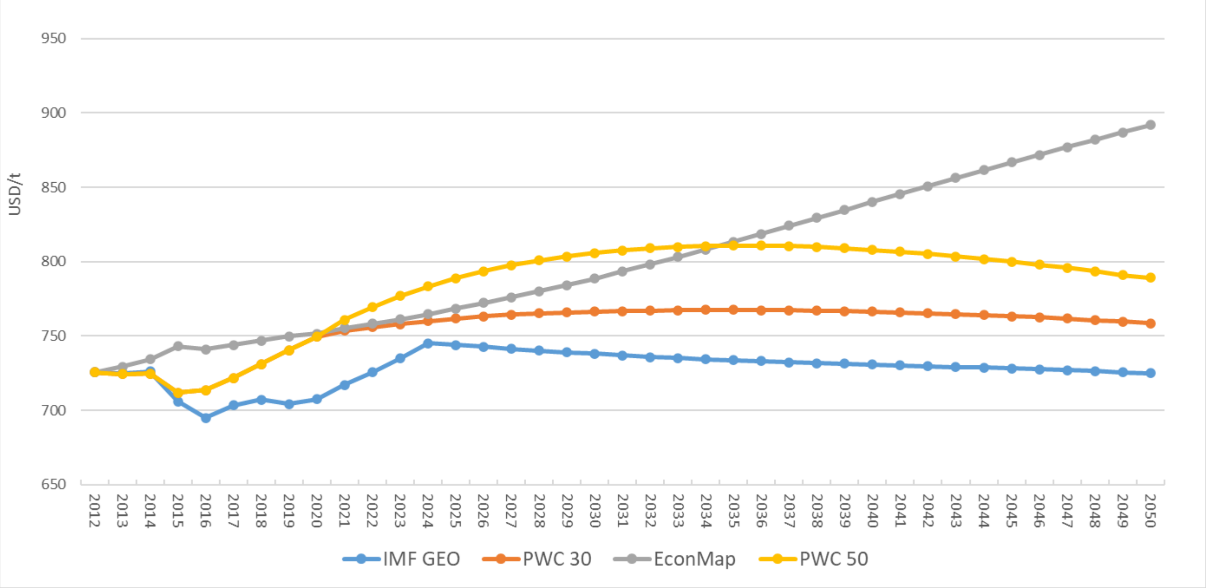


NB: 2049 in the 'PWC 50' scenario was found to be infeasible by the model's solver; x-axis starts at 314 USD/t

Figure 44, Figure 45 and Figure 46 display the world prices for crops, ruminant and non-ruminant animals respectively. Looking at crops in Figure 44, the first notable feature is that the difference in world prices between the scenarios is mild. There is only an 8.3 USD/t difference between the highest and lowest world crop price between GDP scenarios in 2050. All GDP scenarios cause in a hump in the world price of crops, with an initial increase in prices, which reverses partway through the modelled timeline and results in declining prices by the final year of the projection.

Higher GDP implies higher global incomes. Higher incomes, however, do not necessarily imply an increase in demand. Regional income elasticities determine the response to increases in income, where regions with high-income levels may demand fewer staple foods as incomes increase, and instead increase their consumption of luxury foods such as ruminant animal products. Hence, the motivators of change in crop prices are likely to be income increases in poorer regions and decreases in wealthier regions.

Figure 45: World price for ruminant animals between GDP scenarios, 2012-2050



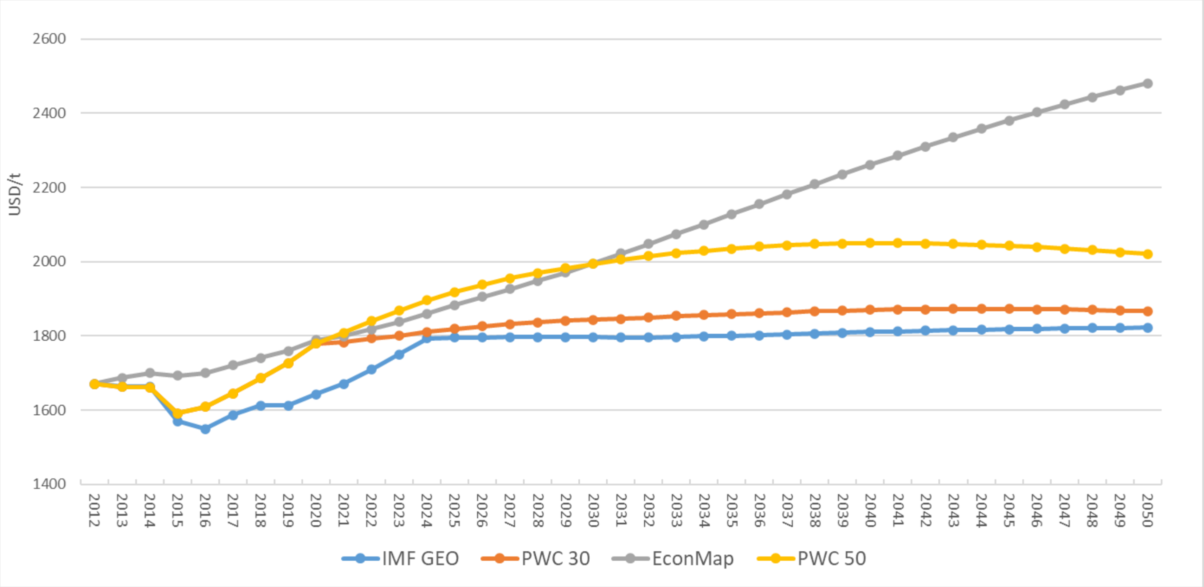
The prospects for ruminant animal prices (Figure 45) are relatively consistent under most GDP scenarios, with prices rising above their 2012 levels after 2020, but declining slightly leading into the end of the simulation. The difference between these scenarios is about 8.9 percentage points of change from the base year, with only the 'IMF GEO' scenario registering prices under the base level in 2050, and then only marginally so.

The exception to this trend is in the 'EconMap' GDP projections, which sees constantly rising world prices for ruminant animals finishing almost 23 per cent higher than in the base year. As discussed earlier, the 'EconMap' scenario does not have the largest overall increase in world GDP but does have the highest increase in GDP for the South Asia region. This income increase puts much higher demand pressures on ruminant animals, causing the strong price response.

World prices for non-ruminant animal commodities (Figure 46) are closely aligned with the developments for ruminant animals. Again, all scenarios see a general stabilisation of prices within the modelling timeframe with the exception of the 'EconMap' projection, which has significant growth over most of the projected timeline. This results in prices almost 50 per cent higher than in the base year, an increase of 568 USD/t. This is again as a result of higher incomes in South Asia.

All GDP scenarios project higher prices for non-ruminant animal products in 2050, although they are expected to at least stabilise depending on the extent of GDP increases in South Asia.

Figure 46: World price for non-ruminant animals between GDP scenarios, 2012-2050



We have already discussed how the income and income elasticities on the consumption side of the model drive changes in price, dependant on the regions in which these income changes occur. Table 22 therefore shows the absolute and relative change in global demand for food, by region and GDP scenario.

The variance in consumption as food between scenarios is largest in the crop commodity, with an absolute difference of 485 mil.t between the IMF GEO and the EconMap scenarios. Relative to the size of global consumption in the base year, consumption of non-ruminant animal products has the highest variance between scenarios (280 mil.t or 47% of the base year consumption).

Table 22: Consumption as food, different GDP scenarios in 2050

	Million tonnes				
	Base (2012)	IMF GEO	PWC 30	EconMap	PWC 50
Crops	3684	5308	5641	5792	5605
Ruminant animals	402	634	707	770	759
Non-ruminant animals	594	1106	1177	1386	1292
Fish from all sources	115	153	154	158	156
	% change from base in 2012				
Crops	-	144.1%	153.1%	157.2%	152.1%
Ruminant animals	-	157.7%	175.8%	191.5%	188.7%
Non-ruminant animals	-	186.4%	198.3%	233.6%	217.8%
Fish from all sources	-	132.7%	133.1%	136.9%	135.2%

The 'EconMap' scenario has the highest levels of consumption of all the GDP scenarios, while having less than a third of the global GDP increase of the 'PWC 50' scenario. This reinforces the previously discussed idea that the key driver of change between GDP scenarios is the relative regional changes in GDP, rather than the magnitude of the global increase. The 'EconMap' scenario shows 151 mil.t more consumption of crops than the next highest scenario, 11 mil.t more in ruminant animals, and 94 mil.t non-ruminant animals. The increases in ruminant and non-ruminant animals are driven largely by increased demand in South Asia. Increases in crop commodities are instead driven by changes in Oceania & South-East Asia, South Asia, and Sub-Saharan Africa. Note that crop consumption in South Asia drops off in the 'EconMap' scenario as the dynamic income elasticities change with the significant growth in incomes in that scenario.

The consumption of fish as food increases by over 30 per cent relative to the base year but is relatively unchanged between scenarios in 2050.

7.5 TFP Scenarios

Table 23: TFP scenarios assumptions

Grouping	Scenario name	GDP	population	TFP/yield growth
4)TFP	i. linear TFP	IMF GEO	medium variant	linear
	ii. exp. TFP	IMF GEO	medium variant	exponential
	iii. log. TFP	IMF GEO	medium variant	logarithmic
	iv. flat TFP	IMF GEO	medium variant	none
	v. endo. TFP	IMF GEO	medium variant	endogenous

The inclusion of endogenous TFP is one of the novel features of the LAO model, and key to the type of analysis this thesis aims to provide. The TFP is a crucial component in the development of production over the long-term, and an often under-examined part of long-term analysis for agriculture. This section presents scenarios using various projections of TFP (shown in Table 23).

The baseline scenario discussed at the beginning of this chapter uses the endogenous specification for TFP (described in section 5.5.5), which utilises GDP and historical data to project the development of investment into agricultural research and development. As this specification of TFP is governed by internal modelling parameters and other external variables, it is not possible to alter it to examine the influence of TFP on model projections. Instead, a second version of the model, which utilises an exogenously specified TFP, has been used to examine change in exogenous TFP projections.

These various exogenous projections of TFP are used in order to test the influence of TFP on the development of agricultural supply, demand and prices, as seen through the LAO model's processes. Other than scenario 4-v, the baseline with endogenous TFP, the scenarios all use simple projections from TFP data 1992-2012, they include: an exponential projection of TFP ('exp TFP'), a linear projection ('linear TFP'), a logarithmic projection ('log TFP'), and with no TFP growth from 2012 onwards ('flat TFP')[31].

Table 24 shows the resulting production for each scenario in 2050. Results are mostly as expected with higher TFP growth implying greater production between 2012 and 2050. There are some results of note, however. For instance, liner TFP is relatively similar in total production outcomes than in the endogenous TFP scenario (the baseline scenario). The TFP resulting from the endogenous specification is higher than those given by the linear projection. Furthermore, even assuming no growth in TFP ('flat TFP' scenario), world production increases from the base year for all commodities, although, as expected, at a smaller rate than the growth in all other scenarios. The growth in this scenario implies a much higher increase in area harvested and animal numbers.

---

[31] Annual average growth rates for the TFP projections are shown in Table 3.

Table 24: Production by commodity in different TFP scenarios, in 2050

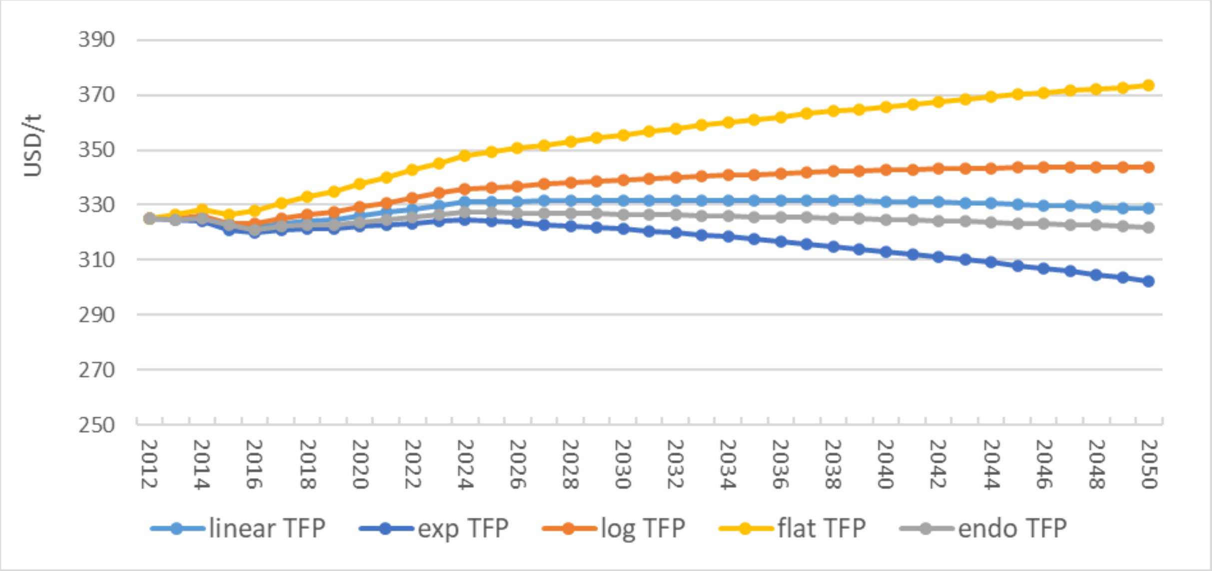
	Million tonnes					
	Base (2012)	linear TFP	exp TFP	log TFP	flat TFP	endo TFP
Crops	8,322	11,608	11,881	11,489	11,353	11,679
Ruminant animals	790	1,091	1,183	1,052	995	1,103
Non-ruminant animals	670	1,149	1,293	1096	1,023	1,202
	% change from base in 2012					
Crops	-	139.5%	142.8%	138.1%	136.4%	140.3%
Ruminant animals	-	138.0%	149.7%	133.1%	125.9%	139.6%
Non-ruminant animals	-	171.5%	193.0%	163.6%	152.7%	179.3%

Total production, however, does not reflect the full impact of TFP change as regions can increase their area under crops or number of animals to substitute production in the absence of yield or TPF growth. The implication of some of these TFP scenarios on the split between yield and area/animal change will be shown below under each commodity subheading.

Crops

Beginning with the most significant results of the TFP scenarios, Figure 47 shows the various results for the world price of crops between 2012 and 2050 given the different exogenous projections of TFP. The importance of TFP on the outcomes for the world price of food is immediately apparent. The difference between the growth of TFP determines if the world price of crops is declining (as in the 'exp TFP' scenario), or if crop prices are rising into the future ('flat TFP' scenario). The difference in the spread between these extremes is only about 71 USD/t, but this spread encompasses the turning point between rising and declining world prices. The 'linear TFP' projection leads to a projection of slightly declining world prices of TFP approaching 2050, and ultimately prices marginally higher than those in the base year. 'Endo TFP' (the baseline FP specification), implies slightly lower prices that with linear projected TFP, and are also declining towards the end of the modelled period.

Figure 47: World price for crops between different TFP scenarios, 2012-2050

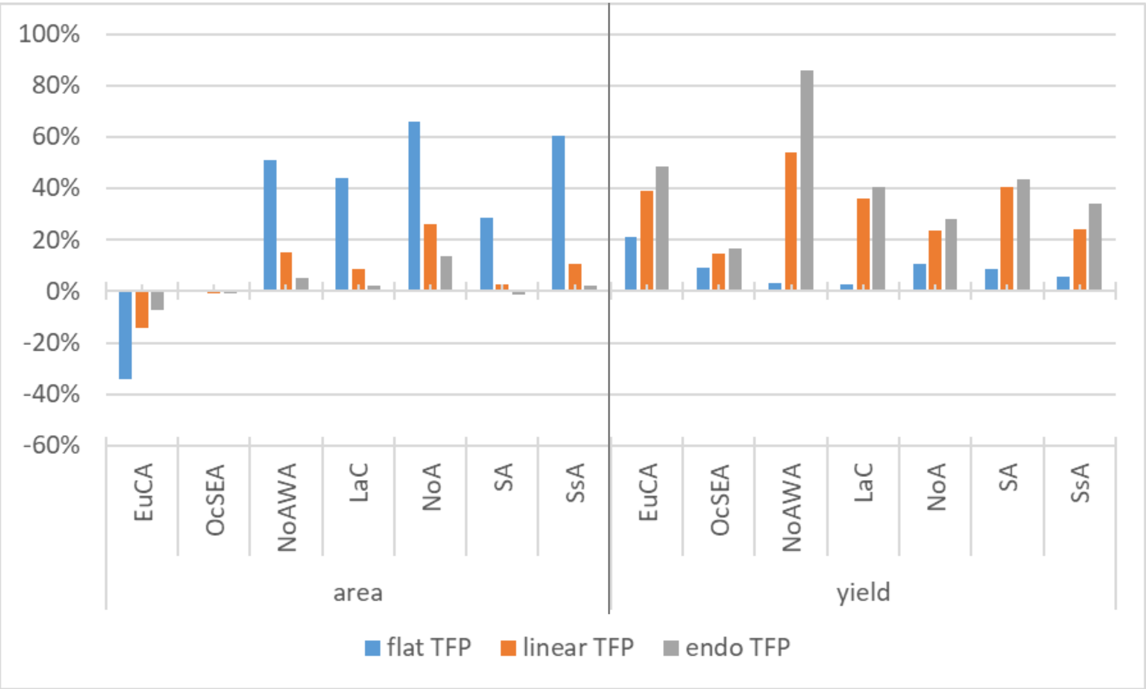


The ‘flat TFP’ scenario is the worst-case scenario in terms of productivity. As seen in Figure 47, the ‘flat TFP’ scenario shows a 15 per cent increase in crops prices by 2050. The significance of this scenario is that it implies low global crop prices are sustainable only with at least a linear growth of agricultural TFP.

At first, the results for changes to world prices given no TFP growth (‘flat TFP’ scenario) seem conservative. That is, the prospect of no growth in productivity might be expected to have a more severe impact on crop prices. However, within the structure of the model, in the absence of growth from TFP, compensations are made from other areas in order to meet global demand for crops.

Figure 48 shows the relative growth in the two key factors of crop production: area, and yield. Yield is driven primarily from the growth of productivity and varies drastically between the ‘flat TFP’ scenario, where muted yield growth is exhibited, and the ‘linear TFP’ scenario, where between 17 and 42 per cent yield growth is present. Yield growth is non-zero in the ‘flat TFP’ scenario as there is a price elasticity for yield, as discussed in the methodology chapter (section 5.6.4).

Figure 48: Percentage growth of area and yield between TFP scenarios, 2012- 2050



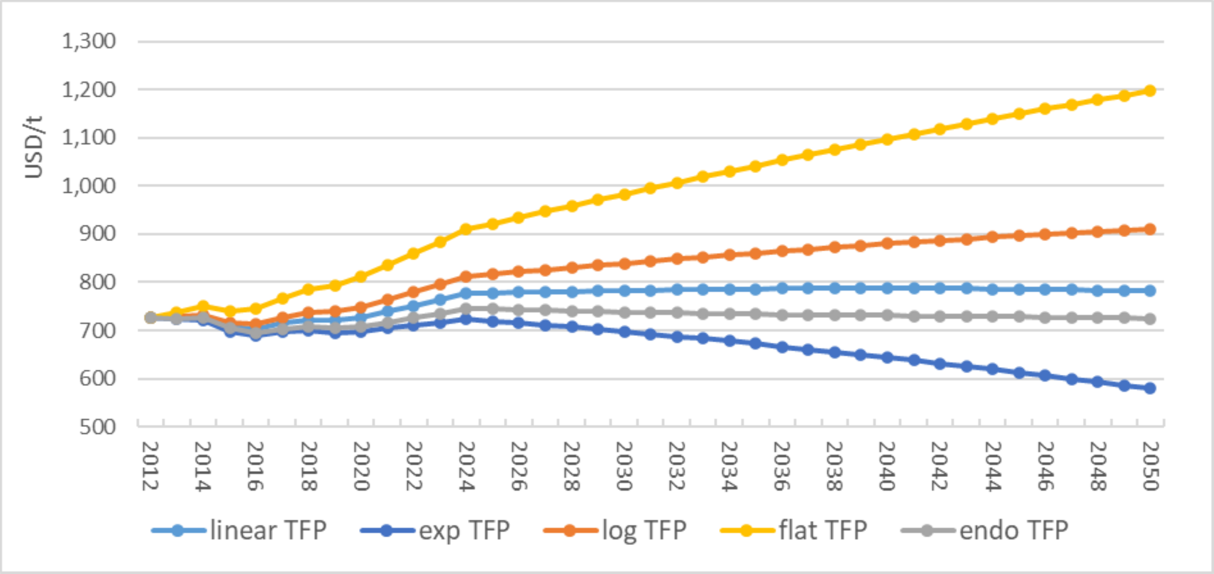
Conversely, the growth in area for crops is highest in the 'flat TFP' scenario (with the exception of the 'EuCA' region). This indicates that in the absence of yield growth the area devoted to growing crops is increased to compensate.

In the 'linear TFP' scenario, stable and even decreasing world prices for crops are maintained with minimal or no expansion of crop lands. Whereas under the 'flat TFP' scenario, even with significant growth of croplands, prices continue to rise. The only constraints in the LAO model on the expansion of cropland is currently based on the availability of water. If the expansion of cropland was further restricted, then the world price for crops under 'flat TFP' growth would presumably be even greater.

Ruminant animals

In the case of ruminant animals, the prospects of maintaining low world prices from TFP growth are weaker. The world price for ruminant animal products under different exogenous projections of TFP are shown in Figure 49. Only under the optimistic exponential growth ('exp TFP') scenario do world prices decrease below their initial values in the base year. At the other extreme, the 'flat TFP' scenario of no productivity growth implies a 65 per cent increase in world price between 2012 and 2050.

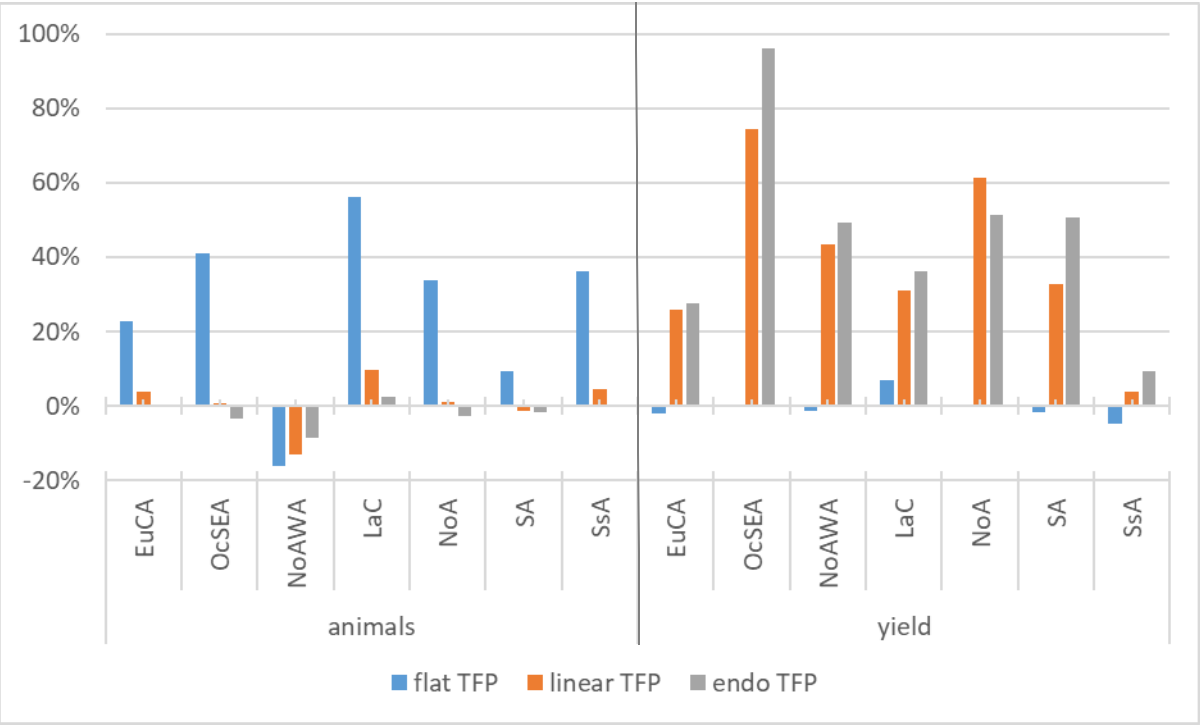
Figure 49: World price for ruminant animals between different TFP scenarios, 2012-2050



In the middle of the spread of results shown in Figure 49, the linear TFP projection results in a stable world price following an initial price increase prior to 2025; ultimately resulting in prices about eight per cent above their level in the base year. However even with the relatively conservative logarithmic projection of TFP ('log TFP' scenario), the model projects increasing prices for ruminant animal products over the long-term, with an increase of almost 25 per cent over the examined period. Lastly, the baseline TFP ('endo TFP'), shows gradually decreasing prices at the end of the modelled period, ending up in 2050, slightly below their initial position.

Decomposing the component factors responsible for total production of ruminant animals in these scenarios, Figure 50 shows the growth of animal numbers and yields by region between 2012 and 2050.

Figure 50: Percentage growth of animal numbers and yield for ruminant animal products between TFP scenarios (2012- 2050)



In terms of animal numbers, the endogenous TFP scenario (‘endo TFP’) implies such a strong increase in yield growth that animal numbers decrease in all regions while the world price for ruminant animals decline (base scenario 7.2.1). The results for ‘exp TFP’ imply a 10 per cent decrease in ruminant animal numbers from the base year (2012). Both of these results imply a decrease in global emissions associated with ruminant animals. The results also show, with linear projected TFP growth or lower, the number of ruminant animals is expected to grow in all regions (bar ‘NoAWA’ and ‘SA’). This is a concerning, since the expansion of pastureland for ruminants is responsible for environmental damage such as the increase in GHGs and nutrient leaching associated with stocking ruminant animals, as well as the potential for forestland being cleared in order to accommodate pastureland. The model’s coverage, however, is broad and the exact impacts on land-use implied by these results is uncertain. The highest increases in animal numbers of between 10 and 56 per cent, for the ‘linear TFP’ and ‘flat TFP’ scenarios respectively, are both in Latin America, where the expansion of pastureland for ruminant animals has caused deforestation of the Amazon rainforest (Barona et al., 2010; Malhi et al., 2008) severely contributing to global climate change.

The yield growth for ruminant animals is much as expected. The ‘flat TFP’ scenario has a slight positive yield growth owing to the response to price and inputs. The linear and endogenous TFP scenarios both imply significant yield growth of between 4 and 74 per cent in the ‘linear TFP’ scenario, and between 9 and 96 per cent in the ‘endo TFP’ scenario. The variation between regions is due to the differing sensitivity to changes in TFP growth. The Europe & Central Asia and Sub-Saharan

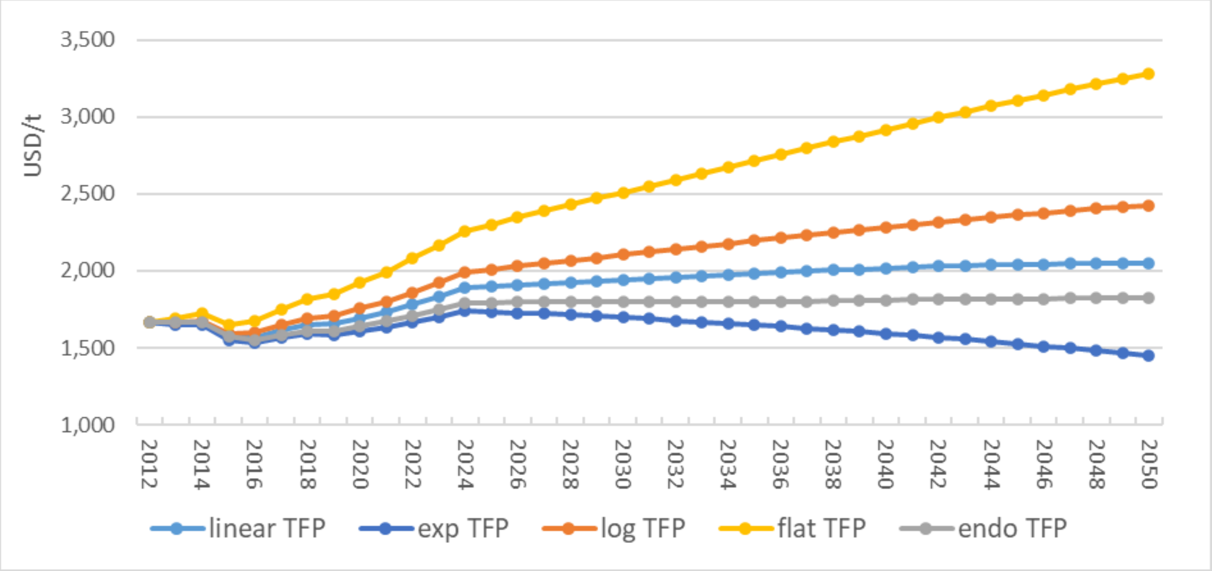
Africa regional groups have the lowest yield response to higher TFP, whereas North America, and Oceania and South Asia have the highest yield growth from the endogenous TFP specification.

Note that compared to the change in harvested area for crops, ruminant animal numbers are much less elastic to changes in price. This means that if production growth slows due to a cessation of yield growth, when prices subsequently rise, animal numbers are slower to respond than in an equivalent situation for harvested area. This leads to smaller corrections in price effects, as lost production from yield drops are not replaced by quick increases in animal stocks. Whereas for crops the shock from lower TFP could be somewhat absorbed through the increase of harvested area. This is a result of lower elasticities of animal numbers to price in the LAO model and may reflect the longer lags in breeding additional livestock compared with planting new crop areas.

Non-ruminant animals

Similarly, to the prospects for ruminant animals, the projections for non-ruminant commodities also point towards an upwards trend in world prices under most TFP scenarios. Figure 51 shows the world prices for non-ruminants across the various exogenous TFP scenarios. There is a significant growth in prices from 2012 to 2050 under the ‘endo TFP’ (+9%), ‘linear TFP’ (+23%), ‘log TFP’ (+46%), and ‘flat TFP’ (+97%) scenarios. The exponential TFP growth scenario (‘exp TFP’) is the only scenario with declining world prices going into the final year of the projection, with the prices in 2050 dipping below their initial levels (13% lower).

Figure 51: World price for non-ruminants between TFP scenarios, 2012-2050



Of examined commodities, TFP outcomes for non-ruminant animals have the highest potential to result in higher prices. Flat TFP implies an almost doubling of prices, in comparison to only a 15 per cent increase in crops, or a 65 per cent increase in ruminant prices. Due to the higher price of non-ruminants per tonne in the base year, the implied the absolute price increase is also the largest. It is only under the ‘exp TFP’ scenario in which non-ruminant animal prices are expected to trend downwards approaching 2050. These price increases generally indicate that current prices for non-ruminant animals are unsustainable (given the LAO model’s baseline assumptions) unless high continuous productivity growth is obtained.

Figure 52: Percentage growth of production factors for non-ruminant animals between TFP scenarios, 2012- 2050

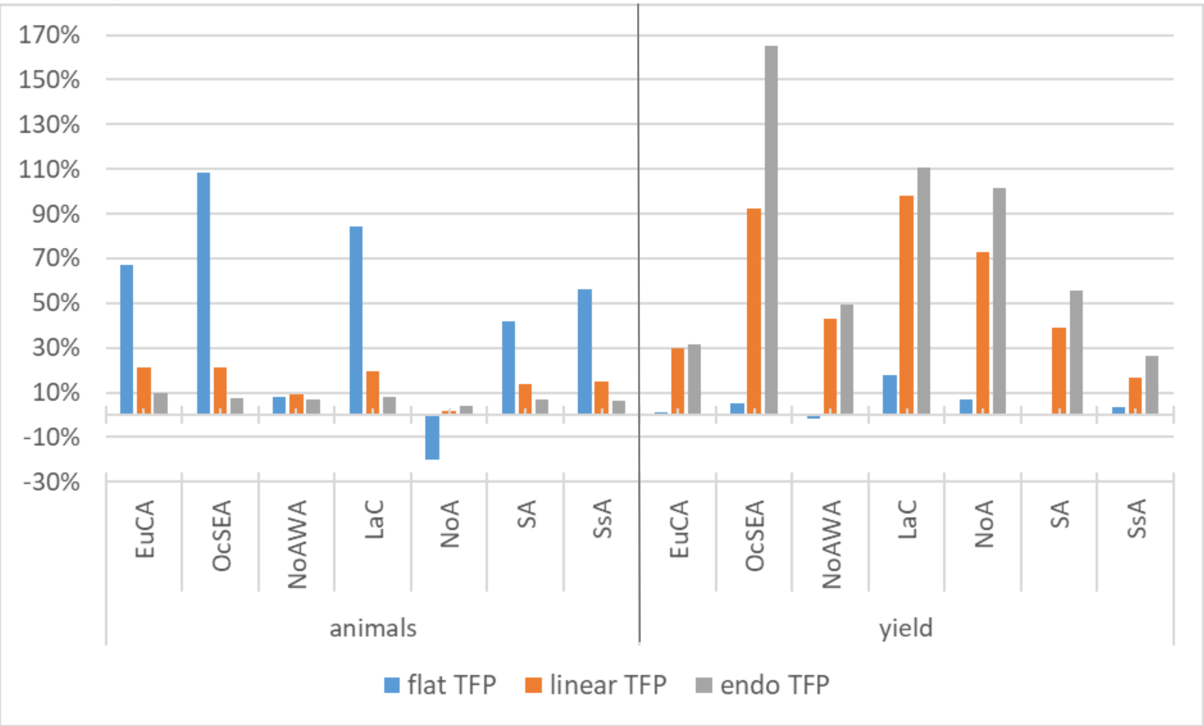


Figure 52 shows the breakdown of production growth into growth in animal numbers and growth in yield. The changes in yield are consistent with the pattern displayed for the other commodities, with higher TFP driving higher yield growth, with some variation between regions depending on regional sensitivities to price and TFP. One element of note in the results for non-ruminant animals is the relative size of yield growth, which is higher than for both crops and ruminant animals in the linear TFP and endogenous TFP scenarios. This is in part due to the yield response to the higher prices experienced with non-ruminant animal products.

The ‘flat TFP’ scenario entails a significant increase in non-ruminant animal numbers in all regions other than ‘North Africa & West Asia’, and ‘North America’ (in which animal number seems relatively in-elastic to changes in TFP and prices). Yet even with these large increases in animal numbers (over 50% growth in global non-ruminant animals), total production lags behind global demand, thus driving up world prices significantly.

It is also worth noting that the LAO model holds no constraints on maximum of animal numbers, whereas in reality resource and land constraints may limit growth. Therefore, some scenarios which imply a strong growth of animal numbers may underestimate the price impacts, if the growth in animal numbers is unachievable.

7.6 Climate Change Scenarios

There are two sets of climate change scenarios. Section 7.6.1 adapts the LAO model to account for the greenhouse gas emissions associated with all other scenarios (1-4). This accounting is carried out using the emissions factors in the LAO model (section 5.6.3). This offers an extra dimension of impacts from the previously examined scenarios for policy makers and researchers, shedding light on the environmental implications for agricultural GHGs given the assumptions outlined in each scenario.

Section 7.6.2 then uses the LAO model to simulate the yield impacts of different climate change scenarios, in order to test the economic impacts for the future of agriculture.

7.6.1 GHG accounting

This section describes the GHG emissions in some of the scenarios already presented in this chapter. The results below are presented as the difference in GHG profiles from 2050, and 2012, the base year of the modelling.

Figure 53: TFP scenario outcomes impacts on GHG emissions. Change from the base scenario in 2050

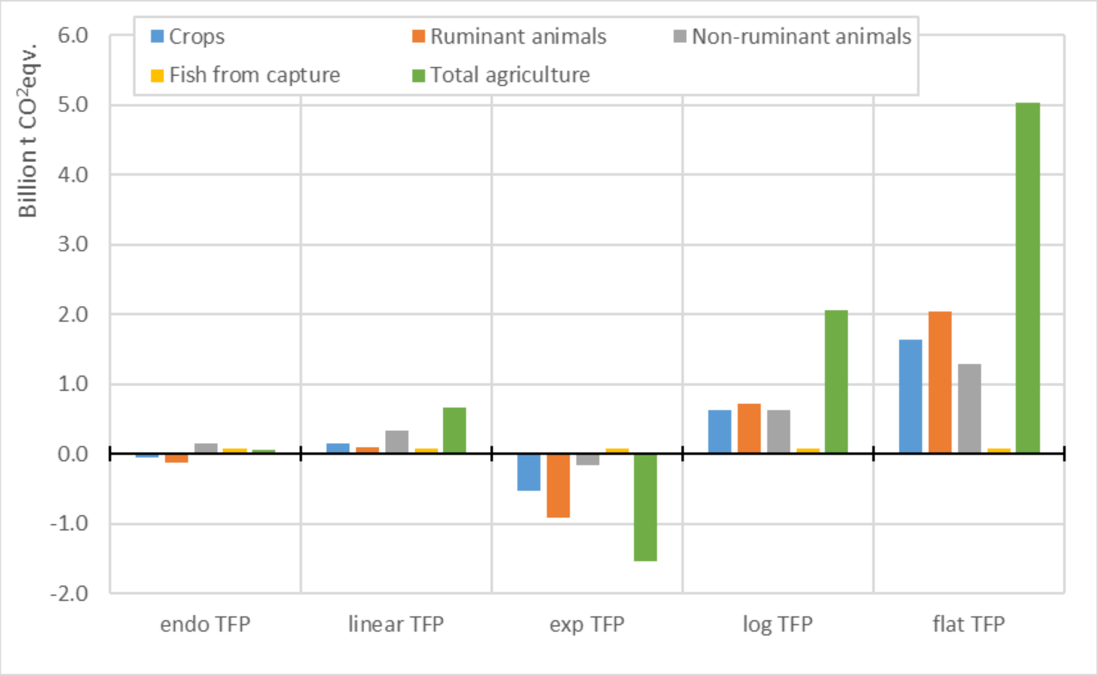
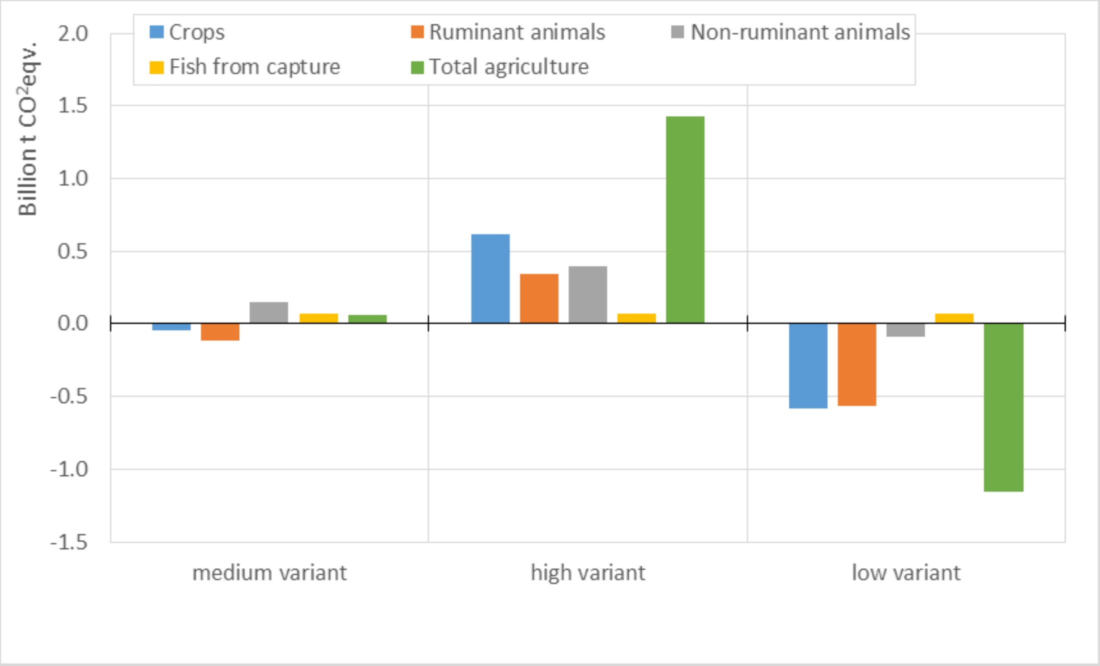


Figure 53 shows the implied GHG outputs of the different commodity groups from the modelling of different TFP outcomes (scenarios 4.i-v). Scenarios which assume a higher level of TFP (the exponential growth scenario being the highest) have reduced levels of GHGs from the base year. The cessation of TFP growth (flat TFP scenario) implies an additional five billion tonnes of GHGs from agriculture. The majority of this comes from animal products, in particular ruminant animals, with over two billion tonnes of GHGs from increased production of ruminant animals alone.

One caveat of these results is that this representation of GHG outputs assumes a static emission factor associated with each region and farm type. These emissions factors would be expected to change in the future with changing farm-types, and farming methods, both of which will most likely be implied with changes to TFP.

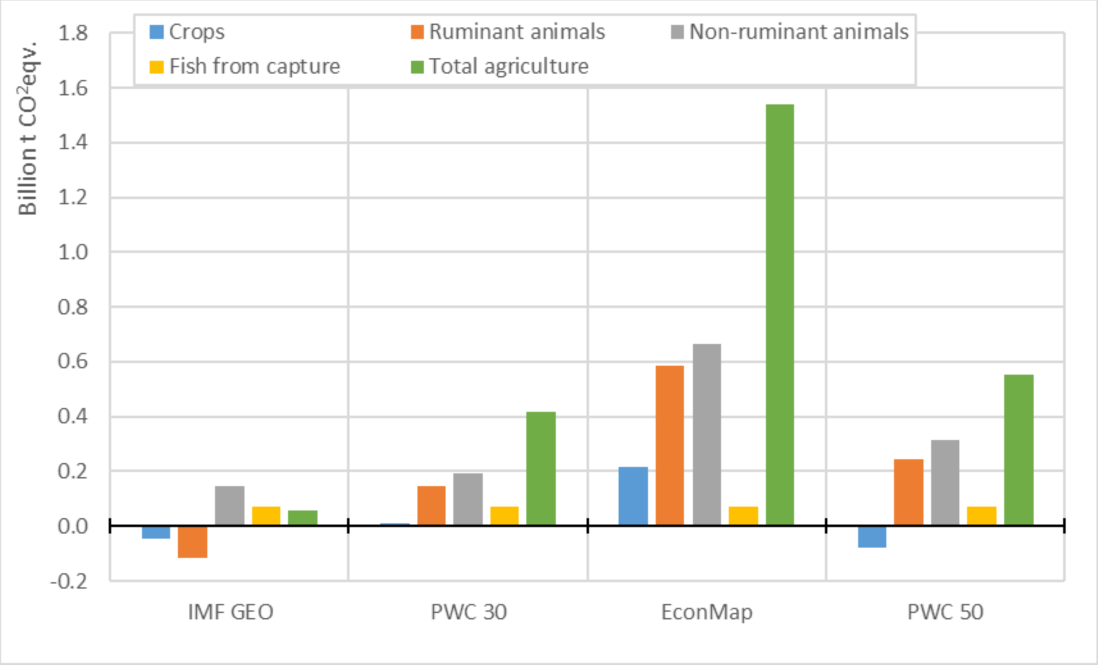
Figure 54: Population scenario outcomes impacts on GHG emissions. Change from the base scenario in 2050



In terms of population growth (scenarios 2.i-iii) shown in Figure 54, the GHG profiles for the high and low population variants are between 1.0 and 1.5 billion tonnes above and below the medium variant. Change in crop demand leads to a 1.0 billion tonne variance between the high and low variant scenarios, this variance is equivalent to 16 per cent of the total crop GHGs in the base year (2012). The variance between extremes and the base year in the case of ruminant animals is 11 per cent and 22 per cent for non-ruminant animals.

These population scenarios demonstrate the potential GHG flow-on impacts from population growth. The high and low population variants give the bounds of the impact of agriculture on GHGs globally. It is interesting to note that the low population variant scenario still has a higher global population than in 2012, the base year. Yet even with a lower population, the scenario has significantly lower GHGs associated with agriculture. This is because, while the low population scenario has increasing production for all commodities, the area harvested, and animal numbers are lower than their levels in the base year. The increase in yields makes this possible, with growing yields satisfying additional demand, while decreasing the area harvested (or animal numbers in the case of animal products). While yield growth is positive in the medium and high scenarios, it is not sufficient to meet demands for agricultural products without also expanding the harvested area and animal numbers beyond those in 2012.

Figure 55: GDP scenario outcome impacts on GHG emissions. Change from the base scenario in 2050



Finally, the model can analyse the implied GHG emissions for the scenarios regarding alternative projections of GDP[32] over the modelled timeline. Figure 55 shows the net emissions from these scenarios, for all commodity groups, and total agriculture (as captured by the LAO model). The 'EconMap' projection of GDP causes the highest GHG impact of the examined scenarios. As previously discussed, the 'EconMap' scenario implied a higher than average growth of GDP in the South Asia region. This GDP growth in South Asia caused a higher uptake of animal consumption than in many other scenarios, also implying further demand for crops to facilitate animal feed requirements. It is due to these features that the 'EconMap' scenario indicates such strong growth of GHG emissions, particularly in both of the animal commodity groups, but also to a smaller extent in crops.

The two GDP scenarios derived from PWC reports on growth ('PWC 30' & 'PWC 50'), show relatively similar outcomes for GHG emissions, with a difference of 132 million tonnes of CO_2 equivalent across all agriculture. One key difference is in the crop commodity group, which sees a decrease in the 'PWC

---

[32] The alternative projections of GDP are detailed in section 6.3.2.

50’. This can be attributed to a gradual increase in crop yields promoted by the higher GDP in the ‘PWC 50’ scenario spurring on agricultural R&D investments and TFP growth.

Between the different impacts shown for GHG emissions under each set of scenarios, the potential impacts on GHG emissions are highest for changes in TFP. The results here are similar to the trajectory of price potentials examined early in scenarios (4.i-v), which is to be expected as the GHG emissions are merely reflecting a different side to the same issue of yield comparative consumption. The results track essentially the same drivers of change in the production system. Thus, the continuation of TFP is extremely important for minimising impacts on the GHG profile for agricultural.

Similarly, the development of GDP in South Asia is a key area of concern given the potential for the increase in consumption of non-ruminants and their associated GHG emissions. This is of course not to discourage the growth of GDP in South Asia (GDP being linked with many positive benefits for development and wellbeing of populations), but instead to direct policymakers to apply particular care in mitigating the potential GHG impacts from the growth in the consumption of animal products.

7.6.2 SSP/RCP scenarios

Table 25: SSP & RCP scenario assumptions

Grouping	Scenario name	GDP	population	TFP/yield growth
5) SSP	i. SSP1	SSP1	SSP1	endogenous
	ii. SSP2	SSP2	SSP2	endogenous
	iii. SSP3	SSP3	SSP3	endogenous
	iv. SSP4	SSP4	SSP4	endogenous
	v. SSP5	SSP5	SSP5	endogenous
6) RCP	i. RCP 1.9	IMF GEO	medium variant	RCP 1.9 yield Δ
	ii. RCP 2.6	IMF GEO	medium variant	RCP 2.6 yield Δ
	iii. RCP 3.4	IMF GEO	medium variant	RCP 3.4 yield Δ
	iv. RCP 6.0	IMF GEO	medium variant	RCP 6.0 yield Δ

The second approach to assessing the impacts of climate change using the LAO model is in incorporating the bio-physical impacts of climate change on crop yields. This has been performed by using the changes in yields in the SSP scenarios under each RCP taken from the IMAGE model[33] (shown in Table 25).

The implied macro-economic futures from the different SSPs can be shown using the LAO modelling framework, followed by an analysis of the different representative concentration pathways under

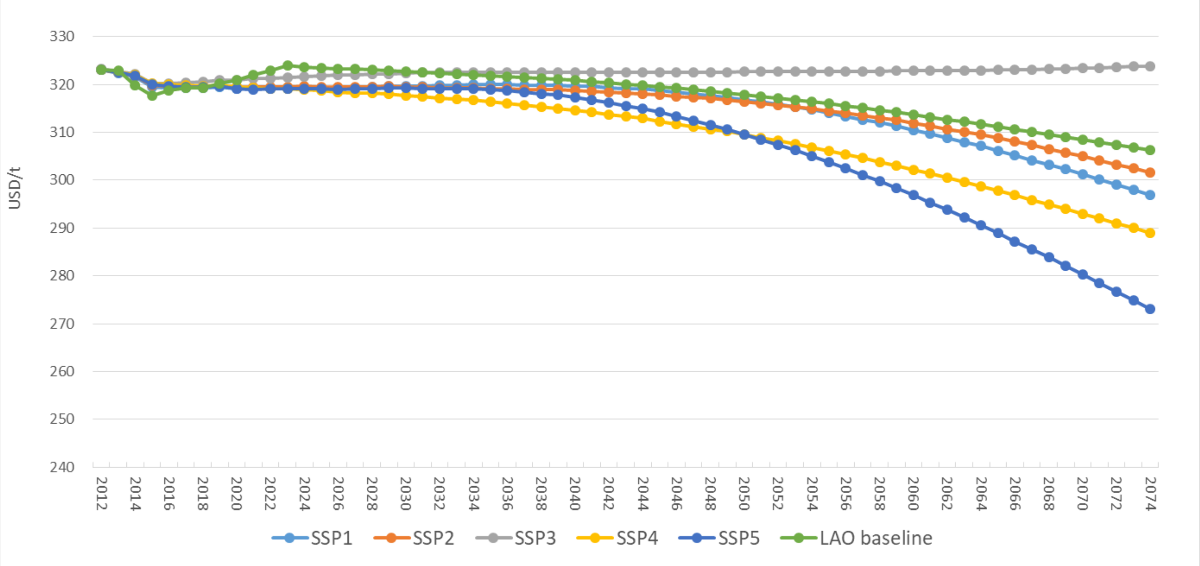
---

[33] The changes in macroeconomic elements in SPP scenarios, and the change in yield under the RCP scenarios are described further in section 6.4.1 and in Appendix Table X16 & Table X17.

one SSP. SSP2 was chosen as it implies the ‘middle of the road’ challenges, the closest approximation of business-as-usual from the SSPs. This focuses the analysis solely on the changes implied by the different RCPs examined, rather than a SSP with more extreme macro-economic changes.

The baseline time horizon in the LAO model has been extended to 2075 to reflect the longer time horizon used in integrated assessment models to capture the impacts of climate change over a longer time period.

Figure 56: World crop prices, SSP scenarios i-v, RCP 3.4, and the LAO baseline, 2012-2075



First, Figure 56 shows the various SSP scenarios, to contrast the different levels of macro-economic variables (GDP & population) with the LAO baseline. These SSP scenarios do not include an exogenous TFP or technological growth component, instead using the endogenous LAO TFP growth, in order to ensure comparability.

In terms of world crop prices, the LAO baseline GDP and Population assumptions entail the second highest crop prices in 2075, only below the prices in SSP3. SSP3 implies growing nationalism and regionalisation. SSP5 has the lowest associated crop prices, with an almost five per cent drop from the base year. These results also reflect the population growth implied by the different SSP scenarios, with SSP3 implying the highest population by 2075, and SSP5 the lowest.

Interestingly, the ‘middle of the road’ SSP2 scenario closely matches the trajectory and end result of the LAO baseline, with a difference of one USD per tonne. This gives some additional confidence that the LAO ‘baseline’ represents a similar scenario of business-as-usual as used in comparable models. Conversely, the other SSPs represent the range of impacts which social and political factors can have on the prospects for global agricultural markets.

Figure 57: World prices for crop commodities under different RCP scenarios (2012-2075)

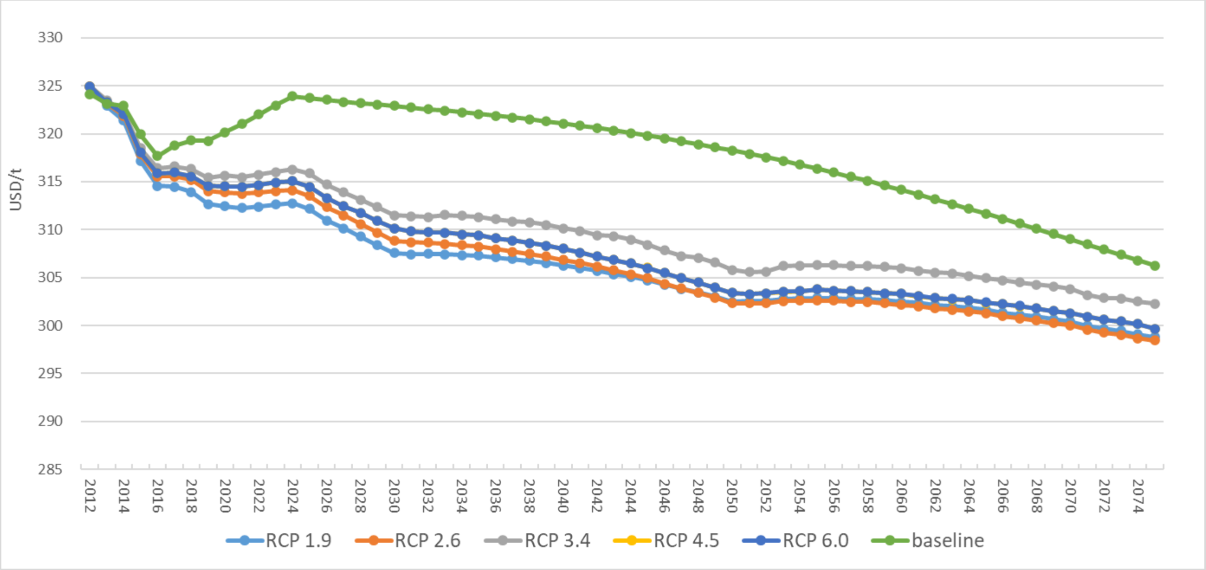
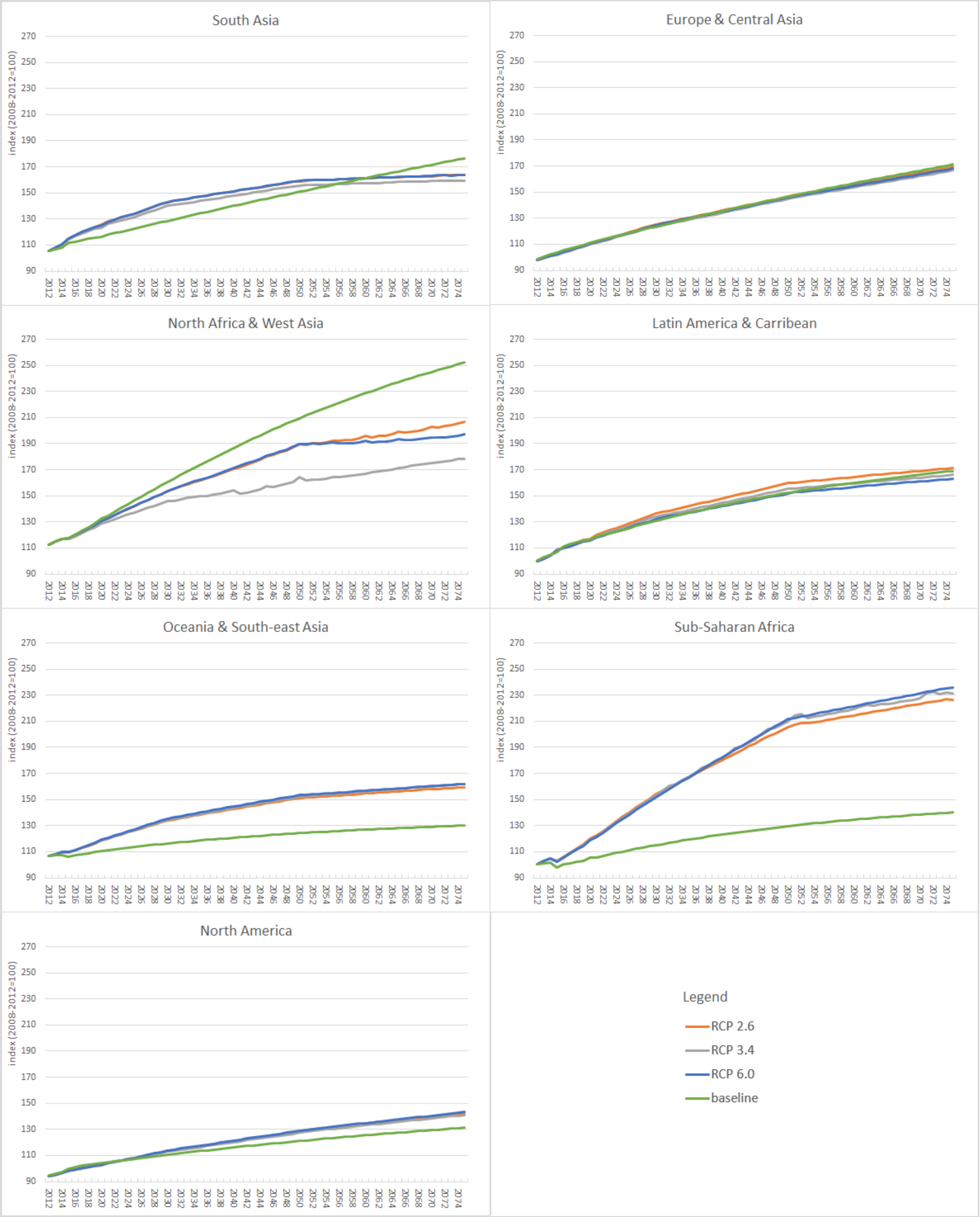


Figure 57 compares the world prices for crops given the RCP yields taken from the IMAGE model with the LAO endogenous TFP baseline. It is clear that the prospects for declining global crop prices are optimistic even given the projected yield impacts from climate change (as projected by the IMAGE model). Further, the prices projected using the IMAGE model's yields are all lower than the price path projected by the LAO model's baseline scenario (presented in green). The variance between the IMAGE yield scenarios, due to the differing levels of climate change, are not pronounced. The largest price difference between IMAGE yield scenarios across the entire projection is only slightly more than four USD/t. This implies that the climate impact on yields between the various scenarios is minimal.

Figure 58: Regional crop yields under different climate change scenarios and baseline (2012-2075)

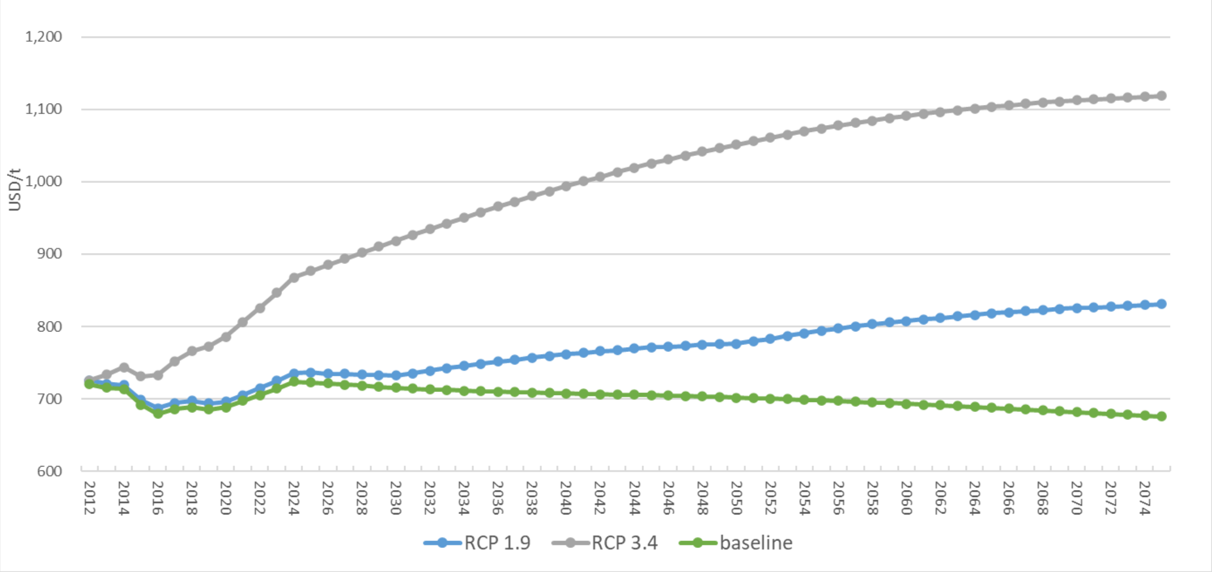


In order to explore the reasons for the price difference shown between the IMAGE climate yields and the baseline presented in Figure 57, the regional yield differences between these scenarios are shown above in Figure 58. The yields are presented as an index of a five-year average in the base period (2008-2012). Projected yields under climate change are much higher in Oceania & South-East Asia, Sub-Saharan Africa and North America, than in the endogenous TFP baseline. This difference is most pronounced in the case of Sub-Saharan yields, which by 2075 are 69 per cent higher in the 'RCP

6.0’ scenario than in the LAO baseline. Yields in Oceania and South Asia under climate projections are similarly pronounced in comparison with the LAO baseline, the ‘RCP 6.0’ scenario implying 24 per cent higher crop yields in 2075.

On the other hand, the LAO baseline sees higher crop yields in South Asia, and North Africa & West Asia. While in the case of South Asia the climate change scenarios imply higher yields for much of the modelling timeline, eventually this growth tapers after 2050. Yields in Europe & Central Asia, and Latin America & the Caribbean are largely comparable between the scenarios.

Figure 59: World price for ruminant animals under different RCP scenarios and baseline, 2012-2075



Looking to the impact on animal commodities, Figure 59 shows the world price projections for ruminant animals. The differences in outcomes for all climate change scenarios other than the SSP0 1.9 scenario are marginal. Thus, only the ‘RCP 3.4’ results are shown in order to simplify the presentation of the figure. In the case of crops, the climate change scenarios showed a more optimistic outcome for prices. However, here ruminant animals in the LAO model’s projections show significantly lower price projections than those implied by the yield changes found in the IMAGE model. In 2075, the ‘RCP 3.4’ scenario has ruminant prices 54 per cent higher than in the base year, and 66 per cent higher than those in the LAO baseline. The ‘RCP 1.9’ scenario, however, maintains relatively low ruminant prices, like the LAO baseline, until 2030 where they diverge, resulting in prices 15 per cent higher than the base year in 2075.

Figure 60: World price for non-ruminant animals under different RCP scenarios and baseline, 2012-2075

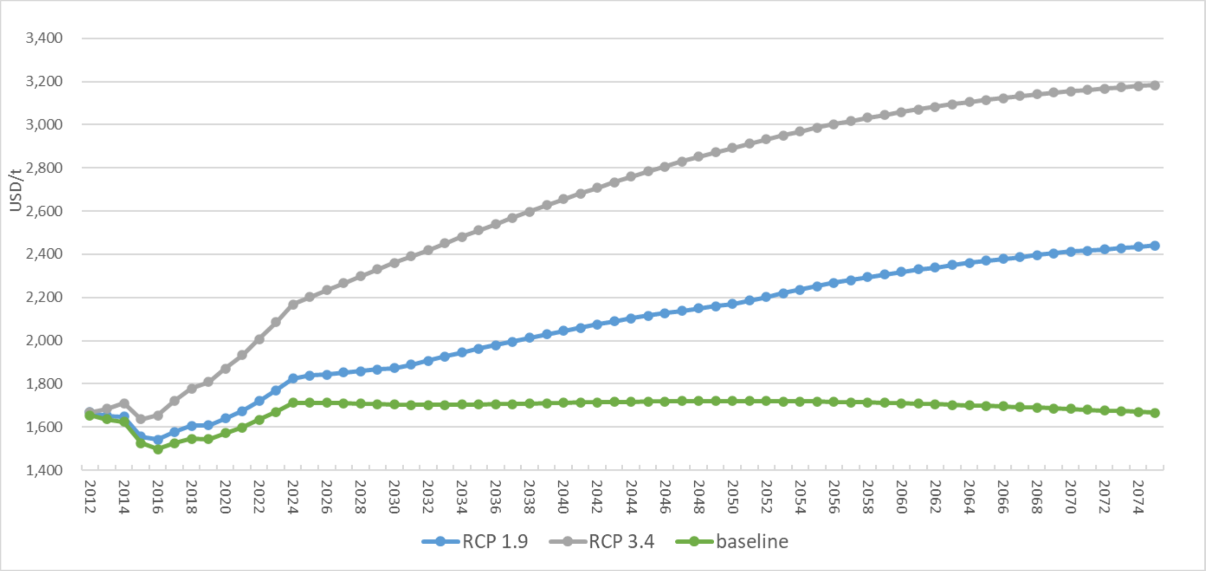


Figure 60, shows the results for world prices of non-ruminant animals. The results are similar to those for ruminant animals, where the LAO baseline has a slightly decreasing price projection, and the RCP scenarios show significant increases in prices. The 'RCP 3.4' scenario has an ultimate increase to 90 per cent higher than the base year; or 91 per cent higher than the LAO baseline in the same year (2075). The 'RCP 1.9' scenario, with lessened impacts on the environment, strikes a balance between the two other projections with a 46 per cent increase in non-ruminant prices form the base year to 2075.

7.7 Conclusion

This chapter of the thesis has presented the results from the scenario analysis performed with the LAO model. This analysis has: shown the state of world agriculture given a range of exogenous inputs for the macroeconomic variables in the LAO model (population, GDP and TFP); and shown the implications for GHGs and under various combinations of the RCP/SSP scenarios. Some key findings from the modelling presented in this chapter were: stable world prices for crops and ruminants in the baseline scenario; the importance of income growth in South Asia in the development of global food consumption towards 2050; TFP growth having a strong impact on maintaining stable world food prices and GHGs; and yield changes in projections of the impacts of climate change. The following chapter, Chapter 8, will discuss and analyse the results presented in this chapter, and how they relate to the research objectives posed in Chapter 4.

8. Discussion

8.1 Introduction

Chapter 7 presented the results from the LAO model, analysing the potential outcomes from changes in key variables, relevant to the development of global agricultural markets. This chapter builds upon this analysis by discussing their implications in the wider global context.

This discussion focuses on four areas of interest. The first is the relevance of the LAO model for performing future research, including the internal coherence of its results and its comparability with other models. The second is around the key exogenous variables assessed in Chapter 6 (population, GDP and TFP). The third and fourth areas are how the model's results relate to two key issues for global agriculture: food security and climate change. The chapter finishes with a brief conclusion of these areas of discussion.

8.2 Validity of the LAO Model

Overall, from a practical modelling point of view the LAO model performs well. As noted in section 7.1, all presented scenarios found locally optimal, feasible solutions except for one year in scenarios 3.iv, the 'PWC 50' scenario. This occurs when the solver algorithm can find no scenario in which all key variables are super basic[34]. In the LAO model, this implies no state in which global production and consumption are balanced given a particular world price (subject to all imposed constraints and conditions implied in the equation structure). A stable equilibrium price was found for the next year of the simulation, 2050, which implies the feasibility of the underlying assumptions of the scenario.

The good internal performance of the model gives some confidence in the validity of the relationships expressed within the model. However, due to the number of simultaneous equations making up the systems of demand and supply in the model, the relationships between individual equations and the total output of the model are complex. In practical terms, therefore, it is important to ensure the outputs of the model are robust as well. This can be performed in two ways. First, validate the model's outputs against historic data by replicating historic years in the model. This test's the model's ability to replicate real market outcomes. Secondly, the model's outputs can be compared to outputs from its peers. Ensuring other models of similar types report findings largely in line with those outputs of the LAO model gives further confidence.

---

[34] Variables are super basic when they are unbound and used to help minimise or maximise the objective function variable in a non-linear model. The absence of super basic variables indicates the solver has no points of freedom with which to minimise or maximise the objective function.

Due to the nature of the long-term lags in the returns to agricultural research and development and the limited historic time-series of the inputs into R&D investment, the ability to test the outputs of the LAO model against historic data is limited (the development and expression of agricultural TFP being a key component of the model). Thus, the relevance of checking the results of the LAO model when using identical inputs as other models with similar aims is integral towards confirming that the results produced by the LAO model are reasonable.

8.2.1 Comparisons with the AgMIP suite of models

In order to demonstrate the comparability of the LAO results with the suite of models used for other analysis, Table 26 demonstrates the demand-side outputs of the LAO model compared with those from the suite of models used in the AgMIP research (as discussed in section 3.6.1). The LAO model performs within the bounds of the other models' outputs, with the exception of the world price for animal products, where the LAO model's results have a higher price than any other examined model. This may be due to the fact this variable is a synthetic aggregation of other prices (ruminant & non-ruminant products), rather than an explicitly modelled commodity. The world price for crops in the LAO model is also relatively high compared to the AgMIP models. This may suggest that demand in the LAO model is less sensitive to changes in world prices, resulting in higher shifts in price. Overall, the LAO model performs similarly for crop consumption and price, but higher for animal products.

Table 26: Change in demand in AgMIP models for SSP2, 2005-2050

	Crops		Animal Products	
	Consumption as food	World Price	Consumption as food	World Price
	percentage	index	percentage	index
AIM	62	1.21	88	1.12
ENVISAGE	65	0.93	94	0.90
EPPA	82	0.80	62	0.86
FARM	97	0.85	102	0.97
GCAM	55	0.93	79	1.04
GLOBIUM	57	1.00	84	1.06
GTEM	84	1.04	144	0.80
IMPACT	63	1.31	78	1.03
MAgPIE	55	1.54	242	1.04
MAGNET	66	0.93	61	0.85
LAO	63	1.39	212*	1.39*

*aggregate of ruminant and non-ruminant products

Source: Valin et al., 2014

8.2.2 Comparison with the SIMPLE model

As discussed in the literature review in Chapter 3, among the many models used in this research area concerning agriculture, markets, and climate change, the SIMPLE model best embodies the approach taken in this thesis. The work done with the SIMPLE model helps validate the general approach and the focus on TFP as a key component of production projection. The LAO model adds to the evidence base offered by the SIMPLE model and provides some novel analysis with the TFP approach being applied in an alternate specification and to commodity groups beyond crops.

Explaining the differences between the LAO and SIMPLE model is interesting for at least two reasons. First, the approaches are similar, where the broad concept of the LAO modelling approach was inspired by the SIMPLE model albeit with different aims and focuses. The SIMPLE model uses the same a R&D lagged approach using Alston et al.'s (2011) gamma lag specification, however SIMPLE bases this on private R&D, public R&D, international research by CGIAR agricultural research centres, and spill-overs from public R&D in other regions (Fuglie et al., 2022). Second, both models use Fuglie's (2015a) data on historical TFP, and the FAOSTAT for base production data (although using different base-years, and a different final use and coverage of TFP data). These common data sources mean the implications of key differences in the structure and approaches of the models can be explored by comparing the respective outputs.

In the SIMPLE model, processed and animal foods are not the primary focus of the analysis, with both groups not being traded within the model framework. This assumption is reasonable given the low levels of inter-regional trade noted in the base year of the FAO data used for LAO. However, this may restrict simulations over the long run if larger regional consumption changes occur, implying the need to increase inter-regional trade. In the LAO model scenario analysis, where no restriction was placed on trade for animal goods, the levels of trade increased significantly with increases in consumption, most markedly in South Asia. Restricting inter-regional trade in the LAO model would result in much higher local producer prices for animal products as regional production alone would have to meet this new demand. Practically, there are no explicit barriers to the growth of inter-regional trade, beyond additional trade costs. Thus, rising prices would encourage further production and export on the world market, as is seen in the LAO results, where the Europe and Central Asia, Latin America and Caribbean, North America, and Oceania and South-East Asia regions serviced the growth in demand for ruminant and non-ruminant commodities. Of course, due to the coarseness of the LAO commodities, there may be some specific animal commodities which are less suitable for inter-regional trade (liquid milk for example). However, international markets and trade for most animal products currently exist on some-scale, usually incorporating technological solutions to traditional barriers to transport (refrigerated shipping for meat, and dairy powders). It is reasonable, therefore, to assume there is a clear potential for the expansion of regional trade in these goods.

There is, of course, the potential for political factors to cause trade restrictions. As mentioned earlier, for example, SSP3 accounts for lower global trade. None of the examined scenarios using the LAO model imposed exogenous restrictions on trade, but prices for food would be expected to increase with less global trade (as predicted under the HO model of trade), especially given the dependence of inter-regional trade predicted in the modelled scenarios.

Hertel and Baldos (2016) use the SIMPLE model to test the price implications for crops given two different projections of TFP, including upwards pressures from demand for biofuels, and increased demand from income and population growth. The results from these projections indicate either a 45.7 per cent (with historic TFP projection) or 7.0 per cent (with future TFP projections) decrease in crop price between 2006 and 2050. The LAO model TFP scenarios are much less optimistic (in terms of the affordability of food), where the endogenous TFP scenario in the LAO model sees only a one per cent drop in crop prices. It is only in the most positive exogenous TFP scenario (with exponential TFP growth) that crop prices decline seven per cent. Thus, although both models predict declining crop prices in their baseline, driven largely by growth in crop TFP, the SIMPLE model shows a much greater degree of sensitivity in world crop prices to the development of agricultural TFP. This is evidenced by the sharper decrease in crop prices in the SIMPLE model.

There are reasons these sensitivities could be different between the models, including the use of yield frontiers in the SIMPLE model, and the different approach used to account for land-inputs, and the more complete integration of animal products used in the LAO model's structure.

Concerning the use of yield frontiers, Grassini, Eskridge and Cassman (2013) caution against using yield projections that do not take into account maximum biophysical yield potentials. The LAO model does not have limits for yields, in part due to the lack of global data needed to construct reliable maxima for the crop commodity. Yield potentials could potentially constrain yield growth at an earlier stage of the model's projections (especially in the exponential TFP growth scenarios). Yet this constraint would restrict overall production growth leading to higher global prices overall, whereas the SIMPLE model projects lower prices than those in the LAO model. Therefore, this difference cannot account for the observed discrepancy between models.

Another difference between the modelling approaches in the composition of productivity is the relationship between land and other inputs. The price ratio between land and non-land inputs is a key component of productivity in the SIMPLE model. This approach acknowledges the impact this relationship will have on intensification in farming approaches, i.e., the cheaper non-land inputs are relative to land inputs, the more intensive farming will be, and production will tend towards less intensive land-uses. In contrast to this approach, the LAO model has a cost index for non-land inputs (and separate prices for oil) with land separated out. The change in harvested area is modelled as a function of regional producer prices. This is a common approach for partial equilibrium models, but does not account for the explicit value of farmland. Consequently, the relative price ratio and substitution relationship between land and non-land inputs cannot be modelled explicitly. Once again, however, this omission in the LAO model's approach would imply lower world prices (as noted by Hertel and Baldos, 2016, when only accounting for technical change). There is then the possibility that due to the LAO framework not accounting for input substitution and maximum potential yield possibilities, that the results are optimistic in terms of the world price for crops.

Other potential factors for differences between the two model's outputs is the allowance for CO_2 fertilisation. The LAO model does not account for CO_2 fertilisation due to the mixed evidence on the significance of the effect (as discussed in section 3.5.2). In the SIMPLE model, however, the CO_2 fertilisation effect increases the annual growth rate of crop yields by between 0.72 and 0.05 per cent in various regions. This equates to the difference between 25 million additional undernourished peoples (without CO_2 fertilisation), and a reduction of 33 million undernourished peoples (with CO_2 fertilisation) (Hertel & Baldos, 2016).

8.3 Scenario Analysis

Having established the feasibility of the LAO model and its comparability with similar models of its type, this sub-section provides some discussion specific to the different scenario groups presented in Chapter 6, beginning with the baseline scenario.

8.3.1 Baseline

As discussed in Chapter 6, the baseline scenario represents the 'most likely' outcome under 'business as usual' in terms of the exogenous inputs determining the levels of population, inputs, and GDP growth in the model. The prospects for agriculture in the baseline are then important for assessing general questions on how we expect agricultural markets to develop.

As explained in section 6.2.1 the focus of the baseline results is on the implications for world price implied by agricultural supply and demand in each scenario. The world price is an important variable as it is a succinct summation of the balance between global production and consumption, reflected in one of the research questions central to this research: What are the prospects and directionality of real agricultural prices over the long term?

In terms of world prices, the baseline prospects are relatively stable. For crops and ruminant animals, world prices are stable over the examined period and even fall slightly below their initial levels in the base year. Adding to this, when testing the response to different levels of GDP and population estimates, the model indicates lower or stable world prices as the more common outcome. For GDP, some scenarios indicate higher crop and ruminant prices than those in the baseline, but all world prices are tending downwards in the latter years of the simulation. In regard to the population scenarios, only the high population scenario has world prices for crops and ruminant animals trending upwards.

While this does not show that world prices are expected to remain low or stable in all potential futures, the majority of scenarios show that low or stable prices for crops and ruminants are at least possible and are actually more common. GDP and population are the two key drivers of growth on the demand-side, yet with the best exogenous projections available for these variables, there is nothing implicit in these projections that means stable or decreasing world prices are untenable.

Production of ruminant animals in Latin America & the Caribbean increases from 2012 to 2050 by over 70 per cent in the baseline scenario. Although the majority of this increase comes from yield shifts, this baseline projects an increase of 2.5 per cent in ruminant animal numbers. This is potentially a cause for concern as historically expansion of pastoral lands in Brazil has come from deforestation of the Amazon, causing environmental and ecological damage. Loss of forest mass and bio-diversity in the Amazon rainforest has consequences for climate regulation, greenhouse gas sequestration and the ecology of the planet. This is also a concern in the case of crop production (which is expected to increase in the baseline) as the expansion of soybeans has encroached on the Amazon in Brazil, by displacing other agriculture, which then promotes deforestation (Fearnside, 2001).

Looking to the production prospects and drivers of production growth, the modelling identifies changes in yield as being the key driver of production growth. This is applicable for crop and animal products. While the definition of yield between the crop and animal products is different, this result points to growth coming from intensification and TFP growth, rather than an expansion of area or animal numbers.

Considering the results for ‘fish from capture’; prices increase dramatically as capture limits are met. As a result, prices of fish from aquaculture increase steadily in the baseline. The simple limit implemented in the LAO model structure may not reflect a likely outcome as it implies unanimous agreement by all regions to restrict fishing to their maximum replenishable limits. Note that the FAO’s assessment puts levels of biologically sustainable fishing in 2017 at about 66 per cent of total fish stocks (down from 90 per cent in 1974) (FAO, 2020). Thus, a more likely projection of fish from capture may resemble a fluctuating sine wave pattern of partial over-fishing and then allowing stocks to recover; or a consistent trend of over-fishing leading to decreasing fish stocks over-time. Additionally, the approach to fish-stock between regions in the LAO model is the same, whereas the management implemented between regions could be more nuanced. Overall, the implementation of fishing stocks in the model are, in this way, over-optimistic, as they assume regions will not fish beyond their maximum potential sustainable stocks.

In the context of world agriculture, the findings of this baseline are reassuring. Given the parameters set out in the baseline scenario, the findings of the LAO model indicate there are no structural reasons for increasing crop prices in the long-run. The same holds for ruminant animal products. Increased prices for non-ruminant animal and fish products indicate increased pressures on some food systems, and a decrease in the affordability of some products. In general, the projection suggests that all food types (especially not staple foods), are not increasing in price, which points towards a more optimistic outlook for global agriculture and food security. This should somewhat counter Malthusian worries about the ability of world agriculture to support growing populations, if the assumptions behind the baseline scenario prove to be realistic.

8.3.2 Impacts of GDP & Population change

One issue motivating this thesis (as discussed in section 2.4) is concern that there is something inevitable about population driven demand out-pacing the agricultural production capability of the globe, or that the price spikes of 2008 to 2012 were indicative of fundamental structural changes in agriculture that would lead to increasing food prices in this century. Seemingly, this is not the case, as discussed with reference to the baseline scenario. Further, if we look to the scope of potential developments in GDP and population growth, these factors do not point to increasing agricultural prices, except under specific circumstances, such as animal prices under the ‘EconMap’ GDP scenario or in the high population variant scenario.

The key difference between scenarios comparing exogenous GDP projections is in the distribution of GDP increases between regions. This is highlighted most clearly in the difference in the ‘EconMap’ scenario, which has a much higher increase in GDP for the SA region compared with other projections. Interestingly, the ‘EconMap’ is not the scenario with the highest increase in global GDP, but still registers the highest price impacts due to the regional specificity of these GDP changes. This reflects differences in income elasticities between regions, where a marginal increase in income will have a different consumption response depending on regional wealth and historic consumption. The results show then that the marginal addition of income in South Asia has a much more pronounced impact on the global demand of food stuffs than a comparable increase in incomes for regions such as Europe & Central Asia or North America. This is to be expected, as the marginal demand for staple foods is lower in regions with higher income as well as the overall share of household budgets apportioned to purchasing food. We expect then the income elasticity for all foods to decrease as a region's income increase.

However, despite the generally positive outcomes from the model regarding crop and ruminant prices, the outlook for non-ruminant animals is somewhat different. The baseline scenario shows non-ruminant world prices, which are trending upwards. The GDP scenarios show this trend increasing only in scenarios with higher global GDP leading to even higher prices for non-ruminants (although in some scenarios these prices have begun to decline somewhat by the end of the projected period). The prospects for non-ruminant animals are mostly tied to developments in demand in South Asia.

8.3.3 Impacts of Total Factor Productivity

The maintenance of TFP growth is vital to supporting steady or declining world prices for all examined commodities, with marked increases in prices under the 'flat TFP' scenarios. The growth of total factor productivity, however, is generally not sufficient to reverse the trend of rising world prices for non-ruminants. Only with exponential growth of TFP do prices drop for non-ruminants.

Interestingly, the TFP response for the yield of non-ruminants is very strong in Oceania and South-East Asia. The results from the endogenous TFP base show a very high change in yields for Oceania and South-East Asia. This is in part due to the strength of the relationship between own investment in R&D and TFP growth seen in the historic data for Oceania and South-East Asia.

The TFP scenarios results illustrate how it is only with an absence of TFP (in the 'flat TFP' scenario) that a significant change in area harvested or animal numbers is projected. This suggests that yield growth is more elastic in relation to world prices than with both harvested area and animal numbers. Thus, when pressure is placed on the production systems the response from yield growth counteracts this pressure before a significant change in area or animal numbers is seen. This may not be the case if the linear TFP specifications in the model is sufficient to maintain stable world prices, or the R&D investment in the endogenous specification is sufficient regardless of world price.

8.4 Food security

The LAO model is not ideal for testing food security outcomes since the model considers demand (as food) for agricultural goods in units of primary products consumed. Comparing it to the structure of other models, some utilise a measure of consumption in calorific energy or processed foods. This approach would allow for a broader comment on malnutrition, and whether per capita consumption per region is considered adequate. Although not a perfect indicator, the development of real commodity prices from the modelling exercise is an indicator of the affordability of foods, and the pressures on the food system at a global level.

In terms of demand, the results from the LAO modelling show two key areas of rapid growth: demand from population growth in Sub-Saharan Africa, and demand from income growth in South Asia. These are the most significant regional demand changes, representing a 169 per cent increase in crop consumption and a 182 per cent increase in non-ruminant consumption from the base scenario in Sub-Saharan Africa; and a 136 per cent increase in non-ruminant consumption and 90 per cent increase in ruminant commodities in South Asia.

As the production prospects in these regions do not increase in line with the increases in total demand for food, this deficit needs to be resolved through intra-regional trade. This is somewhat concerning as not every forecast of socio-economic futures predict a broadening of global trade. SSP3, for example, implies a ‘regional rivalry’ with political barriers to international trade.

One potential positive outcome of a trade deficit would be if the need for agricultural trade to meet regional needs for food demand promoted a pathway focused more on global trade and interdependence, which would foster global co-operation. Furthermore, meeting the challenges posed by climate change is a global problem, which will require global co-operation and strategy. Thus, any potential cooperation implied by the need for trade may work towards strengthening coordinated global efforts to combat the implications of climate change. Conversely, the deficit could imply a turn to expansionist policies as regions hope to secure access to extra-regional productive areas in order to meet domestic demand. This may be unlikely if low prices on food are maintained, thus reducing the perceived risks around the availability of food.

The increases in demand in Sub-Saharan Africa are more concerning than those in South Asia as the relative increase in agricultural production in Sub-Saharan Africa is much smaller. This is partly due to the very low levels of TFP growth, with Sub-Saharan Africa having the lowest increase in crop TFP in the baseline scenario and across all of the exogenous TFP scenarios examined. In terms of yield changes, the low TFP in Sub-Saharan Africa implies the lowest absolute growth of any region between 2012 and 2050. Other regions have lower percentage yield growth rates (Oceania & South-East Asia generally has the lowest yield crop growth rates across scenarios), but Sub-Saharan Africa experiences the lowest yields in the base year and by 2050 has not equalled base year level crop yields from any other region. Due to the high level of aggregation, yields in the LAO model are not perfectly comparable between regions, since different compositions of the ‘crops’ commodity could bias the overall yield with higher yield commodities. Regardless, the lack of projected development in yield in scenarios with either exogenous or endogenous forecasts is concerning.

8.5 Climate change

The suite of scenarios (5.i-v & 6.i-iv) in Chapter 6, using inputs from the IMAGE modelling packages, including the various SSP scenarios coupled with the different RCPs, were used to test climate change outcomes within the LAO modelling framework.

Surprisingly, the outcome for the yield changes from the RCP scenarios were overall higher than those in the LAO baseline. This is somewhat surprising as climate change is expected to have negative impacts on crop yields. For example, the IPCC projects an increase in global food prices by 2050 (medium confidence) (Porter et al., 2014) and a 1-29 per cent increase in cereal prices under SSPS1/2/3 under RCP 6.0 (high confidence) (IPPC, 2019). While the AgMIP project projects a 9.9 per cent decrease in global crop yields between 2000 and 2050 due to the effects of climate change (Muller & Robertson, 2014). The stronger crop yield growth seen in the RCP scenarios (compared to the LAO baseline) was most significant in Sub-Saharan Africa and the Oceania & South-East Asia regions. This should be of additional concern due to the implications for food-security in Sub-Saharan Africa and warrants further attention as to the causes of this discrepancy. This is especially important if it entails some difference in the development of agricultural technologies or practices, which may be addressed through policy means.

One possible explanation for this difference is that exogenous yield growth in the IMAGE-MAGNET model was not decomposed into climate impact and technological growth for this modelling exercise. However even considering the combined yield effects from the exogenous growth trends and the climatic impact, there is a clear disparity between the IMAGE-MAGNET yield projections and those determined by the endogenous TFP module in the LAO model. This is surprising if it is due to climate change, as the literature predicts a generally negative impact on yields. This indicates these projections have not accounted for all the negative factors and are thus unrepresentatively optimistic; or alternatively, the exogenous technological growth outweighs the negative impacts brought on by climate change. If it is due to the technical growth, there remains a worrying implication as these exogenous trends predict much higher growth than the endogenous TFP driven growth expected by the LAO model. While the LAO model's predictions are based on a very broad regional level, the underlying model of growth should hold. Thus, the exogenous technological growth implied in the IMAGE-MAGNET model is relatively high and could be giving an overly optimistic projection of crop-prices based on an exogenously derived growth function.

At the very least, this disconnect points towards the need for further exploration into the mechanics of growth in agriculture and their integration into modelling platforms. Alternatively, these technological growth factors could be assessed in parallel models. One component of the link between investment into agricultural R&D and growth in TFP that has not been analysed as part of this thesis is the potential for increasing the rates of investment, in order to encourage returns in agricultural TFP. Further examination and research into the sensitivity and development of this link would aid policy makers in the effectiveness of encouraging R&D investment as a long-term strategy for addressing anticipated shortcomings in growth.

8.6 Conclusion

This chapter has discussed key findings from the results presented in Chapter 7. This thesis has contributed to the existing literature by providing an economic approach to the development of long-term agricultural markets, specifically with the inclusion of an endogenous TFP component and animal commodities to assess the development of long-term productivity development for animal products and their inter-relation with cropping. Animal commodities are also important for understanding agriculture’s greenhouse gas profile, due to their high GHG emissions.

The LAO model baseline scenario, indicates that world prices of crops are unlikely to rise, indicating no underlying structural pressures of rising crop prices. This does not hold for animal products, which are projected to have increasing world prices under several scenarios. The outcomes for TFP scenarios indicate the continuing importance of maintaining productivity growth in meeting demand for food towards the middle of the century.

The results from the LAO model on climate change deviated somewhat from those found in the literature but this offered insights into the potential limitations of using exogenous growth specifications in similar modelling frameworks, where the use of exogenous growth could vastly over-estimate the yield growth in some vulnerable areas. The discrepancies between the results found in this exercise and the literature point towards an area which requires further research and exploration. This could lead to policymakers under-estimating the need to enhance agricultural production in the future under the impacts of climate change. This is especially important given that these estimates are likely already underestimating the impacts of climate change as they do not factor in the volatility expected with the increasing frequency of extreme weather impacts, and other associated impacts such as heat-stress and the increased occurrence of pests and diseases affecting crop and livestock production. Furthermore, due to the long lags in returns to investments into agricultural R&D (one key area policymakers could utilise to enhance agricultural production into the future), action and investment would need to occur 25 years in advance in order to realise the height of returns to investment at the salient time.

The following and final chapter explains how these results have addressed the research objectives proposed in the fourth chapter of this thesis, as well as exploring some limitations and shortcomings of the chosen research method and potentials for addressing these issues. It will also highlight areas for improvements in the chosen approach, and extension research that could build upon the findings outlined in this thesis.

9. Conclusion

9.1 Introduction

This last chapter provides conclusions to resolve the research aim and research objectives presented in Chapter 4. Policy implications and suggestions based on these results are offered and the shortcomings and limitations in the research methodology are evaluated. This includes some discussion on how this research contributes to the wider literature, identifying areas where further research could be performed to extend or improve upon the research and conclusions put forward in this thesis. Furthermore, the scope of this thesis has dictated that some useful extensions or inclusions to the research methodology were not possible; these cases are also highlighted.

9.2 Summary

Agriculture is facing many challenges over a long-term horizon, such as global population growth, climate change and food security. While there are biophysical and climate models, designed to operate on these long-term horizons, the standard tools that utilise an economic framework, such as CGE and PE models, are usually designed to operate within policy timeframes of 5 to 15 years. This methodological gap means that for longer term analysis, either methodologies designed for analysis in shorter timeframes are extended or an economic module is applied in integrated assessment modelling platforms as a secondary concern. Both approaches have shortcomings, which may undermine some of their findings.

Consequently, the aim of this thesis was to develop a long-term economic model to assess the prospects and directionality of agricultural prices, the importance of TFP growth to satisfying food demand, and the impacts of climate change on yields. It did this using the approach of the SIMPLE model as a foundation for the development of the Long-term Agricultural Outlook (LAO) model. Section 8.2 has discussed the validity of the model finding the model performed well internally and produced results comparable with those produced by the suite of models utilised in the AgMIP publications.

This section describes how the scenario analysis with the LAO model addresses the four research objectives outlined earlier in Chapter 4.

The first research objective was to assess the development and directionality of real agricultural prices over the medium and long-term framed by the best available projections of key macro-economic drivers.

This first objective was addressed in the set-up and simulation of the 'baseline' scenario. The baseline represented a moderate or 'most likely' scenario, representing business as usual, framed with exogenous macro-economic variables taken from external sources. The results from the baseline scenario indicate an optimistic future for food prices and the affordability of food over both the medium- and long-term horizons, where world prices for crop and ruminant animal products are decreasing, albeit marginally. This contradicts concerns that the food price spikes of 2008 and 2012 were indicative of underlying structural trends in agricultural markets, that would entail rising prices for foods over the medium- and long-term. Of the land-based commodity groups, only non-ruminant animal commodities displayed growing world prices over the medium- and long-term. The upwards trajectory of world prices of non-ruminants resulted in an almost ten per cent increase over the time-horizon of the LAO baseline scenario. The increase in non-ruminant prices is predominantly driven by increased consumption as food in the South Asia region.

Fish commodities are less integral to answering questions on global food security, accounting for only four per cent of global food consumption in 2017 (FAO, 2021), yet they do compose a large portion of diets in some regions (accounting for 8.2 per cent of food consumption in the 'OcSEA' region, for example). The prospects for fish commodities in the baseline are the most dramatic amongst all examined commodities, with sharply increasing 'fish from capture' prices and steady increases in 'fish from aquaculture' prices. This occurs due to the switch from 'fish from capture' to 'fish from aquaculture' as the primary source of production. Fish from capture prices rise as capture limits are reached, and prices for fish from aquaculture rise as additional demand generated from increases in income and population cannot be satisfied by 'fish from capture' under constraints.

Given the context of the last 50 years, the base year of 2012 is a relatively high point for real agricultural prices. Therefore, it is important to consider when discussing the decline of world prices that this is in the context of a high starting point relative to real agricultural prices over the previous 50 years. Thus, while changes in world prices are generally declining, the prices shown in the LAO model's results are high compared to those experienced in the 1980s. Additionally, the projected increase in non-ruminant prices shown in the 'baseline' scenario results in some of the highest prices in the 90 year span from the initial base-data to the final year of the projection (1960-2050) with only the price spikes in 1974-75 registering higher prices (under the combined world price aggregation used in LAO). The historic data for fish is much more limited than those for animal and crop commodities, so while the baseline for real fish prices is higher than seen in the base data (1990-2012), it is harder to make any definitive statements on the relative price of fish commodities over the long-term. The baseline scenario indicates that the outlook for fish commodities and non-ruminant animal commodities is one of rising world prices. For these commodities higher prices may be the 'new normal'. Interestingly the rising prices for non-ruminant products are driven by income increases raising *per capita* demand rather than the population increases central to the Malthusian concerns discussed at the beginning of this thesis.

Overall, the results for the baseline scenario suggests that the prices and supply of food will not be a barrier to food security leading up to 2050. Additionally, testing the limits of some key variables, this will likely be the case unless the levels of the UNDESA high population scenario are realised, depending on the extent of GDP growth in South Asia, which has the potential to cause a dramatic impact on world prices for non-ruminant commodities.

The second proposed objective of this thesis was to assess the potential of agricultural TFP to promote production in order to meet the additional expected demand over the medium- and long-term.

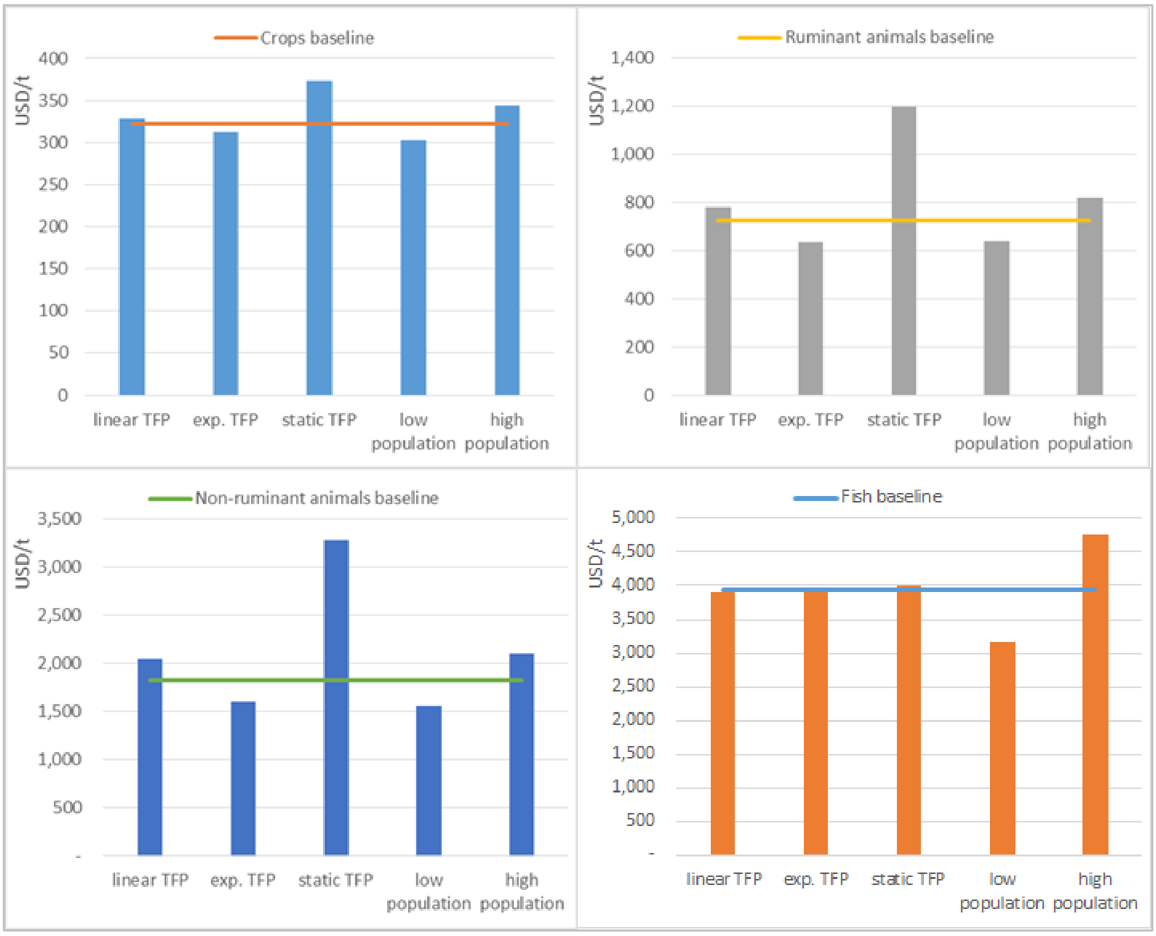
Some aspects of this question are addressed in the 'baseline' scenario, which utilises the novel approach of incorporating and calculating productivity growth endogenously as a factor of lagged investments into agricultural research and development, and the spill-over from applicable research and development performed in other regions. According to this methodology, the endogenous TFP function projects an optimistic future for the growth of TFP, where the level of growth in TFP is sufficient to facilitate the agricultural production necessary to maintain and even reduce agriculture prices for crop and ruminant commodities. This is demonstrated by a one per cent fall in crop world prices by 2050, and stable ruminant prices (with a less than one per cent fall by 2050). This was not the case for non-ruminant animals where world prices rose over nine per cent under the endogenous TFP specification in the baseline scenario.

The FAO report *World Agriculture towards 2030/2050* (Alexandratos & Bruinsma, 2012) projects an aggregate growth rate for crop yields of eight per cent per annum from 2005/2007 to 2050. The LAO baseline, utilising the endogenous specification of TFP, puts this aggregate growth rate slightly higher at 8.8 per cent. While this difference may seem minimal, given the timespan and scale of the modelling, it represents an average deficit of 169 million tonnes of produced crops yearly. This indicates that the resulting yields using an endogenous specification are comparable to the FAO's estimates but are more optimistic in terms of yield growth.

The endogenous TFP specification in the LAO suggests that the current investments made into agricultural R&D should be sufficient to maintain low food prices, with the exception of non-ruminant animal products, for which demand is expected to outpace production growth, driving world prices higher.

This is, however, only part of the picture for the prospects of TFP, as the baseline does not cover a range of possible outcomes for some of the key variables. Figure 61 presents alternative TFP scenarios. This shows that implementing a simple linear progression of TFP results in higher world prices (in 2050) than shown under the endogenous TFP baseline. This is true for crops, ruminant animals, and non-ruminant animals.

Figure 61: Relative world prices in 2050 between key scenarios



The significance of overall TFP growth to the prospects for agriculture was tested by running the LAO model with no TFP growth (scenario 4.iv). Figure 61 shows the static TFP scenarios alongside the other key scenarios contextualising the change in world prices brought on by the different projected TFP outcomes. While the prospect of no TFP growth is an unlikely outcome, it is interesting that the resulting world prices for crop and animal products are much higher than those prices implied by the highest population scenario. This reinforces the notion that global agricultural systems are reliant on consistent TFP growth to meet demand needs without increasing prices.

The impact on world prices associated with the cessation of TFP growth is much greater for the two animal commodities than for crops. Overall, the range of price outcomes between scenarios is the narrowest for crops. This implies that crop production and demand are less sensitive to changes in the tested macro-economic elements than for the animal commodities.

The growth for fish products does not change between the different TFP scenarios, as the equation structure of the model does not account for TFP for fish commodities. There is a simple linear function for technological change included in the production equation. This technological change function was not altered in any of the examined scenarios. This can be observed in Figure 61, where there are only minimal changes in the aggregate world price for fish, between the TFP scenarios (due to cross-price impacts).

The third objective concerned the prospects for agriculture (and in particular agricultural yields) under the impacts of climate change. Here the conclusions are less clear. The scenarios incorporating the different levels of RCP warming using the results from the IMPACT model show a distinct decrease in world prices for crops under most levels of warming. This result seems surprising given the comparative progression in world prices in the LAO baseline and may indicate a divergence in the two models' projection of TFP (noted in Sub-Saharan Africa, and Oceania and South-East Asia). This is interesting in itself as it may point to the need for more robust endogenous TFP approaches to be utilised in IAM's climate projections.

The final research objective concerns the impacts associated with developments in population, economic growth, on the regional production and consumption of agricultural commodities and the effect on total greenhouse gases. The key finding of this research in relation to the final objective is the significance of regional income and population growth in South Asia. South Asia is projected to have the highest range of population change between the high and low variant population scenarios, and while per capita consumption for crops and ruminants is low relative to other regions, South Asia is expect to have the highest consumption per capita of non-ruminant animal products by 2050. This equates to an increase of 384 mil. t of additional consumption between 2012 and 2050 in the bseline, or 457 mil. t over the same period in the high population variant. In terms of income growth, the EconMap GDP scenario (3.iii) projected the highest growth of GDP in the South Asia region. Even with the dynamic income elasticities in the LAO model, in which the income elasticity becomes less elastic as incomes rise, per capita consumption of non-ruminant animal products in 2050 were over 33 per cent higher than in the baseline scenario. This is equivalent to an additional 606 mil.t consumed between 2012 and 2050 in the EconMap scenario, 222 mil. t more than in the baseline scenario in 2050.

Projections of income levels in Sub-Saharan Africa are highly dependant on the GDP projection. The baseline projection has the lowest increase in GDP for Sub-Saharan Africa, and implies few gains in consumption per capita in the region. Under the other simulated GDP projections rising incomes implying much higher per capita consumption of crops in Sub-Saharan Africa. This is equivalent to up to 496 mil. t additional consumption of crops in 2050 in the PWC 50 (3.iv) scenario above level in the baseline. This is encouraging in terms of food security in the region, while not implying higher prices due to relatively smaller crop consumption in high-income regions such as North America and Europe & Central Asia.

In terms of agriculture's effect on GHGs, the increase in ruminant and non-ruminant animal consumption is the most substantial, especially in scenarios that assumed a higher increase of GDP per capita in the South Asia region. The development for TFP was also a key issue, where scenarios with lower TFP growth rates implied much higher levels of agricultural GHGs, as demand for agricultural goods had to be satisfied by an expansion of crop area and increased animal numbers, rather than through a growth in yields.

9.3 Policy Implications

One key takeaway from the results of the LAO scenarios is that the projected changes in demand are driven largely by projected increases in income in South Asia (especially in some GDP scenarios). This increase in South Asian income causes a significant increase in demand for both ruminant and non-ruminant products. This change in diets will have significant implications for the affordability of animal products globally. Additionally, the increase in production of animal products will cause a large increase in agriculture's total GHG emissions.

In order to address these problems, it would be prudent to focus the investment into agricultural R&D on increasing the production of non-ruminant products. Alternatively, techniques of addressing the GHG emissions associated with their production may be necessary to limit the high levels of GHG emissions expected. This could include methods of enhancing the production potential per head, thus lowering the emissions intensity of final non-ruminant products, through, for example, better management of animal health or selective breeding (He Waka Eke Noa, 2021; ICCC, 2019).

A second key result concerns the aforementioned limited yield growth for crops in Sub-Saharan Africa. The interpretation of these results points to a worrying situation. Considering either the historic growth of TFP or the historic investment in agricultural R&D, the potential for adequate development of crop production in Sub-Saharan Africa is low, especially given the projected growth in population and income in the region, which imply large increases in the demand for foodstuffs. The problem is partly due to agriculture in Sub-Saharan Africa prioritising land expansion rather than intensification or labour productivity, and partly due to unsustainable land degrading practices that work to undermine yields (OECD-FAO, 2016).

There are areas of Sub-Saharan Africa with potential for agricultural growth, such as Guinea's Savannah, but the historically low funding into agricultural research is recognised (World Bank, 2009). Hence, thus realising this potential would entail investment beyond the historic norm in this region.

One difficulty in addressing these low yields is that according to the model of TFP development, investment into R&D spending has very high returns on investment, but the lag time required to realise that investment is extremely long (up to 97 years). Thus, even if high investment was implemented in Sub-Saharan Africa immediately, the deficit projected in this modelling exercise would still have to be accounted for, since the returns in increased yields attributed to the R&D would be actualised over a long-term horizon, peaking around 25 years, with the majority of the impact occurring after 2050.

Another approach to addressing the issue of lower yields lies in closing the ‘yield gap’. It is often not the case that novel technologies and means of production are necessary in the advancement of yields. Instead, knowledge of how to achieve higher yields is already present in the global pool of knowledge. However, lack of access to this knowledge, lack of access to necessary inputs or capital to implement this knowledge, or even the inability to tailor this knowledge to region-specific conditions and challenges, are the barriers to growth. The LAO model attempts to reflect some of these effects by including: the spill-over effect from R&D (the ability to utilise knowledge from other regions); the lag effect in the relationship between TFP and R&D (the time taken to implement new knowledge); the input cost variable (the affordability of necessary inputs for growth); and periods of high-prices (simulating the availability of capital to producers). With the inclusion of these factors in the modelling framework, there is provision for some transfer of knowledge from other regions to Sub-Saharan Africa in the endogenous baseline scenario. Even in this scenario, however, the TFP growth in Sub-Saharan Africa is minimal. As this spill-over effect is based on historic data, we can conclude that either historically this effect has not been sufficient to counter low yield growth, or that even with robust influence from external research this has not been sufficient, or timely, to produce globally comparable yield growth.

The model’s projections are based on the underlying relationships in historic data, framed with up-to-data macro-economic projections. Thus, the modelled results suggest that given these historic relationships, the prospect for yield growth in Sub-Saharan Africa is not substantial. The goal of policy makers could then be to address these potential issues by implementing policy which would either increase the levels of agricultural R&D beyond current levels, or to directly implement policies to disseminate external knowledge and practices to producers in Sub-Saharan Africa (enhancing the ‘spill-over’ effect). In the case of yield growth, either further investment needs to be made or the relevance and application of inter-regional R&D needs to be expedited.

9.4 Contribution to the Literature

The LAO model and the scenario analysis presented in this thesis contribute to the literature by providing a broad analysis of the major drivers of agricultural supply and demand within a dynamic framework. This helps illustrate the pathway and development over time of changes in these major drivers and the associated measures of economic and environmental outcomes. This work also provides, in this dynamic context, measures of TFP growth for animal products in this dynamic context. Most studies into agricultural TFP focus on crops (grains in particular). Hence, the LAO model adds to the discussion on the drivers of TFP growth for animal products, on the price outcomes of this growth, and on the interplay between crop and animal products as they develop over the long-term.

The importance of developing a long-term model is two-fold. First it provides a ‘missing link’ between the standard CGE and PE frameworks used by economists and the time horizons used in the IAMs and climate models. Of course, the IAMs have economic modules and PE and CGE models have been used to project into the long-term; however, this project has used a purely economic framework which distinguishes it from the IAMs. In using a highly aggregated simple framework, the research is able to better manage the sources of uncertainty over the long term, distinguishing it from most CGE and PE models. One example of the benefits of using this approach is the differences in yield outcomes under the RCP scenarios. This modelling approach is not a complete approach to answering these challenges but can be utilised to provide some additional economic context in a simple and low time-cost framework.

A second benefit of designing this model for use over longer time horizons than most PE models is that it allows analysis of the long lags which the literature has identified in returns to investment in agricultural R&D. Although this thesis has not focused on the sensitivities in the relationship between investments in R&D and TFP growth or explored changes in investment as a driver of TFP growth and ultimately changes to agricultural markets and real prices, the model and scenario analysis none-the-less provide results on the outcomes of agricultural R&D and TFP growth over the long-term. Future work with the model could expand on these linkages.

9.5 Limitations and Further Research

At the heart of economic modelling is a tension between granularity and scope. Due to constraints in data, time, and processing power, not all aspects of the economy can be covered in precise detail. Concessions for the level of detail incorporated, or the scope of how much of the whole economy is included, must often be made.

With the available data, the scope of the LAO model could be broadened, such as including finer commodity and regional disaggregation. The concept behind constructing a simple model, however, is to reduce the detail outside of the focus of the current research question. This minimises the number of variables, which could be subject to uncertainty over the long-term. Thus, any potential for broadening the model should be considered in relation to the specific relevance to research questions. These issues are discussed further in section 9.5.2 below.

The model is solved using the GAMS/CONOPT solver, which is suitable for solving DNLP models. There are other solvers similarly suitable for the DNLP PE model framework used by the LAO model, which might yield somewhat different results. One such solver is the MINOS solver. Testing the model with both solvers would give a more complete picture of the individual characteristics of the solver's mechanisms and distinguish any results which are indicative of the solvers' tendencies, rather than the expression of the underlying data and relationships between parameters.

9.5.1 Model structure

The elasticities used in the yield equations were estimated from a double-log specification using an OLS estimator. As discussed in the methodology chapter, this is the common approach in many economic models where the specification may be made on non-stationary data. While not common in this style of modelling, this approach could be improved with further econometric testing (such as the augmented Dickey Fuller test), which could be performed to assess if the time series data contains unit-roots before estimating parameters. This may necessitate estimating the parameters based on the Nth difference of the data in order to ensure stationarity. This may also require altering the equation structure of the production function to accommodate differenced series.

Another limitation of the chosen model structure is that no constraints were placed on the potential expansion of cropland. This is unlikely to be restrictive at the global scale, as there is still an abundance of potential land for use in agriculture globally (especially in Latin America and Africa, albeit with some caveats to the productive capacity of this land) (Ramankutty et al., 2002). Additionally, there is a concern about the loss of prime agricultural land to over-farming or urbanisation. Still the percentage of land lost to desertification, urbanisation and nutrient-loss is relatively small, especially over the time-scales used in this modelling exercise (FAO, 2021). Nutrient loss has the potential to impact upon the yield potential of crops or imply a higher requirement of inputs to maintain yields. However, implementing the degradation of cropland explicitly in the model is difficult, as some of the degradation of land would be expected to impact on yields rather than the extent of agricultural lands. Theoretically these declines in crop yields should already be expressed in the historic data for yields, and so should be accounted for as part of the estimation of yield growth, unless there is an expectation for these changes to yields to occur at a historically unprecedented rate. One such set of unprecedented effects on yields are the associated changes implied by climate change; however, these changes have been examined separately in this modelling exercise under the ‘IMAGE SSP RCP’ scenarios.

Similarly, there are no constraints on the total number of animals in each region in the LAO model. For example, the number of ruminant animals in Europe and Central Asia increases significantly in the baseline. This would create competition for agricultural lands, even under the most intensive farming practices. Additionally, pasture-grazed and ruminant production systems can place heavy burdens on the environment with the leaching of nutrients into groundwater and waterways (Voorburg, 1991; Tamminga, 2003; Houlbrooke et al., 2004). These environmental limits may also constrain the potential for expansion of ruminant stocking before land constraints became relevant. Additional research could impose some of these environmental or policy driven constraints on the production and expansion of ruminant animals, which may lead to higher prices for ruminant animals than shown in the presented results. It is also important to note that in the baseline very few regions are projected to show an increase in either total area harvested or animal numbers, thus minimising this limitation in the presented set of results. However, the potential for the lack of constraints to misrepresent the potential for agricultural expansion remains.

TFP and yields between regions are not entirely comparable due to the composition of each commodity. To illustrate, the ‘crops’ commodity may be composed of a majority of high yield/low value crops in one region, and by a majority of low yield/high value crop in another region. Thus, comparing these two commodities as equivalents may give an inaccurate picture of the state of agricultural yields. This problem would be alleviated somewhat if the crops commodity was disaggregated into major groupings (cereals, roots & tubers, fruit & vegetables, etc.).

Greenhouse gas emissions in the LAO model are based on static regional emissions factors. These static emissions factors are applied on a per hectare basis, in the case of the crop commodity, and on a per head basis, in the case of animal commodities. This may limit the strength of the conclusions on the outputs concerning greenhouse gas emissions, as the emission factors of all commodities would be expected to change alongside changes in yields, the composition of commodities, and with changing climatic conditions. These static emissions factors are then a very coarse measure of the implications for agricultural GHG emissions. Ideally more dynamic emissions factors, accounting for yield growth, would be utilised. However, with the current level of regional and commodity aggregation in the model, the emissions will necessarily have to be derived on a weighted average basis, and thus present a coarse representation of agricultural GHG outputs. This limitation should be considered in particular with the conclusions on GHG emissions under different TFP scenarios, as they may underestimate the GHG emissions associated with TFP-driven growth from yields. Making growth sourced from increased area and animals appear to have a comparatively higher GHG impact than growth sourced from TFP growth

9.5.2 Model scope

The broad scope of the aggregated commodity groups is useful when considering issues around real food prices and the linkages with macro-economic drivers, TFP, and climate change. However, in order to perform analysis on the specificities of food security, such as the calorific and nutritional content of food, it would be necessary to disaggregate some commodity groups. The 'crop' commodity grouping, in particular, would benefit from disaggregation, at least into some key sub-categories which are more distinct in their production methods and nutritional composition[35]. Food groupings could be taken from the FAOSTAT's aggregate crop groupings including 'Cereals', 'Roots and Tubers' 'Fruit and Vegetables' 'Oil Crops'. Having commodity aggregation on this level would broaden the scope of possible analyses to more specific policy recommendations, to be more directly applicable for policy makers. The task of judging the capacity of global agriculture to provide adequate nutrition to meet the demands implied by population growth (as highlighted by Alexandratos (2005)) would be made easier if the allocation could be specified more clearly within the nutritional content of specific crop types. There is some evidence to suggest that changes in nutritional content of crops may change alongside yields under climate change (Jablonski, Wang & Curtis, 2002). Examining food security and nutrient availability under the LAO model framework would require a more in-depth accounting of the nutritional content of crops.

The splitting of commodity groups would also allow for more specific analysis on the differences in production between regions. This would have implications for global trade when traded goods are less homogenous. The disaggregation of these commodities would be beneficial; however, it would increase the complexity of the model requiring further analysis and the potential to undermine some of the benefits of the simple modelling approach. This task is beyond the scope of this thesis but could be explored as an extension to this research.

In a similar vein to further disaggregating of commodities in the LAO model, the set of regions considered could also be amended to broaden the scope of the modelling or improve its functioning. In particular, splitting up the South Asia region may balance the model's regional distribution of production and consumption more appropriately and provide for better comparisons between regions. The size of the South Asia region dwarfs the other regions in population and consumption size. The original groupings were based on a variation of the United Nations development groups, with some minor changes in order to complement the parameterisation of the model (such as the

---

[35] For example, 6.4% of crops in the base year were tree crops (FAOSTAT, 2022) and would have a lagged production response to price change, unlike other crop sub-types.

inclusion of Central Asia into a region with Europe). However, given the relative size of production and demand of the South Asia region, future versions of the model may benefit from the further break down of these groups. Especially as projected change in the South Asia region provided some of the most interesting and globally impactful developments in the scenario analysis.

Splitting up the South Asia region could be performed by separating the Indian sub-continent from the rest of South Asia. This division between these regions would be largely comparable in terms of the relative size in population and consumption. Furthermore, the Indian sub-continent is somewhat distinct in the composition of its agricultural consumption and production, which would further warrant it as a worthwhile region to isolate from the rest of South Asia.

Part of the analysis in this thesis has addressed the implications for climate change on global agriculture, and likewise the implications of climate change on agriculture. While some interesting results and conclusions have been drawn from these scenarios, a more complete picture of these interactions between agriculture and climate change would require the model to include forests and markets for forestry products. Competing demand for land-use between agricultural practices would cause some cross-demand for land between the commodities currently considered in the LAO model and forestry. The exclusion of forestry means the model is unable to examine some potentially beneficial environmental policies options such as additional forestry planting and management in order to offset greenhouse gas emissions.

9.5.3 Scenarios

In the scenario analysis performed, many scenarios were based around examining key exogenous macro-economic variables (population, TFP, GDP). However, there has been limited testing of bundles of these variables (the ‘IMAGE SSP RCP’ scenarios presented). The presented scenarios help demonstrate the different impacts of these variables on agriculture and the sensitivity of these parameters in the model. However, it would also be informative to examine the effects of combined bundles of these variables. Consider, for example a ‘perfect storm’ scenario, combining the variables which placed the most stress on the agricultural system (high population/high GDP/low TFP). This would likely result in much higher prices for all commodities. Such a combination would be unlikely due to the linkages between the elements (i.e., high GDP would imply higher TFP over the long-run, unless some obfuscating circumstances were at play). It would, however, highlight the potential ‘worst-case’ for agriculture, which might be useful in setting the extreme bounds of possible outcomes. Future research could test some of these scenario bundles.

Testing the LAO model’s results in comparison to other models in scenario analysis gives some idea of the reliability and comparability of the model results. This was demonstrated with the replication of the IMAGE SRES/RCP model scenarios (5.i-iv & 6.i-iv). Overall, these results were largely consistent with other models running the same scenario inputs. Further research could examine historic validation of the model as a whole or for some individual equations. That is, running the model on historic data using an earlier base year and seeing how closely the model's projections align with historical data. This method is used by Baldos and Hertel (2014a) and would help illustrate which areas of the modelling approach are in-line with real data, and to identify and improve areas of weakness, where the model is unable to replicate historic data.

In the baseline scenario, the world price for 'Fish from capture' rises steadily from 2023, when most regions (other than 'South Asia' and 'Latin America & Caribbean') have reached their maximum sustainable production. Total global production for 'Fish from capture' ceases at about 89 million tonnes. The demand for 'fish from capture' and 'fish from aquaculture' should be contiguous and are modelled as perfect substitutes. If this function in the model is performing as intended one might expect the price of 'fish from capture' to reach a stable relationship with the price of 'fish from aquaculture' after reaching its maximum production and additional spill-over demand causes the price for 'fish from aquaculture' to increase. To an extent this does occur in the model baseline, with aquaculture production becoming the predominate source of fish production by 2050 (alongside a 22 per cent increase in producer price for 'fish from aquaculture'). The increase in the price for 'fish for capture', however, continues increasingly steadily after the production has become constrained, ending up at 119 per cent of the price in the base year. This increase is beyond the level we would expect from natural growth in demand for fish commodities, and is instead, more likely, an artefact of the modelling approach rather than representative of the effect such a limit would create. This limitation does not have major implications for the conclusions of this thesis, yet the pronounced increase in fish prices will have minor flow-on effects on other commodities which have cross-price relationships in the model's demand structure. Future research could amend this limitation by ceasing solving for the world price of 'fish from capture' once the maximum production is exceeded, and a price equilibrium reached, focusing instead on the solving for a price for fish from aquaculture to service additional demand for fish.

The different possible outcomes for 'fish from capture' based on fishing policies and quotas, is briefly discussed in Chapter 8. These alternative approaches to managing fish-stocks could be modelled as different scenarios in order to assess their impact on global food security and the sustainability of fishing, ultimately helping to inform policy approaches to fishing management. This would require further research into the dynamics of fish-stocks and modelling capture rates beyond the scope of this current research inquiry.

9.5.4 Data

The strength of any model is dependent on the quality and reliability of its exogenous inputs, and data. The LAO model currently uses a base year of 2012, due to the availability of all required data at the time of developing the modelling framework. Currently data from the principal sources of the model would allow for this to be updated to 2018, an addition of six years of data. An additional six years in the model's base data is not as vital as it would be in a short-or medium- term model, for which the up-to-date trends and price movements are key but would none-the-less strengthen the model's outputs, in particular the specifications of the endogenous TFP component.

For population, only UNDESA scenarios were considered in LAO. While these are highly reputable and widely used estimates of population prospects, there is potentially a weakness in the research framework by only considering prospects derived from one institution's methodological approach. Due to the ubiquity of the use of UNDESA's projections, this is less egregious than if only one approach for estimating GDP was used, due to the absence of a singular authoritative source.

With the macro-economic elements used in the modelling approach, the population and GDP in LAO are treated as distinct elements. In reality the two elements are inter-dependant, thus, decoupling the two elements in the modelled scenarios may not be an accurate representation of how the global macro-economic context would develop. In the context of the modelling, there is however a reason for isolating different variables, in order to test their sensitivity individually for the outcomes of the modelling. Ideally, both the GDP and population projections should be taken from the same sources and used in conjunction; this should at least ensure the macroeconomic inputs are mutually consistent. A macro-economic model could be constructed to assess the linkages between the macro-economic factors used in the model, but is beyond the scope of this current research.

Most assumptions for productivity in the modelling structure assume no ceiling for the production potential of crops or animal commodities. In reality this assumption does not hold (as discussed in section 3.2), with evidence in Grassini, Eskridge and Cassman (2013) even indicating ceilings for some crops may have already been reached in some areas. There are a number of factors limiting the production potential for yield on any given parcel of land. A large body of literature exists on defining this yield potential and addressing the yield gap in regions not realising their yield potentials. Most of the factors limiting the realisation of potential yields are spatially specific, at the regional level or lower (Reidsma, Ewert & Lansick, 2007; Timsina & Conner, 2001). This limits the ability for such a regionally aggregated modelling structure to address these yield potentials in a meaningful way. Neumann, et al. (2010) propose one method for deriving a stochastic frontier production function which is more appropriate for distinguishing the production potential at a broader level, utilising temperature, precipitation, soil fertility constraints, and market influence. This paper also provides a global estimate of yield frontiers for wheat, maize, and rice. This methodology could also be applied to LAO's aggregate commodities to ensure a global maximum is not exceeded in terms of yields.

The discussion in the modelling analysis chapter focussed on the development of TFP scenarios. While this served to demonstrate the importance of TFP to the overall development of agricultural world prices, some of the nuance of the discussion depends on how realistic the presented TFP scenarios are. One of the most interesting facets of the LAO model is the inclusion of an endogenous specification for the development of TFP based on R&D funding for agriculture, lags, and research spill-overs between regions. Due to this novel element, further examination of the components of the endogenous equation structure and constituent elements may enhance the discussion on the development of TFP and its components. Specifically, testing the levels of investment into agriculture and how they might influence TFP over the long-run (and ultimately real prices for agricultural commodities), would give further insight into these key relationships. This expansion was not central to the research questions proposed by this thesis, yet are tangentially relevant and could be fruitful grounds for future research.

9.6 Conclusion

As discussed in Chapter 1, the world is facing major long-term challenges around food security and climate change. This requires long-term agricultural modelling to help assess outcomes in global agricultural markets. This thesis has provided a novel model capable of assessing the balance between global agricultural supply and demand, given these challenges. The results presented in this thesis have provided perspective over the long-term developments in agricultural markets, and from which, recommendations for policy makers have been provided. Furthermore, this thesis lays the groundwork for future research into long-term analysis of agricultural markets, with the inclusion of animal products and long-term lags in R&D contributions to TFP, thus, advancing methodological approaches in the field of economic modelling for agriculture.

References

Adenäuer, M. (2008). CAPRI versus AGLINK-COSIMO: Two partial equilibrium models – two baseline approaches. European Association of Agricultural Economists 2008 International Congress, Aug 26-29, Ghent.

Aguiar, A., Chepeliev, M., Corong, E., McDougall, R. & van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis* 4(1), pp:1-27.

Alexandratos, N. (2005). Countries with Rapid Population Growth and Resource Constraints: Issues of Food, Agriculture, and Development. *Population and Development Review* 31(2), pp: 237-258.

Alexandratos, N. & Bruinsma, J. (2012). World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO.

Alston, J. (2002). Spillovers. *The Australian Journal of Agricultural and Resource Economics* 46(3), pp: 315-346.

Alston, J., Anderson, A., James, J. & Pardy, P. (2011). The Economic Returns to U.S. Public Agricultural Research. *American Journal of Agricultural Economics* 93(5), pp: 1257-1277.

Alston, J., Anderson, A., James, J. & Pardy, P. (2012). Shifting Patterns of Agricultural Production and Productivity in the United States. In 'Productivity Growth in Agriculture: An International Perspective', Fuglie, K., Wang, S. & Ball, V (Eds), C.A.B. International, pp: 193-227. Alston, J., Beddow, J. & Pardey, P. (2009). Agricultural Research, Productivity, and Food Prices in the Long Run. *Science* 325, pp: 1209-1210.

Alston, J., Chang-Kang, C., Marra, M., Pardey, P. & Wyatt, T. (2000a). A Meta-Analysis of Rates of Return to Agricultural R&D, International Food Policy Research Institute Research Report 113, Washington D.C.

Alston, J., Craig, B. & Pardey, P. (1998). Dynamics in the creation and depreciation of knowledge, and the returns to agricultural research. EPTD Discussion Paper 56. International Food Policy Research Institute. Washington D.C.

Alston, J., Pardey, P., Wood, S. & You, L. (2000b). Strategic Technology Investments for LAC Agriculture: A Framework for Evaluating the Local and Spillover Effects of R&D. International Food Policy Research Institute. Prepared for an IDB-sponsored project 'Policies on Food, Agriculture and the Environment, and Indicators and Priorities for Agricultural Research'.

Alston, J. & Pardey, P. (2001). Attribution and other problems in assessing the returns to agricultural R&D. *Agricultural Economics* 25, pp: 141-152.

Anker, R. (2011). Engel's Law Around the World 150 Years Later. Working Paper Series 247. University of Massachusetts Amherst Political Economy Research Centre.

Appleyard, D., Field, A. & Cobb, B. (2006). International Economics: 5th Edition. McGraw-Hill/Irwin.

Armington, P. (1969). A Theory of Demand for Products Distinguished by Place of Production. *IMF Staff Papers* 16, pp: 159-176.

Baldos, U. & Hertel, T. (2012). SIMPLE: a Simplified International Model of agricultural Prices, Land use and the Environment. GTAP Working Paper No. 70.

Baldos, U. & Hertel, T. (2014a). Global food security in 2050: the role of agricultural productivity and climate change*. Australian Journal of Agricultural and Resource Economics* 58. pp: 554-570.

Baldos, U. & Hertel, T. (2014b). Bursting the bubble long term crop commodity prices, GTAP Working Paper No. 80.

Barbier, E.B. (1989). Economics, Natural-Resource Scarcity and Development: Conventional and Alternative Views, Earthscan Publications, London.

Barnett, H.J. & Morse, C. (1963). Scarcity and Growth: The economics of natural resource availability. John Hopkins Press, Baltimore.

Barona, E., Ramankutty, N., Hyman, G. & Coomes, T. (2010). The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environmental Research Letters* 5. pp: 1-9.

Barriopedro, D., Fischer, E., Luterbacher, J., Trigo, R. & García-Herrera, R. (2011). The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. *Science* 332(6026), pp: 220–224.

Bergeaud, A., Cette, G. & Lecat, R. (2016). Productivity Trends in Advanced Countries between 1890 and 2012. *Review of Income and Wealth* 62(3), pp: 420-444.

Bobenrieth, E., Wright, B. & Zeng, D. (2013). Stocks-to-use ratios and prices as indicators of vulnerability to spikes in global cereal markets. *Agricultural Economics* 44, pp: 43-52.

Bosello, F. Eboli, F. & Pierfederici, R. (2012). Assessing the Economic Impacts of Climate Change. An Updated CGE Point of View. FEEM Working Paper "Note di lavoro" 2012.002.

Briggs, J. (2009). Green Revolution, In Kitchin, R. & Thrift, N. (eds). *International Encyclopedia of Human Geography*. Elsevier Science. pp: 634-638.

Britz, W. (Ed.) (2004). CAPRI Modelling System Documentation: Common Agricultural Policy Regional Impact Analysis. Report for FP5 'CAP-STRAT' project, Bonn, April.

Britz, W. & Keeney, R. (2010). The CAPRI model – an overview with a focus on comparison to GTAP. Presented at the 13th Annual Conference on Global Economic Analysis "Trade for Sustainable and Inclusive Growth and Development", Bangkok, Thailand, June 9-11.

Burfisher, M., Robinson, S. & Thierfelder, K. (2004). Regionalism: Old and New, Theory and Practice. In 'Agricultural Policy Reform and the WTO: Where Are We heading?', Anania, G., Bohmnan, M., Carter, C. & McCalla, A. (Eds.), Edward Elgar Publishing, Cheltenham, UK, pp: 593-622.

Cagatay, S. & Saunders, C. (2003). Lincoln Trade and Environment Model (LTEM): An Agricultural Multi-Country, Multi-Commodity Partial Equilibrium Framework. AERU research report 254. Lincoln, New Zealand.

Cagatay, S., Saunders, C. & Wreford, A. (2003). Lincoln Trade and Environment Model (LTEM): Linking Trade and Environment. AERU research report 263. Lincoln, New Zealand.

Centre d'Études Prospectives et d'Informations Internationales [CEPII]. (2016). Macroeconomic data: EconMap. Accessed from: http://www.cepii.fr/cepii/en/bdd_modele/download.asp?id=11

Center for Global Trade Analysis [CGTA]. (2019). GTAP history. Accessed from: https://www.gtap.agecon.purdue.edu/about/history.aspx

Chavas, J. & Cox, T. (1992). A Nonparametric Analysis of the Influence of Research on Agricultural Productivity. *American Journal of Agricultural Economics* 74(3), pp: 583-591.

Chepeliev, M. & Aguiar, A. (2018). Agricultural Production Targeting in the GTAP Data Base: a Look Ahead. Presented at the 21st Annual Conference on Global Economic Analysis, Cartagena, Colombia. Updated: 19th of June.

Choi, J. & Helmberger, P. (1993). How Sensitive are Crop Yields to Price Changes and Farm Programs? *Journal of Agricultural and Applied Economics* 25(1), pp: 237-244.

Clements, K. & Chen, D. (1996). Fundamental Similarities in Consumer Behaviour. *Applied Economics* 28(6), pp: 747-757.

Committee for the Prize in Economic Sciences in Memory of Alfred Nobel (2018). Economic growth, technological change, and climate change. Scientific background paper, Royal Swedish Academy of Sciences, Stockholm.

Conforti, P. (Ed). (2011). In Looking Ahead In World Food and Agriculture: Perspectives to 2050. FAO. pp: 191-228.

Davis, J., Oram, P. & Ryan, J. (1987). Assessment of agricultural research priorities: An international perspective. Documentation. Australian Centre for International Agricultural Research, Canberra.

Delgado, C., Rosegrant, M. & Meijer, S. (2001). Livestock to 2020: The Revolution Continues. Paper presented at the annual meetings of the International Agricultural Trade and Research Consortium (IATRC), Auckland, NZ, Jan. 18-19.

Dellink, R., Lanzi, E. & Chateau, J. (2019). The Sectoral and Regional Economic Consequences of Climate Change to 2060. *Environmental Resource Economics* 72, pp. 309-363.

Durance, P. & Godet, M. (2010). Scenario building: Use and abuses. *Technological Forecasting & Social Change* 77, pp: 1488-1492.

The Economist (2007). Dec 8th Edition.

European Parliamentary Research Service [EPRS] (2020). Briefing EU agricultural policy and climate change. European Parliamentary Research Service. Climate Action Research Tracking Service.

Golub, A., Hertel, T. & Sohngen, B. (2008). Land Use Modeling in Recursively-Dynamic GTAP Framework. GTAP Working Paper No. 48.

Grant, J., Hertel, T. & Rutherford, T. (2007). Extending General Equilibrium to the Tariff Line: US Dairy in the Doha Development Agenda. Presented at the 10th Annual Conference on Global Economic Analysis, Purdue, US. Jun 7-9.

Gerbens-Leenes, P., Nonhebel, S. & Krol, M. (2010). Food consumption patterns and economic growth. Increasing affluence and the use of natural resources. *Appetite* 55, pp: 597-608.

Fearnside, P. (2001). Soybean cultivation as a threat to the environment in Brazil. *Environmental Conservation* 28(1), pp: 23-38.

Fischer, G. (2009). World food and agriculture to 2030/50: How do climate change and bioenergy alter the long-term outlook for food, agriculture and resource availability? Technical Paper from 'Expert Meeting How to Feed the World in 2050. FAO.

Fischer G., van Velthuizen, H., Shah, M. & Nachtergaele, F. (2011). GAEZ v3.0: Global Agro-ecological Zones Model documentation. IIASA. Luxemburg.

Food and Agriculture Organization of the United Nations [FAO] (2006). Livestock's long shadow: environmental issues and options. Rome.

Food and Agriculture Organization of the United Nations [FAO] (2009). The State of Agricultural Commodity Markets 2009. Trade and markets division. Rome.

Food and Agriculture Organization of the United Nations [FAO] (2017). The future of food and agriculture: Trends and challenges. Rome.

Food and Agriculture Organization of the United Nations [FAO] (2018). The State of Agricultural Commodity Markets: Agricultural trade, climate change and food security. Rome.

Food and Agriculture Organization of the United Nations [FAO] (2019a). FAO Food Price Index. Accessed from: http://www.fao.org/worldfoodsituation/foodpricesindex/en/

Food and Agriculture Organization of the United Nations [FAO] (2019b). FAOSTAT database. Accessed from: http://www.fao.org/faostat/en/#home

Food and Agriculture Organization of the United Nations [FAO] (2019c). Fishery Statistical Collections: Global Production database. Accessed from: http://www.fao.org/fishery/statistics/global-production/en

Food and Agriculture Organization of the United Nations [FAO] (2019d). Fishery Statistical Collections: Global Aquaculture Production database. Accessed from: http://www.fao.org/fishery/statistics/global-aquaculture-production/en

Food and Agriculture Organization of the United Nations [FAO] (2019e). Our Priorities - The Strategic Objectives of FAO. Rome.

Food and Agriculture Organization of the United Nations [FAO] (2020). The State of World Fisheries and Aquaculture 2020. Rome.

Food and Agriculture Organization of the United Nations [FAO] (2021). FAOSTAT database. Accessed from: http://www.fao.org/faostat/en/#home

Food and Agriculture Organization of the United Nations [FAO] (2022). FAOSTAT database. Accessed from: http://www.fao.org/faostat/en/#home

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, World Food Programme [FAO, IFAD & WFP] (2015). Achieving Zero Hunger: the critical role of investments in social protection and agriculture. Rome, FAO.

Fouré, J., Bénassy-Quéré, A. & Fontagné, L. (2012). The Great Shift: Macroeconomic Projections for the World Economy at the 2050 Horizon. CEPII Working paper 2012-03.

Fouré, J., Bénassy-Quéré, A. & Fontagné, L. (2013). Modelling the world economy at the 2050 horizon. *Economics of Transition* 21(4), pp: 617-654.

Fuglie, K. (2012). Productivity Growth and Technology Capital in the Global Agricultural Economy. In 'Productivity growth in agriculture: an international perspective' Fuglie, K., Wang, S. & Ball, V. (Eds.), pp: 335-368.

Fuglie, K. (2015a). Agricultural total factor productivity growth indices for geographic regions, 1961-2012. Accessed from: https://www.ers.usda.gov/data-products/international-agricultural-productivity/update-and-revision-history/

Fuglie, K. (2015b). Accounting for growth in global agriculture. *Bio-based and Applied Economics* 4(3), pp: 201-234.

Fuglie, K. (2017). R&D Capital, R&D Spillovers, and Productivity Growth in World Agriculture. *Applied Economic Perspectives and* Policy 0(0), pp: 1-24.

Fuglie, K., Ray, S., Baldos, U. & Hertel, T. (2022). The R&D cost of climate mitigation in agriculture. *Applied Economic Perspectives and Policy*, pp: 1-20.

Gardner, B. (2002). American Agriculture in the Twentieth Century: How it Flourished and what it Cost. Harvard University Press. Cambridge MA, USA.

Geissdoerfer, M., Savaget, P., Bocken, N. & Hultink, E. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production* 143, pp: 757-768.

Ghisellini, P., Cialani, C. & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production* 114, pp: 11-32.

Glaeser, B. (2011). The Green Revolution Revisited: Critiques and Alternatives. Routledge.

Goodwin, B., Marra, M., Piggo, N. & Muller, S. (2012). Is Yield Endogenous to Price? An Empirical Evaluation of Inter- and Intra-seasonal Corn Yield Response. Presented at AAEA annual meeting. Seattle. Aug 12-14.

Grassini, P., Eskridge, K.M. & Cassman, K.G. (2013). Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications* 4, pp: 1-11.

Griggs, D. (1992). The Transformation of Agriculture in the West. Basil Blackwater Ltd. Oxford.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M., Shyamsundar, P., Steffan, W., Glaser, G., Kanie, N. & Noble, I. (2013). Sustainable development goals for people and planet. *Nature* 495. pp: 305–307.

Grilliches, Z. (1998). R&D and Productivity: the Econometric Evidence. University of Chicago Press.

Huang, H. & Khanna, M. (2010). An Econometric Analysis of U.S. Crop Yield and Cropland Acreage: Implications for the Impact of Climate Change. Presented at the AAEA, CAES, & WAEA joint annual meeting. Denver. Jul 25-27.

Havlik, P., Schneider, U., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., De Cara, S., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T. & Obersteiner, M. (2011). Global land-use implications of first and second generation biofuel targets. *Energy Policy* 39(10), pp: 5690-5702.

Havlik, P., Valin, H., Gusti, M., Schmid, E., Leclèrce, D., Forsell, N., Herrero, M., Khabarov, N., Mosnier, A., Cantele, M. & Obersteiner, M. (2015). Climate Change Impacts and Mitigation in the Developing World: An Integrated Assessment of the Agriculture and Forestry Sectors. World Bank Group Policy Research Working Paper 7477.

He Waka Eke Noa (2021). Greenhouse gases: Farm Planning Guidance. He Waka Eke Noa – The Primary Sector Climate Action Partnership. Accessed from: https://hewakaekenoa.nz/wp-content/uploads/2020/12/2020-He-Waka-Eke-Noa-Greenhouse-gases-Farm-Planning-Guidance.pdf

Heckscher, E. (1919). The effect of foreign trade on the distribution of income. *Ekonomisk Tidscrift* 21, pp: 497-521: reprinted in 'Readings in the Theory of International Trade', American Economic Association, 1949.

Herrington, G. (2021). Update to limits to growth – Comparing the World3 model with empirical data. *Journal of Industrial Ecology* 25, pp: 614-626.

Hertel, T. (Ed.) (1997) Global Trade Analysis: Modeling and applications. Cambridge University Press. New York.

Hertel. T. (2011). The Global Supply and Demand for Agricultural Land in 2050: A Perfect Storm in the Marking? *American Journal of Agricultural Economics* 93(2), pp: 259-275.

Hertel, T. & Baldos, U. (2016). Global Change and the Challenges of Sustainably Feeding a Growing Planet. Springer. Switzerland.

Hertel, T., Steinbuks, J. & Baldos, U. (2013). Competition for land in the global bioeconomy. *Agricultural Economics* 44(1), pp: 129-138.

Houlbrooke, D.J., Horne, D.J., Hedley, M.J., Hanly, J.A., & Snow, V.O. (2004) A review of literature on the land treatment of farm-dairy effluent in New Zealand and its impact on water quality, *New Zealand Journal of Agricultural Research* 47(4), pp: 499-511.

Huffman, W. & Evenson, R. (1996). Do formula or competitive grant funds have greater impacts on state agricultural productivity? *American Journal of Agricultural Economics* 88(4), pp: 783-793.

Ianchovichina, E & McDougall, R. (2001). Structure of Dynamic GTAP. GTAP Technical Paper No. 17.

International Monetary Fund [IMF] (2019). World Economic Outlook Database October 2019 Edition. Accessed from: https://www.imf.org/external/pubs/ft/weo/2019/02/weodata/index.aspx

International Monetary Fund [IMF] (2020). World Economic Outlook Database October 2020 Edition. Accessed from: https://www.imf.org/en/Publications/WEO/weo-database/2020/October

Interim Climate Change Committee [ICCC] (2019). Action on agricultural emissions: Evidence, analysis and recommendations.

International Energy Agency [IEA] (2016). Renewables information. IEA, Paris.

International Energy Agency [IEA] (2019). World Energy Statistics 2019, IEA, Paris.

International Labour Organization [ILO] (2020). ILOSTAT: Labour costs. Accessed from: https://ilostat.ilo.org/topics/labour-costs/

Intergovernmental Panel on Climate Change [IPCC] (2007). Climate change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Pachauri, R. & Reisinger, A. (eds). IPCC, Geneva.

Intergovernmental Panel on Climate Change [IPCC] (2019). Chapter 5: Food Security. Mbow, C. & Rosenweig, C. (coordinating lead authors)]. In Climate Change and Land. IPCC, Geneva, Switzerland. pp: 690-924.

Jablonski, L., Wang, X. & Curtis, P. (2002). Plant reproduction under elevated CO_2 conditions: a meta-analysis of reports on 79 crop and wild species. *New Phytologist* 156(1), pp: 9-26.

Jaffe, A. (1988). Demand and Supply Influences in R&D Intensity and Productivity Growth. *The Review of Economics and Statistic* 70(3), pp: 431-437.

Jansson, T., Kuiper, M. & Adenäuer, M. (2009). Linking CAPRI and GTAP, SEAMLESS Report 39, SEAMLESS integrated project, EU 6th Framework Programme, contract no. 010036-2.

Keeney R. & Hertel, T. (2005). GTAP-AGR: A Framework for assessing the implications of multilateral changes in agricultural policies. GTAP Technical Papers No. 24.

Kendrick, J. (1973). Productivity Trends. *Business Economics* 8(1), pp: 56-61.

Korhonen, J., Honkasalo, A. & Seppälä, J. (2018). Circular Economy: The Concept and its Limitations. *Ecological Economics* 143, pp: 37-46.

Lee, H., Hertel, T., Sohngen, B. & Ramankutty, N. (2005). Towards An Integrated Land Use Data Base for Assessing the Potential for Greenhouse Gas Mitigation. GTAP Technical Paper No. 25.

Leip, A., Britz, W., Weiss, F. & de Vries, W. (2011). Farm, land, and soil nitrogen budgets for agriculture in Europe calculated with CAPRI. *Environmental Pollution* 159, pp: 3243-3253.

Licker, R., Johnston, M., Foley, J., Barford, C., Kucharik, C., Monfreda, C. & Ramankuty, N. (2010). Mind the gap: how do climate and agricultural management explain the ‘yield gap’ of croplands around the world? *Global Ecology and Biogeography* 19, pp. 769-782.

Lobell, D., Baldos, U. & Hertel, T. (2013). Climate adaptation as mitigation: The case of agricultural investments. *Environmental Research Letters* 8, pp: 15-28.

Lobell, D., Cassman, K. & Field, C. (2009). Crop Yield Gaps: Their Importance, Magnitudes and Causes. *Annual Review of Environment and Resources* 34, pp: 179-204.

Lobell, D. & Gourdji, S. (2012). The Influence of Climate Change on Global Crop Productivity. *Plant Physiology* 160, pp: 1686-1697

Lotze-Campen, H., von Lampe, M., Kyle, P., Fujimori, S., Havlik, P., van Meijl, H., Hasegawa, T., Popp, A., Schmitz, C., Tabeau, A., Valin, H., Willenbockel, D. & Wise, M. (2014). Impacts of increased bioenergy demand on global food markets: an AGMIP economic model intercomparison. *Agricultural Economics* 45(1), pp: 103-116.

Malhi, Y., Timmons, J., Betts, R., Kileen, T., Wenhong, L. & Nobre, C. (2008). Climate Change, Deforestation, and the Fate of the Amazon. *Science: New Series* 319 (5860), pp: 169-172.

Malthus, T. (1798). An Essay on the Principle of Population as it Affects the Future Improvement of Society with Remarks on the Speculations of Mr. Godwin, M. Condorcet, and Other Writers. London.

Mann, M., Rahmstorf, S., Kornhuber, K., Steinman, B., Miler, S. & Coumou, D. (2017). Influence of Anthropogenic Climate Change on Planetary Wave Resonance and Extreme Weather Events. *Scientific Reports* 7, pp: 1-10.

Meadows, D., Meadows, D., Randers, J. & Meadows, D. (1972). Limits to Growth. Earthscan, London.

Meadows, D., Randers, J. & Meadows, D. (2005). Limits to Growth: The 30-year Update. Earthscan, London.

Mendelsohn, R., Nordhaus, W., & Shaw, D. (1994). The Impact of Global Warming on Agriculture: A Ricardian Analysis. *The American Economic Review* 84 (4), pp: 753-771.

Muhammed, A., Seale, J., Meade, B. & Regmi, A. (2011). International Evidence on Food Consumption Patterns: An Update Using 2005 International Comparison Program Data. U.S. Department of Agriculture, Economic Research Service Technical Bulletin 1929, (Revised 2013).

Muller, C. & Robertson, R. (2014). Projecting future crop productivity for global economic modelling. *Agricultural Economics* 45(1), pp: 37-50.

Narayanan B., Hertel, T. & Horridge, J. (2010). Linking Partial and General Equilibrium Models: A GTAP Application Using TASTE. GTAP Technical Paper No. 29.

Nelson, G., Rosegrant, M., Koo, J., Roberston, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., Magalhaes, M., Valmonte-Santos, R., Ewing, M. & Lee, D. (2009). Climate Change: Impact on Agriculture and Cost of Adaptation. International Food Policy Research Institute Food Policy Report.

Nelson, G., van der Mensbrugghe, D., Ahammad, H., Blanc, E., Calvin, K., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., von Lampe, M., Mason d'Croz, D., van Meji, H., Muller, C., Reilly, J., Robertson, R., Sands, R., Schmitz, C., Tabeau, A., Takahashi, K., Valin, H. & Willenbock, D. (2014). Agiculture and climate change in global scenarios: why don't the models agree. *Agricultural Economics* 45(1), pp: 85-101.

Neumann, K., Verburg, P., Stehfest, E. & Muller, C. (2010). The yield gap of global grain production: A spatial analysis. Agricultural Systems 103(5), pp: 316-326.

Nguyen, T. & Scrimgeour, F. (2019). Heterogenous Impacts of Climate Change – The Ricardian Approach Using Vietnam Micro-Level Panel Data. Paper presented to the NZARES conference, 29-30 August, Hamilton, New Zealand.

O'Brien, P., & De La Escosura, L. (1992). Agricultural productivity and European industrialization, 1890-1980. *Economic History Review* 45(3), pp: 514-536.

Ohlin, B. (1933). Interregional and International Trade. Harvard University Press, Cambridge.

O'Neill, B., Kriegler, E., Riahi, K., Ebi, K., Hallegatte, S., Carter, T., Mathur, R. & van Vuuren, D. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climate Change* 122, pp: 387-400.

Organisation for Economic Co-operation and Development [OECD] (2014). OECD Science, Technology and R&D Statistics. Accessed from: https://www.oecd-ilibrary.org/science-and-technology/data/oecd-science-technology-and-r-d-statistics_strd-data-en

Organisation for Economic Co-operation and Development [OECD] (2015). Aglink-Cosimo Model Documentation: A partial equilibrium model of world agricultural markets. OECD Publishing, Paris. Accessed from: http://www.agri-outlook.org/about/Aglink-Cosimo-model-documentation-2015.pdf

Organisation for Economic Co-operation and Development [OECD] (2016). Alternative Futures for Global Food and Agriculture. OECD Publishing, Paris.

Organisation for Economic Co-operation and Development – Food and Agriculture Organizations of the United Nations [OECD-FAO] (2016). OECD-FAO Agricultural Outlook 2016-2025. OECD Publishing, Paris. Paris/Food and Agriculture Organization of the United Nations Accessed from: http://dx.doi.org/10.1787/agr_outlook-2016-en

Organisation for Economic Co-operation and Development – Food and Agriculture Organizations of the United Nations [OECD-FAO] (2017). OECD-FAO Agricultural Outlook 2017-2026. OECD Publishing, Paris/Food and Agriculture Organization of the United Nations, Paris. Accessed from: https://doi.org/10.1787/agr_outlook-2017-en

Organisation for Economic Co-operation and Development – Food and Agriculture Organizations of the United Nations [OECD-FAO] (2018). OECD-FAO Agricultural Outlook 2018-2027. OECD Publishing, Paris/Food and Agriculture Organization of the United Nations, Rome. Accessed from: https://doi.org/10.1787/agr_outlook-2018-en

Organisation for Economic Co-operation and Development – Food and Agriculture Organizations of the United Nations [OECD-FAO] (2019a). OECD-FAO Agricultural Outlook 2019-2028. OECD Publishing, Paris/Food and Agriculture Organization of the United Nations, Rome. Accessed from: https://doi.org/10.1787/agr_outlook-2019-en.

Organisation for Economic Co-operation and Development – Food and Agriculture Organizations of the United Nations [OECD-FAO] (2019b). OECD Statistics database: OECD-FAO Agricultural Outlook 2019-2028. Accessed from: https://stats.oecd.org/

Organisation for Economic Co-operation and Development – Food and Agriculture Organizations of the United Nations [OECD-FAO] (2021). OECD Statistics database: OECD-FAO Agricultural Outlook 2021-2030. Accessed from: https://stats.oecd.org/

Oenema, O., Witzke, H., Klimont, Z., Lesschen, J. & Velthof, G. (2009). Integrated assessment of promising measures to decrease nitrogen losses from agriculture in EU-27. Agriculture, *Ecosystems and Environment* 113, pp: 280-288.

O’Neill, B., Kriegler, E., Ebi, K., Kemp-Benedict, E., Riahi, K., Rothman, D., van Ruijven, B., van Vuuren, D., Birkmann, J., Kok, K., Levy, M. & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change* 42, pp: 169-180.

Ott, H. (2014). Extent and possible causes of intrayear agricultural commodity price volatility. *Agricultural Economics* 45, pp: 225-252.

Parry, M., Rosenzweig, C., Iglesias, A., Livermore, M. & Fischer, G. (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change* 14, pp: 53-67.

Pardey, P., Alston, J. & Chan-Kang, C. (2013). Public agricultural R&D over the past half century: an emerging new world order. *Agricultural Economics* 44, pp: 103-113.

Pardey, P., Craig, B. & Hallaway, M. (1989). U.S. agricultural research deflators: 1890-1985. *Research Policy* 18(5), pp: 298-296.

Peterson, W. (1988). International supply response, *Agricultural Economics* 2(4), pp: 365-374.

Peterson, E. (2017). The Role of Population in Economic Growth. *SAGE Open,* pp: 1-15.

Porfirio, L., Newth, D., Cai, Y. & Finnigan, J. (2017). Economic shifts in agricultural production and global trade from climate change: Technical report. CSIRO Climate Science Centre. Australia.

Porter, J., Xie, L., Challinor, A., Cochrane, K., Howden, S., Iqbal, M. & Travasso, M. (2014). Food security and food production systems. In Climate Change 2014: Impacts, Adaption, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C., Barros, V., Dokken, D., Mach, K., Mastrandrea, M., Bilir, T., Chatterjee, M., Ebi, K., Estrada, Y., Genova, R., Girma, B., Kissel, E., Levy, A., MacCracken, S., Mastrandrea, P. & White, L. (Eds.)]. Cambridge University Press, Cambridge and New York, pp: 485-533.

PricewaterhouseCoopers [PWC] (2017). The Long View: How will the global economic order change by 2050? PWC.

Ramankutty, N., Foley, J., Norman, J. & McSweeney, K. (2002). The Global Distribution of Cultivable Lands: Current Patterns and Sensitivity to Possible Climate Change. *Global Ecology and Biogeography* 11(5), pp: 377-392.

Raworth, K. (2017). Doughnut Economics: Seven Ways to Think Like a 21st Century Economist. Random House Business Books, London, UK.

Reidsma, P., Ewert, F. & Lansick, A. (2007). Analysis of farm performance in Europe under different climatic and management conditions to improve understanding of adaptive capacity. *Climatic Change* 84, pp: 403-442.

Reilly, J., Baethgen, W., Chege, F., van de Geijn, S., Erda, L., Iglesias, A., Kenny, G., Patterson, D., Rogasik, J., Rotter, R., Rosenzweig, C., Somboek, W. & Westbrook, J. (1996). Agriculture in a changing climate: Impacts and adaptations. In Climate Change 1995: Intergovernmental Panel on Climate Change Impacts, Adaptations, and Mitigation of Climate Change [Watson, R., Zinyowera, M., Moss, R. & Dokken, D. (eds)], pp: 427–468. Cambridge University Press.

Revell, B., Saunders, J. & Saunders, C. (2014). Assessing the Environmental Impact of Liberalising Agricultural Trade – With Special Reference to EU-Mercosur. Contributed Paper to the 8th Annual Conference of the Agricultural Economics Society, Paris, France.

Riahi, K., van Vuuren, D., Kriegler, E., Edmonds, J., O'Neill, B., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S. & Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 42, pp: 153-168.

Ricardo, D. (1817). Principles of Political Economy and Taxation. London.

Robinson, S., van Mejil, H., Willenbockel, D., Valin, H., Fujimori, S., Masui, T., Kavallari, A., Schmitz, C., Dietrich, J. & von Lampe, M. (2014). Comparing supply-side specifications in models of global agriculture and the food system. *Agricultural Economics* 45(1), pp: 21-35.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F., Lambin, E., Lenton, T., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R., Fabry, V., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. & Foley J. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society* 14(2): 32.

Rosenzweig, C., Elliot, J., Deryng, D., Ruane, A., Müller, C., Arneth, A., Boote, K., Folberth, C., Glotter M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T., Schmid, E., Stehfest, E., Yang, H. & Jones, J. (2014). Assessing the agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *PNAS* 111(9), pp: 3268-3273.

Saunders, C., Cagatay, S. & Moxey, A. (2004). Trade and the environment: Economic and environment impacts of global dairy trade liberalisation. AERU Research Report 366. Lincoln.

Saunders, C., Kaye-Blake, W. & Turner, J. (2009). Modelling Climate Change Impacts on Agriculture and Forestry with the extended LTEM (Lincoln Trade and Environmental Model). AERU Research Report 316. Lincoln, New Zealand.

Saunders, J., Adenauer, M. & Brooks, J. (2019). Analysis of long-term challenges for agricultural markets. OECD Food, Agriculture and Fisheries Papers no. 131, OECD Publishing, Paris.

Schmitz, C., van Meijl, H., Kyle, P., Nelson, G., Fujimori, S., Gurgel, A., Havlik, P., Heyhoe, E., Mason d'Croz, D., Popp, A., Sands, R., Tabeau, A., van der Mensbrugghe, D., von Lampe, M., Wise, M., Blanc, E., Hasegawa, T., Kavallari, A. & Valin, H. (2014). Land-use change trajectories up to 2050: insights from a global agro-economic model comparison. *Agricultural Economics* 45(1), pp: 69-84.

Schultz, T. (1956). Reflections on Agricultural Production, Output and Supply. *Journal of Farm Economics* 38(4), pp: 748-762.

Schneider, U., Havlik P., Schmid, E., Valin, H., Mosnier, A., Obersteiner, M., Bottcher, H., Skalsk ý, R., Balkovič, J., Sauer, T. & Fritz, S. (2011). Impacts of population growth, economic development, and technical change on global food production and consumption. *Agricultural Systems* 104(2), pp: 204-215.

Seale, J., Regmi, A. & Bernstein, J. (2003). International Evidence on Food Consumption Patterns. U.S. Department of Agriculture, Economic Research Service Technical Bulletin 1904.

Seale, J. & Regmi, A. (2006). Modelling international consumption patterns. *Review of Income and Wealth* 52(4), pp: 603-624.

Sheng, Y., Song, L. & Yi, Q. (2017). Mechanisation Outsourcing and Agricultural Productivity for Small Farms: Implications for Rural Land Reform in China. In China's New Sources of Economic Growth, Song, L., Garnaut, R., Fang, C. & Johnston, L. (Eds.). ANU Press. pp: 289-313.

Shrestha, S., Ciaian, P., Himics, M. & van Doorslaer, B. (2013). Impacts of Climate Change on EU Agriculture. *Review of Agricultural and Applied Economics* 16(2), pp: 24-39.

Smith, A. (1776). The Wealth of Nations. Oxford.

Solow, R. (1956). A Contribution to the Theory of Economic Growth. *The Quarterly Journal of Economics* 70(1), pp: 65-94.

Solow, R. (1957). Technical Change and the Aggregate Production Function. *The Review of Economics and Statistics* 39(3), pp: 312-320.

Solow, R. (1973). Is the end of the world at hand? *Challenge* 16, pp: 39-50.

Spratt, S. (2013). Food price volatility and financial speculation. Future Agricultures Consortium Working Paper 47.

Stehfest, E., van Vuuren, D., Karm, T. & Bouwman, L (Eds.) (2014). Integrated Assessment of Global Environmental Change with IMAGE 3.0 Model description and policy applications. PBL Netherland Environmental Assessment Agency, publication no. 735.

Tamminga, S. (2003). Pollution due to nutrient losses and its control in European animal production. *Livestock Production Science* 84, pp: 101-111.

Thornton, P. (2010). Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B* 365, pp: 2853-2867.

Timsina, J. & Connor, D. (2001). Productivity and Management of Rice-Wheat Cropping Systems: Issues and Challenges. *Journal of Field Crops Research* 59, pp: 93-132.

Tobey, J., Reilly, J. & Kane, S. (1992). Economic Implications of Global Climate Change for World Agriculture. *Journal of Agricultural and Resource Economics* 17(1), pp: 195-204.

The United Nations Educational, Scientific and Cultural Organization [UNESCO] (2019). Science, technology and innovation database. Accessed from: http://data.uis.unesco.org/index.aspx?queryid=77

United Nations, Department of Economic and Social Affairs, Population Division [UNDESA] (2017). World Population Prospects: The 2017 Revision, Volume I: Comprehensive Tables (ST/ESA/SER.A/399).

United Nations, Department of Economic and Social Affairs, Population Division [UNDESA] (2019a). World Population Prospects 2019, Volume I: Comprehensive Tables (ST/ESA/SER.A/426).

United Nations, Department of Economic and Social Affairs, Population Division [UNDESA] (2019b). World Population Prospects 2019, Data Booklet (ST/ESA/SER.A/424).

De Vries, W., Leip, A., Reinds, G., Kros, J., Lesschen. J. & Bouwman, A. (2011). Comparison of land nitrogen budgets for European agriculture by various modelling approaches. *Environmental Pollution* 159, pp: 3243-3268.

Valin, H., Havlik, P., Forsell, N., Frank, S., Mosnier, A., Peters, D., Hamelinck, C., Spottle, M. & van der Berg, M. (2013). Description of the GLOBIOM (IIASA) model and comparison with the MIRAGE-BioF (IFPRI) model. EC project project ENER/C1/438-2012 – Lot 2.

Valin, H., Sands, R., van der Mensbrugghe, D., Nelson, G., Ahammad, H., Blanc, E., Bordirsky, B., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Mason-D'Croz, D., Paltsev, S., Rolinski, S., Tabeau, A., van Meijl, H., von Laampe, M. & Willenbockel, D. (2014). The future of food demand: understanding differences in global economic models. *Agricultural Economics* 45, pp: 51-67.

Von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason d'Croz, D., Nelson, G., Sands, R., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D. & van Mejil, H. (2014). Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agricultural Economics* 45(1), pp: 3-20.

Voorburg, J.H. (1991). Pollution by animal production in the Netherlands: solutions. *Revue scientifique et technique* 10(3), pp: 655-668.

van Vuuren, D., Kriegler, E., O'Neill, B., Ebi, K., Riahi, K., Carter, T., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R. & Winker, H. (2014). A new scenario framework for Climate Change Research: scenario matrix architecture. *Climate Change* 122, pp: 373-386.

Watanabe, M., Shiogama, H., Imada, Y., Mori, M., Ishii, M. & Kimoto, M. (2013). Event Attribution of the August 2010 Russian Heat Wave. *SOLA* 9, pp: 65–68.

Weiss, F. & Leip, A. (2012). Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. Agriculture, *Ecosystems and Environmen*t 149, pp: 124-134.

Wegren, S. (2011). Food Security and Russia's 2010 Drought. *Eurasian Geography and Economics* 52(1), pp: 140-156.

Weissleder, L., Adenäuer, M. & Hecklei, T. (2008). Impact assessment of trade liberalisation between EU and Mercosur countries. Presented at the 107th European Seminar of the EAAE, Seville. Jan. 29-Feb. 1.

Williams, J., Jones, C., Kiniry, J. & Spanel, D. (1989). The EPIC Crop Growth Model. *Transactions of the ASAE* 32(2), pp: 497-511

Wieck, C., Britz, W., Hecklei, T., Junker, F. & Perez, I. (2005). How Sustainable is the Latest CAP Reform under Possible Trade Liberalisation Outcomes of the Doha Round? Presented at the IATRC Summer Symposium, Seville. Jun. 19-21.

Wise, M. & Calvin, K. (2011). GCAM 3.0 Agriculture and Land Use: Technical Description of Modelling Approach. Pacific Northwest National Laboratory.

World Bank (2003). World Development Indicators 2003. Washington. Accessed from: http://hdl.handle.net/10986/13920

World Bank (2009). Awakening Africa's Sleeping Giant: Prospects for Commercial Agriculture in the Guinea Savannah Zone and Beyond. Washington. Accessed from: https://openknowledge.worldbank.org/handle/10986/2640

World Bank (2020a). World Development Indicator DataBank. Accessed from: https://databank.worldbank.org/source/world-development-indicators

World Bank (2020b). Global Economic Prospects, June 2020. Washington D.C. Accessed from: http://hdl.handle.net/10986/33748

World Bank (2022). World Development Indicator DataBank. Accessed from: https://databank.worldbank.org/source/world-development-indicators

World Trade Organization [WTO] (2022). Regional Trade Agreements Information System (RTA-IS): Evolution of RTAs, 1948-2022. Accessed from: http://rtais.wto.org/UI/PublicMaintainRTAHome.aspx

Ye, Y., Cochrane, K., Bianchi, G., Willmann, R., Majkowski, J., Tandstad, M. & Carocci, F. (2012). Rebuilding global fisheries: the World Summit Goal, costs and benefits. *Fish and Fisheries* 14(2), pp: 174-185.

Yee, J. & Huffman, W. (2001). Rates of Return to Public Agricultural Research in the Presence of Research Spillovers. Presented at the American Agricultural Economics Association Meetings, Chicago, Illinois. Aug. 5-8.

Appendix

Table X1: Country composition of regional groups in the LAO model

EuCA - Europe & Central Asia			
Albania	Austria	Belarus	Greece
Bosnia and Herzegovina	Germany	Belgium-Luxembourg	France
Czech Republic	Bulgaria	Croatia	Denmark
Estonia	Faroe Islands	Finland	Czechoslovakia
Belgium	Hungary	Iceland	Ireland
Italy	Kazakhstan	Kyrgyzstan	Latvia
Liechtenstein	Lithuania	Luxembourg	Malta
Montenegro	Netherlands	Norway	Poland
Portugal	Republic of Moldova	Romania	Russian Federation
Serbia	Serbia and Montenegro	Slovakia	Slovenia
Spain	Sweden	Switzerland	Tajikistan
The former Yugoslav Republic of Macedonia	Turkmenistan	Ukraine	United Kingdom
USSR	Uzbekistan	Yugoslav SFR	
OcSEA -Oceania & South-East Asia			
American Samoa	Australia	Brunei Darussalam	New Caledonia
Fiji	Nauru	Cook Islands	Myanmar
Indonesia	French Polynesia	Guam	Lao People's Democratic Republic
Malaysia	Marshall Islands	Micronesia (Federated States of)	Kiribati
Cambodia	New Zealand	Niue	Pacific Islands Trust Territory
Papua New Guinea	Philippines	Samoa	Singapore
Solomon Islands	Thailand	Timor-Leste	Tokelau
Tonga	Tuvalu	Vanuatu	Viet Nam
Wallis and Futuna Islands			
NoAWA -North Africa & West Asia			
Algeria	Armenia	Azerbaijan	Oman
Egypt	Occupied Palestinian Territory	Cyprus	Morocco
Iraq	Georgia	Iran (Islamic Republic of)	Jordan
Kuwait	Lebanon	Libya	Israel
Bahrain	Qatar	Saudi Arabia	Sudan (former)
Syrian Arab Republic	Tunisia	Turkey	United Arab Emirates
Western Sahara	Yemen		

LaC - Latin America & Caribbean			
Antigua and Barbuda	Argentina	Bahamas	El Salvador
Bolivia (Plurinational State of)	Ecuador	Belize	Dominican Republic
Cayman Islands	Brazil	British Virgin Islands	Colombia
Costa Rica	Cuba	Dominica	Chile
Barbados	Falkland Islands (Malvinas)	French Guiana	Grenada
Guadeloupe	Guatemala	Guyana	Haiti
Honduras	Jamaica	Martinique	Mexico
Montserrat	Netherlands Antilles	Netherlands Antilles (former)	Nicaragua
Panama	Paraguay	Peru	Puerto Rico
Saint Kitts and Nevis	Saint Lucia	Saint Vincent and the Grenadines	Suriname
Trinidad and Tobago	United States Virgin Islands	Uruguay	Venezuela (Bolivarian Republic of)
NoA -North America			
Bermuda	Canada	Greenland	Saint Pierre and Miquelon
United States of America			
SA -South Asia			
Afghanistan	Bangladesh	Bhutan	China
China, Hong Kong SAR	China, Macao SAR	China, mainland	China, Taiwan Province of
Democratic People's Republic of Korea	India	Japan	Maldives
Mongolia	Nepal	Pakistan	Republic of Korea
Sri Lanka			
SsA - Sub-Saharan Africa			
Angola	Benin	Botswana	Burkina Faso
Burundi	Cabo Verde	Cameroon	Central African Republic
Chad	Comoros	Congo	Côte d'Ivoire
Democratic Republic of the Congo	Djibouti	Equatorial Guinea	Eritrea
Ethiopia	Ethiopia PDR	Gabon	Gambia
Ghana	Guinea	Guinea-Bissau	Kenya
Lesotho	Liberia	Madagascar	Malawi
Mali	Mauritania	Mauritius	Mozambique
Namibia	Niger	Nigeria	Réunion
Rwanda	Saint Helena, Ascension and Tristan da Cunha	Sao Tome and Principe	Senegal
Seychelles	Sierra Leone	Somalia	South Africa
Swaziland	Togo	Uganda	United Republic of Tanzania
Zambia	Zimbabwe		

Table X2: Composition of ‘Crop’ commodity in LAO

Primary Crop Products			
Agave fibres nes	Almonds, with shell	Anise, badian, fennel, coriander	Apples
Apricots	Areca nuts	Artichokes	Asparagus
Avocados	Bambara beans	Bananas	Barley
Bastfibres, other	Beans, dry	Beans, green	Berries nes
Blueberries	Brazil nuts, with shell	Broad beans, horse beans, dry	Buckwheat
Cabbages and other brassicas	Canary seed	Carobs	Carrots and turnips
Cashew nuts, with shell	Cashewapple	Cassava	Cassava leaves
Castor oil seed	Cauliflowers and broccoli	Cereals, nes	Cherries
Cherries, sour	Chestnut	Chick peas	Chicory roots
Chillies and peppers, dry	Chillies and peppers, green	Cinnamon (canella)	Cloves
Cocoa, beans	Coconuts	Coffee, green	Coir
Cow peas, dry	Cranberries	Cucumbers and gherkins	Currants
Dates	Eggplants (aubergines)	Fibre crops nes	Figs
Flax fibre and tow	Fonio	Fruit, citrus nes	Fruit, fresh nes
Fruit, pome nes	Fruit, stone nes	Fruit, tropical fresh nes	Garlic
Ginger	Gooseberries	Grain, mixed	Grapefruit (inc. pomelos)
Grapes	Groundnuts, with shell	Gums, natural	Hazelnuts, with shell
Hemp tow waste	Hempseed	Hops	Jojoba seed
Jute	Kapok fibre	Kapok fruit	Kapokseed in shell
Karite nuts (sheanuts)	Kiwi fruit	Kola nuts	Leeks, other alliaceous vegetables
Lemons and limes	Lentils	Lettuce and chicory	Linseed
Lupins	Maize	Maize, green	Mangoes, mangosteens, guavas
Manila fibre (abaca)	MatÃ	Melons, other (inc.cantaloupes)	Melonseed
Millet	Mushrooms and truffles	Mustard seed	Nutmeg, mace and cardamoms
Nuts, nes	Oats	Oil palm fruit	Oilseeds nes
Okra	Olives	Onions, dry	Onions, shallots, green
Oranges	Papayas	Peaches and nectarines	Pears
Peas, dry	Peas, green	Pepper (piper spp.)	Peppermint
Persimmons	Pigeon peas	Pineapples	Pistachios
Plantains and others	Plums and sloes	Poppy seed	Potatoes
Pulses, nes	Pumpkins, squash and gourds	Pyrethrum, dried	Quinces
Quinoa	Ramie	Rapeseed	Raspberries
Rice, paddy	Roots and tubers, nes	Rubber, natural	Rye
Safflower seed	Seed cotton	Sesame seed	Sisal
Sorghum	Soybeans	Spices, nes	Spinach
Strawberries	String beans	Sugar beet	Sugar cane
Sugar crops, nes	Sunflower seed	Sweet potatoes	Tallowtree seed
Tangerines, mandarins, clementines, satsumas	Taro (cocoyam)	Tea	Tobacco, unmanufactured
Tomatoes	Triticale	Tung nuts	Vanilla
Vegetables, fresh nes	Vegetables, leguminous nes	Vetches	Walnuts, with shell
Watermelons	Wheat	Yams	Yautia (cocoyam)

Table X3: Composition of Livestock commodities in LAO model

Primary livestock products			
Beeswax	Eggs, hen, in shell	Eggs, other bird, in shell	Honey, natural
Meat, ass	Meat, bird nes	Meat, buffalo	Meat, camel
Meat, cattle	Meat, chicken	Meat, duck	Meat, game
Meat, goat	Meat, goose and guinea fowl	Meat, horse	Meat, mule
Meat, nes	Meat, other camelids	Meat, other rodents	Meat, pig
Meat, rabbit	Meat, sheep	Meat, turkey	Milk, whole fresh buffalo
Milk, whole fresh camel	Milk, whole fresh cow	Milk, whole fresh goat	Milk, whole fresh sheep
Offals, nes	Silk-worm cocoons, reelable	Snails, not sea	

Table X4: Sum of Square Errors and adjusted R squared for gamma lag fit

SSE		λ			
		0.7	0.8	0.85	0.9
δ	0.65	2.97	2.23	1.86	1.51
	0.7	2.70	1.98	1.64	1.33
	0.75	2.37	1.70	1.40	1.15
Adjusted R^2		λ			
		0.7	0.8	0.85	0.9
δ	0.65	0.978	0.984	0.986	0.989
	0.7	0.980	0.986	0.988	0.990
	0.75	0.983	0.988	0.990	0.992

NB: colour indicates selected parameters

Table X5: Spill-over proportion of R&D between regions for crop products

	Spill-over from regions						
	Europe & Central Asia	Oceania & South-East Asia	North Africa & West Asia	Latin America & the Caribbean	North America	South Asia	Sub-Saharan Africa
Europe & Central Asia		0.111	0.775	0.256	0.532	0.435	0.216
Oceania & South-East Asia	0.111		0.204	0.265	0.136	0.814	0.373
North Africa & West Asia	0.775	0.204		0.231	0.336	0.516	0.218
Latin America & the Caribbean	0.256	0.265	0.231		0.653	0.366	0.329
North America	0.532	0.136	0.336	0.653		0.360	0.331
South Asia	0.435	0.814	0.516	0.366	0.360		0.400
Sub-Saharan Africa	0.216	0.373	0.218	0.329	0.331	0.400	

Table X6: Spill-over proportion of R&D between regions for ruminant products

	Spill-over from regions						
	Europe & Central Asia	Oceania & South-East Asia	North Africa & West Asia	Latin America & the Caribbean	North America	South Asia	Sub-Saharan Africa
Europe & Central Asia		0.889	0.974	0.795	0.929	0.957	0.807
Oceania & South-East Asia	0.889		0.913	0.962	0.976	0.943	0.977
North Africa & West Asia	0.974	0.913		0.784	0.904	0.979	0.847
Latin America & the Caribbean	0.795	0.962	0.784		0.962	0.850	0.963
North America	0.929	0.976	0.904	0.962		0.940	0.938
South Asia	0.957	0.943	0.979	0.850	0.940		0.898
Sub-Saharan Africa	0.807	0.977	0.847	0.963	0.938	0.898	

Table X7: Spill-over proportion of R&D between regions for non-ruminant products

	Spill-over from regions						
	Europe & Central Asia	Oceania & South-East Asia	North Africa & West Asia	Latin America & the Caribbean	North America	South Asia	Sub-Saharan Africa
Europe & Central Asia		0.958	0.526	0.750	0.909	0.918	0.712
Oceania & South-East Asia	0.958		0.704	0.882	0.968	0.853	0.801
North Africa & West Asia	0.526	0.704		0.939	0.804	0.367	0.780
Latin America & the Caribbean	0.750	0.882	0.939		0.950	0.566	0.818
North America	0.909	0.968	0.804	0.950		0.750	0.812
South Asia	0.918	0.853	0.367	0.566	0.750		0.585
Sub-Saharan Africa	0.712	0.801	0.780	0.818	0.812	0.585	

Table X8: Own-price demand elasticities in the LAO model

		Europe & Central Asia	Oceania & South-East Asia	North Africa & West Asia	Latin America & the Caribbean	North America	South Asia	Sub-Saharan Africa
Feed Use	Crop	-0.25	-1.48	-1.44	-0.04	-1.37	-1.66	-0.12
	Ruminant animals	-0.30	-1.74	-0.23				0.66
	Non-ruminant animals	-0.30	-0.51		-1.74			-0.52
	Fish from Aquaculture	-0.73	-0.64		-0.45	-0.63	-0.06	
	Fish from Capture							
Food Use	Crop	-0.29	-0.35	-0.33	-0.31	-0.21	-0.36	-0.42
	Ruminant animals	-0.40	-0.51	-0.51	-0.50	-0.26	-0.55	-0.57
	Non-ruminant animals	-0.40	-0.50	-0.50	-0.50	-0.26	-0.54	-0.56
	Fish from Aquaculture	-0.30	-0.44	-0.42	-0.40	-0.20	-0.31	-0.48
	Fish from Capture	-0.30	-0.44	-0.42	-0.40	-0.20	-0.31	-0.48
Waste & Other Uses	Crop	-0.29	-0.35	-0.33	-0.31	-0.21	-0.36	-0.42
	Ruminant animals	-0.40	-0.51	-0.51	-0.50	-0.26	-0.55	-0.57
	Non-ruminant animals	-0.40	-0.50	-0.50	-0.50	-0.26	-0.54	-0.56
	Fish from Aquaculture							
	Fish from Capture	-0.30	-0.44	-0.42	-0.40	-0.20	-0.31	-0.48
Biofuel Use	Crop	-0.29	-0.35	-0.33	-0.31	-0.21	-0.36	-0.42
	Ruminant animals							
	Non-ruminant animals							
	Fish from Aquaculture							
	Fish from Capture							

Table X9: Cross-price demand elasticities in the LAO model

		Europe & Central Asia	Oceania & South-East Asia	North Africa & West Asia	Latin America & the Caribbean	North America	South Asia	Sub-Saharan Africa
Crop	Ruminant animals	0.15		0.51	0.30	0.21	0.17	
	Non-ruminant animals			-0.18			0.17	
	Fish from Aquaculture	0.14	0.17					0.45
	Fist from Capture		0.18					
Ruminant animals	Crop	0.15	-1.05	0.51	0.30	0.21	0.17	
	Non-ruminant animals	0.55	1.56		0.35	0.26		0.33
	Fish from Aquaculture	-0.29				-0.10	0.37	
	Fist from Capture				-0.15	-0.10		0.24
Non-ruminant animals	Crop			-0.18			0.17	
	Ruminant animals	0.55	1.56		0.35	0.26		0.33
	Fish from Aquaculture		-1.05	0.35				
	Fist from Capture	-0.15		0.32	0.15		0.37	0.23
Fish from Aquacul.	Crop	0.14	1.22					0.45
	Ruminant animals	-0.29				-0.10	0.37	
	Non-ruminant animals		-1.05	0.35				
	Fist from Capture	0.46	0.26	0.07	0.40	0.30	-0.05	
Fist from Capture	Crop		0.18					
	Ruminant animals				-0.15	-0.10		0.24
	Non-ruminant animals	-0.15		0.32	0.15		0.05	0.23
	Fish from Aquaculture	0.46	0.26	0.07	0.40	0.30	-0.05	

Table X10: Initial income elasticities by commodity and region

	Crops	Ruminant Animals	Non-Ruminant Animals	Fish
EuCA	0.360	0.605	0.591	0.483
OcSEA	0.461	0.672	0.669	0.566
NoAWA	0.432	0.672	0.657	0.542
LaC	0.443	0.702	0.700	0.579
NoA	0.192	0.390	0.357	0.321
SA	0.502	0.665	0.714	0.639
SsA	0.604	0.796	0.785	0.737

Table X11: Parameters of logarithmic income progression

	Crops	Ruminant Animals	Non-Ruminant Animals	Fish
α income	0.636	0.898	0.868	0.735
β income	-0.150	-0.094	-0.091	-0.086

Table X12: Own-price supply elasticities in the LAO model

	Europe & Central Asia	Oceania & South-East Asia	North Africa & West Asia	Latin America & the Caribbean	North America	South Asia	Sub-Saharan Africa
Crop	0.89	1.50	0.80	0.80	1.75	1.75	1.41
Ruminant animals	0.40	1.45	1.20	0.55	1.30	0.64	0.62
Non-ruminant animals	0.90	0.62	0.62	0.64	0.35	0.64	0.62
Fish from Aquaculture	0.38	3.25	1.12	1.41	0.06	0.12	0.00
Fish from Capture	0.38	0.10	0.05	0.10	0.84	0.12	0.03

Table X13: Cross-price supply elasticities in the LAO model

	Crop		Ruminant animals		Non-ruminant animals		Fish from Aquacul.	Fist from Capture
	Ruminant animals	Non-ruminant animals	Crop	Non-ruminant animals	Crop	Ruminant animals	Fist from Capture	Fish from Aquacul.
Europe & Central Asia		-0.8			-0.8			
Oceania & South-East Asia	-0.4		-0.1	-0.6	0.4	0.5	0.0	0.0
North Africa & West Asia		0.6		-1.2	0.3	-0.8	-0.1	-0.1
Latin America & the Caribbean	0.1	0.3	0.2	0.2	0.1	0.3		
North America	-1.6	1.6	-0.4	-0.5	0.7	-1.1	-0.1	-0.1
South Asia				-0.4	0.4	-0.3		
Sub-Saharan Africa		0.4			0.1			

Table X14: Other elasticities in the LAO model

		Europe & Central Asia	Oceania & South-East Asia	North Africa & West Asia	Latin America & the Caribbean	North America	South Asia	Sub-Saharan Africa
Oil Price	Crop	0.00	0.02	0.03	-0.04	-0.02	-0.03	0.07
	Ruminant animals	0.08		0.05	-0.03	-0.05	0.05	0.03
	Non-ruminant animals	0.01	-0.03	0.05	-0.07	-0.10	-0.03	0.00
	Fish from Aquaculture							
	Fish from Capture				-0.06			
Cost index	Crop	-0.95	0.48	0.15	0.13	-1.35	0.63	0.40
	Ruminant animals	-0.20		-0.13	0.04	0.21	-0.15	-0.11
	Non-ruminant animals	-0.12	0.09	-0.13	0.04	0.78	0.03	0.40
	Fish from Aquaculture							
	Fish from Capture							
R&D	Crop	0.2	0.2	0.1	0.1	0.1	-0.2	
	Ruminant animals	0.0	0.2		0.1	0.2	-0.2	0.1
	Non-ruminant animals	0.0	0.2		0.1	0.1	-0.1	
	Fish from Aquaculture							
	Fish from Capture							
R&D spill-overs	Crop	0.1	0.0	0.3	0.3	0.1	0.4	0.2
	Ruminant animals	0.1		0.3	0.3		0.5	0.2
	Non-ruminant animals	0.1	0.1	0.3	0.3	0.2	0.5	0.3
	Fish from Aquaculture							
	Fish from Capture							
Technical growth rate	Crop							
	Ruminant animals							
	Non-ruminant animals							
	Fish from Aquaculture	0.05	0.03	0.04	0.05	0.01	0.01	
	Fish from Capture	0.02	0.02	0.02	0.01	0.04	0.01	0.02

Table X15: Emissions factors for commodities in the LAO model

	Unit (kilotonnes CO2 equivalent)	Europe & Central Asia	Oceania & South-East Asia	North Africa & West Asia	Latin America & the Caribbean	North America	South Asia	Sub-Saharan Africa
Crops	per mil. ha harvested area	5,253.59	11,897.64	3,492.89	5,483.49	215.17	4,034.40	8,270.49
Ruminant animals	per mil. head	1,027.37	7,786.94	424.82	4,162.25	262.26	3,887.93	2,323.14
Non-ruminant animals	per mil. head	161.01	788.49	28.37	734.31	16.77	400.18	811.68
Fish from Aquaculture								
Fish from Capture	per mil. t production	12,039.61	657.52	7,101.54	2,972.73	125.78	2,663.25	21,293.60

Source: FAOSTAT (2019b) & author's own calculations

Table X16: Yield average annual growth rates by region for the RCP scenarios, 2013-2050

		RCP 1.9	RCP 2.6	RCP 3.4	RCP 4.5	RCP 6.0
Crops	EuCA	0.006	0.006	0.005	0.005	0.005
	OcSEA	0.007	0.007	0.008	0.008	0.008
	NoAWA	0.013	0.013	0.009	0.013	0.013
	LaC	0.012	0.012	0.012	0.011	0.011
	NoA	0.006	0.006	0.005	0.006	0.006
	SA	0.009	0.009	0.008	0.009	0.009
	SsA	0.019	0.019	0.019	0.019	0.019
Ruminant Animals	EuCA	0.006	0.000	0.000	0.000	0.000
	OcSEA	0.007	0.005	0.005	0.004	0.004
	NoAWA	0.013	0.002	0.002	0.002	0.002
	LaC	0.012	0.003	0.003	0.003	0.003
	NoA	0.006	0.001	0.001	0.001	0.001
	SA	0.009	0.003	0.003	0.003	0.003
	SsA	0.019	0.004	0.004	0.004	0.004
Non-Ruminant Animals	EuCA	0.006	0.000	0.000	0.000	0.000
	OcSEA	0.007	0.005	0.005	0.004	0.004
	NoAWA	0.013	0.002	0.002	0.002	0.002
	LaC	0.012	0.003	0.003	0.003	0.003
	NoA	0.006	0.001	0.001	0.001	0.001
	SA	0.009	0.003	0.003	0.003	0.003
	SsA	0.019	0.004	0.004	0.004	0.004

Table X17: Macroeconomic annual average growth rates for the SSP scenarios, 2013-2050

		Baseline	SSP1	SSP2	SSP3	SSP4	SSP5
GDP	EuCA	0.018	0.024	0.021	0.016	0.023	0.030
	OcSEA	0.025	0.026	0.020	0.014	0.022	0.031
	NoAWA	0.020	0.034	0.028	0.018	0.026	0.041
	LaC	0.015	0.036	0.027	0.017	0.025	0.043
	NoA	0.024	0.013	0.012	0.013	0.014	0.018
	SA	0.030	0.029	0.024	0.018	0.027	0.034
	SsA	0.025	0.045	0.035	0.023	0.029	0.052
Population	EuCA	0.000	0.001	0.001	-0.001	-0.001	0.003
	OcSEA	0.007	0.005	0.006	0.008	0.005	0.004
	NoAWA	0.013	0.011	0.011	0.014	0.011	0.008
	LaC	0.006	0.004	0.006	0.010	0.004	0.002
	NoA	0.006	0.005	0.007	0.002	0.005	0.011
	SA	0.005	0.003	0.004	0.007	0.003	0.002
	SsA	0.023	0.022	0.018	0.023	0.022	0.014
GDP per capita	EuCA	0.018	0.023	0.020	0.017	0.024	0.027
	OcSEA	0.017	0.021	0.014	0.006	0.017	0.027
	NoAWA	0.008	0.022	0.017	0.004	0.015	0.033
	LaC	0.009	0.031	0.022	0.007	0.021	0.041
	NoA	0.018	0.007	0.005	0.011	0.009	0.007
	SA	0.026	0.025	0.019	0.011	0.023	0.032
	SsA	0.002	0.022	0.016	0.000	0.007	0.038

Table X18: Regional producer prices by commodity in 2012 (USD/t)

	Crops	Ruminant animals	Non-ruminant animals	Fish from capture	Fish from aquaculture
EuCA	292.71	610.17	1604.20	2418.16	3859.22
OcSEA	296.63	844.59	2493.90	2513.06	2311.82
NoAWA	443.75	962.03	1637.62	2843.90	1906.91
LaC	164.36	816.77	1910.78	1739.64	4440.67
NoA	361.03	440.13	1586.19	3728.62	3085.83
SA	418.67	942.72	1561.95	3349.36	1648.99
SsA	266.89	766.58	1213.06	1700.78	2679.92

Table X19: Regional average annual growth rates for GDP scenarios 2013-2050

	IMF USD	PWC 30	EconMap	PWC 50
EuCA	0.018	0.023	0.025	0.043
OcSEA	0.025	0.036	0.031	0.037
NoAWA	0.020	0.015	0.025	0.055
LaC	0.015	0.030	0.024	0.026
NoA	0.024	0.025	0.019	0.056
SA	0.030	0.043	0.052	0.035
SsA	0.025	0.023	0.047	0.052