Global Futures:

Modelling the global economic impacts of environmental change to support policy-making

TECHNICAL REPORT

February 2020

GTAP Global Trade Analysis Project | natural capital PROJECT | WWF

This report presents the first full set of results from the Global Futures project, together with a description of the project background, objectives, methods and conclusions. A summary of the headline results and recommendations is provided in the accompanying Summary Report, available here. The work was based on a project concept developed and funded by WWF UK.

For further information please contact:
Dr. Justin Johnson (jandrewjohnson@gmail.com) or
Toby Roxburgh (troxburgh@wwf.org.uk).

Written by:
Justin Andrew Johnson; University of Minnesota, Minneapolis, USA
Uris Lantz Baldos; Purdue University, West Lafayette, USA
Thomas Hertel; Purdue University, West Lafayette, USA
Chris Nootenboom; University of Minnesota, Minneapolis, USA
Stephen Polasky; University of Minnesota, Minneapolis, USA
Toby Roxburgh; WWF UK, Woking, UK

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Technical advisory group: Rob Alkemade (PBL-Netherlands Environmental Assessment Agency), Carter Brandon (World Resources Institute), Raffaello Cervigni (World Bank), Karen Ellis (WWF UK), Fabien Hassan (Boston Consulting Group), David Leclere (IIASA), Hugo Valin (IIASA), Georgina Mace (University College London), Emily McKenzie (HM Treasury - Dasgupta Review team), Elizabeth Passey (The Wye & Usk Foundation), Giovanni Ruta (World Bank) and James Vause (UN Environment Programme World Conservation Monitoring Centre).

Additional inputs from: Cristiane Close, Cicero de lima Zanetti, Andrea Dreifke-Pieper, Angela Francis, Gunter Mitlacher, Alessandra Prampolini, Samantha Putt del Pino, Katharine Tyndall, Rob Wood and Mark Wright.

Editor: Barney Jeffries (www.swim2birds.co.uk)
Design: Clean Canvas (www.cleancanvas.co.uk)

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Executive summary

The Earth's ecosystems are in steep decline, putting their ability to provide the ecosystem services on which the world's economies rely at risk. Unless we reverse these trends, the implications for human wellbeing are profound. Although the depth of humankind's reliance on nature cannot be fully captured in a single economic metric, such as gross domestic product (GDP), analysing changes in GDP does provide meaningful, and alarming, insights into changes in human wellbeing. Our analysis shows, with new levels of sophistication described below, that the loss of six ecosystem services under a business-as-usual trajectory leads to losses of US$9.87 trillion in real GDP by 2050, estimated as the net present value discounted to 2011 US$. This figure is derived from a new, first-of-its-kind model that combines a global economic model with a high-resolution ecosystem services model, generating results that are relevant for both global scale and local, landscape-level analysis.

Work from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and other global modelling communities provides critical evidence on how nature is responding to human pressures, and how social, biophysical and economic drivers of change might affect ecosystem services. However, less research has been undertaken into specifically how and under what circumstances simultaneous changes in ecosystem services might in turn affect economic performance. As a consequence, political and business leaders (such as heads of state, ministries of finance/planning, banks, businesses and investors), who are key to tackling the underlying drivers and effecting change, currently do not have access to the full range of evidence they need in order to fully understand these risks, nor to develop, prioritise and justify policy responses.

In 2017, WWF initiated the 'Global Futures' project to help fill this gap. The overall goal of the project is to enhance awareness among global political and business leaders of the risks to economic prosperity of global environmental degradation, and to help catalyse action by making the economic case for reversing these trends. The initiative seeks to do this by developing and applying a new, cutting-edge modelling approach for assessing how potential future environmental change would affect the world's economies, trade and industry, and disseminating the outputs widely among global leaders to help advocate for and support more sustainable policy-making.

The initial phase of the project, documented in Crossman et al. (2018), completed a comprehensive review of the state of play in global environment-economy modelling. The authors of that report recommended development of a new integrated modelling approach linking two existing models, namely the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model from the Natural Capital Project, and the Global Trade Analysis Project (GTAP) Computable General Equilibrium (CGE) model from Purdue University. This report presents the model created to meet this recommendation.

At the core of the approach is the GTAP model – the common language used by the world's governments to conduct analysis of policy issues such as trade, climate, energy, agriculture, food and water – which, for the first time, is being linked to a high-resolution global ecosystem service model, InVEST. Several existing projects have presented linked environment-economy models at similar resolutions, but these are at regional (Verburg et al. 2008) or national (Banerjee et al., in review) scales. This integrated modelling framework is used to assess the potential global, national and sectoral economic impacts of environmental change, under a range of alternative scenarios, using metrics that resonate with political economy audiences (e.g. how it will affect GDP, trade, production and prices).

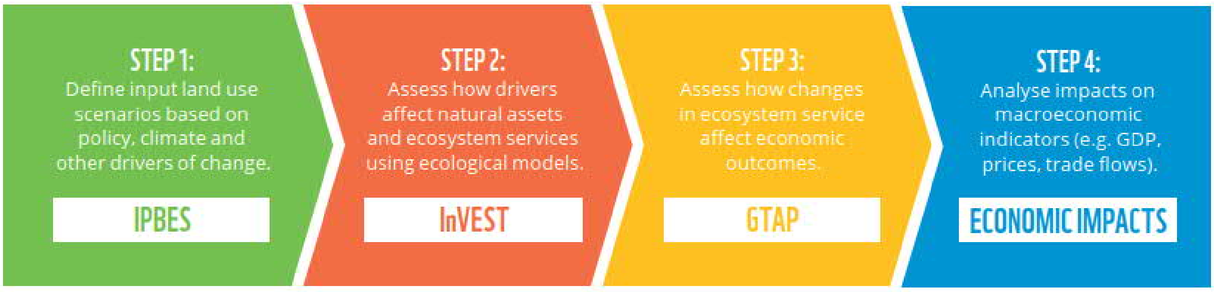
This report is being published in early 2020, a year in which a series of critical policy decisions will be made (related to the UN Sustainable Development Goals, Convention on Biological Diversity and UN Framework Convention on Climate Change) and is intended to inform those decision-making processes.

Key results

Result 1: Creation of a linked ecosystem services and economic model

The first result of this project is the provision of the linked model itself. Specifically, this includes the ability to successfully link four components, shown in figure E.1.

Figure E.1: Steps in the Global Futures modelling framework



For step 1, we created three scenarios: Business-as-Usual (BAU), Sustainable Pathway (SP) and Global Conservation (GC). The BAU and Sustainable Pathway scenarios are derived from the Shared Socioeconomic Pathway (SSP) scenarios produced by IPBES (SSP5 and SSP1, respectively, described in Rozenberg et al. 2014) downscaled to 300m resolution. The Global Conservation scenario was defined based on SSP1 but with the addition of specific grid-cell level conservation prioritisation to prevent expansion of agriculture or development into (1) protected areas, (2) wetlands, (3) areas that provide high levels of pollination services, (4) areas with high carbon storage, and (5) areas with high biodiversity. This was achieved using a tool specifically developed for this report, the Spatial Economic Allocation Landscape Simulator (SEALS) model (based on Suh et al., in review). Additionally, for marine fisheries, we used scenarios from the FISH-MIP group (Eddy et al. 2019) aligned to the scenarios used here.

Step 2 involved running these scenarios through six ecosystem service models (primarily using InVEST), described below. We chose these services because they are ones for which global, high-resolution computation is possible using landscape-scale models and for which the connection to economic impacts is clearly documented in the academic literature:

1. Pollination
2. Coastal protection
3. Water yield
4. Forestry production
5. Marine fisheries
6. Carbon storage

For these services, the primary input that changed was the land-use, land-cover (LULC) map (except for fisheries). Two of the ecosystem service models (water yield and coastal protection) also used future climate change projections of temperature, precipitation and/or sea-level rise.

Step 3 took the outputs from InVEST and transformed them into economic 'shocks' that served as inputs into the GTAP model, which was used to assess the impacts on economic performance indicators such as GDP, prices, trade, and production statistics for different sectors of the economy. These shocks were calculated from the high-resolution ecosystem service output and aggregated specifically to agriculture, forestry and fisheries sectors, and/or countries and regions. These shocks are imposed in the GTAP model as changes in endowments and/or changes in sector- and country-specific total factor productivity.

Finally, step 4 involved aggregating, interpreting and reporting the modelling outputs in a way that connects with decision-makers who will be engaged in relevant policy processes. The model thus provides a new tool that can now be used to analyse various types of policies including spatial planning, protected areas, payments for ecosystem services, commodity certification standards (especially those that are specific to ecosystem services, as in Smith et al. 2018), corporate sustainability commitments, trade policy changes, indirect or unintended consequences of environmental policy (leakage or spillover), along with many others, including assessment of how nation-specific policies fare when considered in a global setting.

Result 2: Business-as-usual will be very damaging to the world economy

We found that changes in the ecosystem services we have modelled will have significant impacts on the global economy. These are summarised in tables E.1-E.3 below. Overall, we found that continuing with the BAU scenario will, by 2050, result in GDP losses of over 0.67% per year compared to GDP in a baseline scenario without any loss of ecosystem services. This represents an annual loss of US$479 billion per year if estimated as a percentage of the size of the 2011 economy (throughout, we use a base year of 2011, which is the most recent year in the GTAP v9 database). The cumulative impact from 2011 to 2050, discounted to 2011 terms, is a loss of US$9.87 trillion under BAU, a loss of US$2.65 trillion under the Sustainable Pathway scenario and a gain of US$0.23 trillion under the Global Conservation scenario.

Throughout this report, we emphasise the percentage change figures because they are direct outcomes of the comparative-static GTAP model. However, to place these figures in context, we also calculate the annual impacts by applying the percentage change shock to the 2011 economy, and the cumulative impact by accounting for economic growth over the period 2011-2050, and converting the stream of GDP losses to net present value using a 3% discount rate (Tol, 2008), as described fully in the methods section.

Result 3: The Sustainable Pathway scenario still incurs a loss to the economy, but the Global Conservation scenario generates a gain

Even pursuing the sustainability goals in the SP scenario will by 2050 result in GDP losses of 0.18% (US$129 billion) per year. However, by pursuing the targeted environmental changes set out in our Global Conservation scenario, the world can experience gains in GDP of 0.02% (US$11 billion) per year by 2050. In particular, we found that:

- Lost habitats that are important for wild pollinators reduced GDP by 0.02% (US$15 billion) per year from reduced agricultural productivity in the BAU scenario. Gains in wild pollinator habitat in both the Sustainable Pathway and Global Conservation scenarios increased GDP by 0.02% (US$12 billion) and 0.06% (US$42 billion) per year, respectively.
- Changes in terrestrial and marine habitats that protect the coast from erosion and flooding (e.g. coral reefs, mangroves, seagrasses and saltmarshes) reduced GDP by 0.46% (US$327 billion) per year in the BAU scenario. This is almost three times higher than losses in the SP and GC scenarios, which totalled 0.19% (US$134 billion) per year in losses each. The change is negative

in all scenarios because sea-level rise and other threats still exist under the Sustainable Pathway and Global Conservation scenarios. This result arises from impacts of reduced coastal protection services on agricultural production and infrastructure.

- Changes in real GDP caused by water scarcity in agriculture varied considerably between regions. Overall, we found there were global annual losses of 0.03% (US$19 billion), 0.02% (US$17 billion), and 0.02% (US$14 billion) from reduced water availability for irrigated agriculture under the BAU, Sustainable Pathway and Global Conservation scenarios, respectively.
- Forest loss and resultant loss of timber production under the BAU scenario caused a net annual loss of 0.01% (US$7.5 billion). The Sustainable Pathway and Global Conservation scenarios, conversely, had gains of 0.01% (US$3.9 billion) and 0.01% (US$8.4 billion) per year, respectively, primarily from increased endowments of forests leading to increased forest-sector productivity.
- Loss in carbon storage had large impacts on the economy. The BAU scenario experienced 0.18% (US$128 billion) of economic losses annually, as calculated using a US$171 per tonne value of the social cost of carbon. The Sustainable Pathway scenario also experienced economic losses of 0.014% (US$10 billion) per year. Conversely, the Global Conservation scenario had a gain of 0.072% (US$52 billion) per year because increased forest cover led to increased carbon sequestration.
- Across all three scenarios, marine fisheries experienced GDP gains. Although global fish stocks and quantity of fish caught are likely to be reduced as a result of higher temperatures, the countries in the model that catch and sell the most marine fish happened to be net positive, leading to an aggregate increase in the value of output from that sector. Changes in fisheries under BAU slightly increased global GDP by 0.02% (US$17.1 billion) while the Sustainable Pathway scenario experienced a similar gain of 0.02% (US$17.1 billion) per year. However, the Global Conservation scenario saw substantial gains of 0.08% (US$57.3 billion) per year, a threefold increase linked to sustainably managed fishing stocks.

These numbers are summarised in tables E.1-3, which show the total GDP change for each scenario specific to each of the six services. Note that when calculating the specific impact of a single service we still are utilising the model where all six services are shocked simultaneously. Separating the impacts of individual services is done by analysing the marginal impact of each service on the equilibrium solution. Additionally, we calculated the cumulative effect of this shock out to the year 2050 in table E.3, adjusting for projected growth of the economy (see methods section for details) and assuming the size of the ecosystem service shock grew linearly until arriving at the total value in 2050. The cumulative estimate is not based on a fully dynamic economic growth model.

Table E.1: Annual percentage (%) change in global GDP due to changes in all ecosystem services under three scenarios

Ecosystem service	Business-as-Usual	Sustainable Pathway	Global Conservation
Pollination	-0.021	0.016	0.058
Coastal protection	-0.457	-0.188	-0.188
Water yield	-0.026	-0.024	-0.019
Forestry productivity	-0.011	0.005	0.012
Fish productivity	0.024	0.024	0.080
Carbon storage	-0.179	-0.014	0.072
All ecosystem services	-0.670	-0.180	0.016

Table E.2: Annual change in GDP (million US$, 2011 baseline) due to changes in all ecosystem services under three scenarios

Ecosystem service	Business-as-Usual	Sustainable Pathway	Global Conservation
Pollination	-15,310	11,789	41,727
Coastal protection	-326,854	-134,169	-134,169
Water yield	-18,617	-16,995	-13,565
Forestry productivity	-7,519	3,856	8,418
Fish productivity	17,083	17,079	57,337
Carbon storage	-127,679	-10,120	51,570
All ecosystem services	-478,895	-128,560	11,319

Table E.3: Cumulative change in GDP by 2050 (million US$, 2011 baseline, 3% discount rate) due to change in all ecosystem services under three scenarios

	Business-as-Usual	Sustainable Pathway	Global Conservation
All ecosystem services	-9,866,000	-2,646,361	232,923

These numbers are conservative estimates as we only included ecosystem services for which there was enough evidence to model and to link these changes to the economic model. Additionally, note that our estimates do not capture the total environmental impact on the economy, but rather the specific contribution that ecosystem services make. This means that many of the effects of climate change, such as reduced labour productivity or reduced agricultural output from increased temperatures, are not considered.

Result 4: Key storylines

In addition to the global figures discussed above, the rich set of results created by GTAP-InVEST also contains many interesting regional or country-level storylines. Here, we describe a few of the key storylines. Many more that are not fully explicitly discussed here can be found in the full study results.

The economic impacts of changes in ecosystem services will be felt unevenly across countries

We found that in addition to having significant adverse global economic effects, the impacts of changes to ecosystem service provision affect different parts of the world disproportionately. In particular, Western and Eastern Africa, Central Asia and parts of South America will be hit particularly hard as a result of the changes in price, trade and production in the new economic equilibrium. This result is shown in figure E.2, which plots the change in real GDP from the combined loss in ecosystem services for the three scenarios.

China stands to gain from following the Global Conservation scenario, primarily because it has a relatively large share of its economy in pollinator-dependent oil crops. Increased pollination services under Global Conservation would increase the competitive advantage of the country in this sector, driving down costs through greater production efficiency, and ultimately leading to greater oil crop supply and thus lower prices.

Countries such as the United States, Australia and the UK see large losses in all scenarios due to increased exposure to coastal damages, although these losses are somewhat mitigated under the Sustainable Pathway and Global Conservation scenarios.

Implementing the actions in the Global Conservation scenario is a pro-poor development strategy

Global equity would be improved by following a Global Conservation scenario. As shown in figure E.3, under BAU, low-income countries see the largest loss in GDP from lost ecosystem services. However, these same countries stand to gain the most (as a percentage of their income) from following the Global Conservation scenario. This is driven by developing countries in Sub-Saharan Africa, Central America and Southeast Asia that see improvements in real GDP.

Figure E.2: Percentage change in GDP due to changes in all ecosystem services under three 2050 scenarios

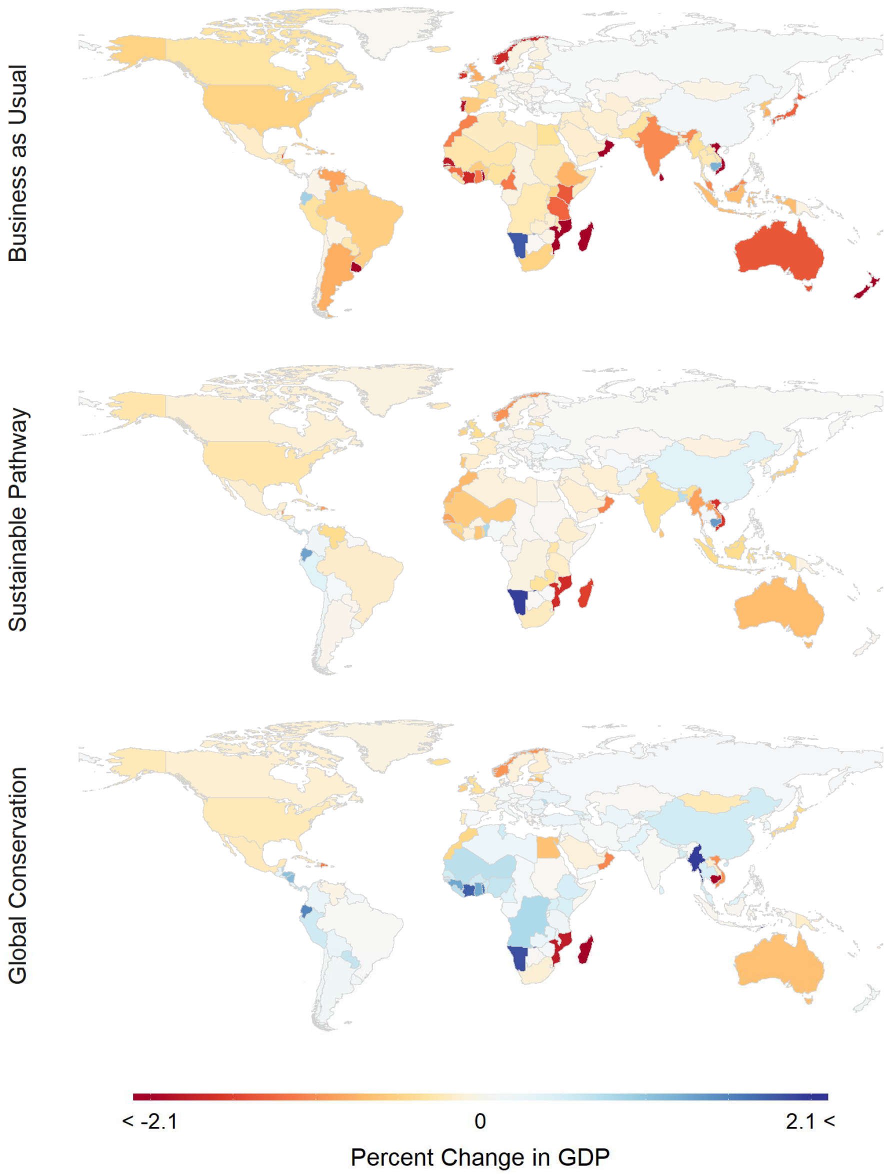
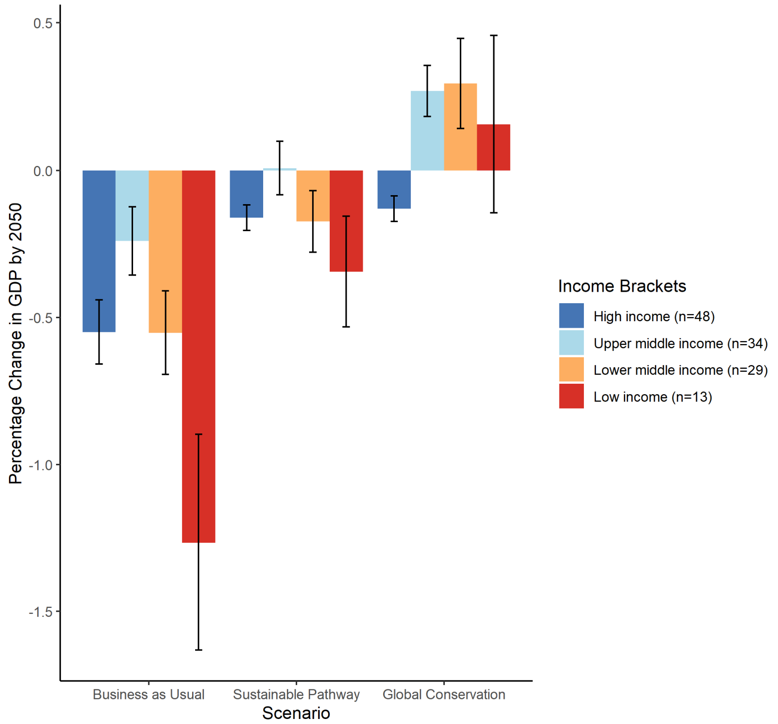


Figure E.3: Percentage change in GDP due to changes in all ecosystem services grouped by regional income classifications for three 2050 scenarios



Other key takeaways:

- Nature can help us to manage the risks from climate change. The biggest loss to the economy is from increased coastal vulnerability in the face of climate change causing sea-level rise – and the biggest gain from the Global Conservation scenario is through improved natural coastal defences which prevent the economic damage from occurring.
- Conversely, nature's loss undermines our ability to tackle climate change. The second biggest economic impact from the loss of nature identified through this study relates to its impact on carbon sequestration. If we are to meet climate challenges in an optimal way, we will have to consider nature as a key contributor to the solution.
- This analysis shows that protected areas are extremely important. Much of the increased value attainable under the Global Conservation scenario was obtained by not allowing development or agricultural expansion in these areas.
- We found that the precise location of where protection or development happened was very important. For example, the Global Conservation scenario led to improved economic outcomes by optimising land-use to deliver economic value both through standard market sectors and through nature. Indeed, the only way to obtain a positive outcome with a net gain in GDP was found by optimising in this way. With informed land-use planning, we stand to gain 0.02% of GDP per year by 2050 compared to a loss of 0.2% per year without explicit land-use planning in the Sustainable Pathway scenario.
- To obtain positive global futures, we need to achieve more sustainable patterns of production and land-use, and reform economic and financial systems to incentivise nature-based decision-making.

Recommendations for further work

The aim of this project was to assess several scenarios of global environmental change through linked ecosystem service and economic models. Two of the key recommendations that emerged are listed here and described in more depth in the concluding section of this report along with additional recommendations.

Recommendation 1:

Work tightly with emerging networks leveraging this work to create a fully endogenised dynamic version of the model. Instead of focusing only on how changes in ecosystems affect the economy, this model would consider impacts flowing in both directions, thereby making the linear model diagram in figure E.1 into a circle. Additionally, this cyclical interaction between the economy and the ecosystem would be recalculated at each time-step to analyse dynamic interactions between the two systems. Organisations including the World Bank and the UK Treasury have funded or are exploring funding opportunities to build the endogenous model.

Recommendation 2:

Develop 'deep-dive' country/region case studies applying the model in specific contexts. One advantage of using the GTAP database is that it can be linked to many other models. This includes regional or national-level models that contain increased detail about employment, land-use, policy, decision-making structure and/or land ownership, while retaining sufficient detail in the rest of the world to be able simultaneously to assess broader forces. In particular, the SIMPLE-G global model and/or the SIMPLE-G-US version of that model (Baldos et al. 2019) are good examples of this potential.

1 Introduction

In this report, we show that future changes in the Earth's ecosystems, and the consequent effects on the provision of ecosystem services, would potentially result in significant impacts on the world's economies, trade and industry. These impacts would be felt unevenly across the global economy, with some countries and sectors that are heavily dependent on nature being hit disproportionately.

To reach these conclusions, we conducted new research that combines an ecosystem services model, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, with an economic model, the Global Trade Analysis Project (GTAP) model, in order to be able to describe the interconnected nature of ecosystems and economic systems. We use three scenarios based on the Shared Socioeconomic Pathways (SSP) framework that were used by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Rosa et al. 2017). We downscaled these scenarios to 300m resolution using the Spatial Economic Allocation Landscape Simulator (SEALS) model (Suh et al., in review). The ecosystem services that we linked to GTAP were pollination, coastal protection, water availability, forestry production, carbon sequestration and marine fisheries. The models and results presented in this report help assess the potential for world governments to simultaneously (1) feed the population, (2) stabilise the climate and (3) restore biodiversity.

Human enterprise at the global scale poses serious threats to ecosystem services through broad-scale land-use change and climate change. Many academic approaches exist to studying these types of threats, but few describe phenomena that bridge both macroeconomic scales and local environmental processes. This phase of the Global Futures project has supported work to build a prototype model able to operate at both scales. The results from using this integrated model are intended to be used at global environmental fora, including the Convention on Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change (UNFCCC). This work leverages key advances in ecosystem services science coming from IPBES and will contribute to the state of evidence in future reports by that body. Work from IPBES and a variety of other global modelling communities provides critical evidence on how social, biophysical and economic drivers of change might affect ecosystem services, but less work has focused on how changes in ecosystem services might impact economic performance.

Often, the specific value of ecosystem services to the economy is unknown or undervalued, leading to suboptimal management. The purpose of this project is to provide improved information relevant to decision-making on the trade-offs, particularly between land conservation and agricultural practice. Existing literature on the macroeconomic impacts of ecosystem services contains very few studies that quantify macroeconomic impacts of ecosystem services outcomes within a global computable general equilibrium (CGE) framework (see the literature review in Appendix A-1). This corroborates the findings of the first phase of the Global Futures project, which noted that there was no existing research able to link macroeconomic and ecosystem services models in a way that could generate the kinds of evidence that decision-makers need.

This report begins by describing the four steps necessary to link these models, which includes defining three scenarios that will be used throughout the report. Next, we present results for each of the models, expressed as monetary outputs or percent changes from the baseline (2011) condition to a future condition (2050). Finally, we conclude with a discussion and conclusion section that contains recommendations for further work. This report presents results that are preliminary and are based on a prototype model that will be expanded and polished in subsequent work. The limitations and methods sections below provide more details on the limitations of the approach to date and implications for interpreting the results.

1.1 Background on models and research networks

The GTAP network was founded in 1992 and has since grown into a global network of 17,000+ individuals in 170+ countries, all contributing to and/or using a common database and modelling framework to assess the economy-wide impacts of trade and environmental policies. GTAP has expanded into environmental issues including analysis of global land-use and the assessment of climate impacts and mitigation activities on food security and poverty.

The Natural Capital Project (NatCap) is a partnership of four world-class academic institutions – Stanford University, the Chinese Academy of Sciences, the University of Minnesota, and the Stockholm Resilience Centre – advancing new science together with, inspired by and implemented through two of the world's largest NGOs, The Nature Conservancy and WWF. NatCap originated the InVEST suite of ecosystem service assessment tools. InVEST comprises 20 models that estimate how the production of ecosystem services can be affected by factors such as land-use change and economic growth. Additionally, InVEST has recently been used in a variety of global and regional assessments, including the IPBES global assessment, work with the Chinese Academy of Sciences on Gross Ecosystem Product (GEP), and work with the World Bank on developing a Natural Capital Index, among others.

1.2 Modelling the economy-wide impacts of changes in ecosystem services

In order to assess the economy-wide consequences (such as GDP impacts) of changes in ecosystem services, we need to integrate an ecosystem service model with an economy-wide model. Furthermore, given that the supply of ecosystem services does not obey national boundaries and the interconnectedness of global markets, this framework should be able to encompass all economic activity across the world, as well as the flows of goods and services, ranging from agricultural commodities to tourism, which link national economies. These trade flows provide opportunities for positive synergies, such as increased biodiversity leading to increased tourism revenue, as well as negative feedback – such as forest regulations in one country spilling over to increased deforestation elsewhere. In short, we need a global economic model that accounts for all economic activity and resource use, as well as the bilateral goods and services trade flows amongst regions. The GTAP database and associated family of global CGE models offers the most widely accepted framework for underpinning such an analysis and is particularly well suited to this type of global environmental analysis.

1.3 Applications and implications of this work

As discussed in the executive summary, the results generated by this model are relevant to decision-making and policy support in several contexts, including the design of payments for ecosystem services programmes, commodity certification standards (such as in Smith et al. 2018), corporate sustainability commitments, trade policy changes, and indirect or unintended consequences of environmental policy (leakage or spillover). Additionally, because the model is based on GTAP, which is itself used throughout many countries and their finance ministries, this modelling framework can also provide the basis for assessing how nation-specific policies fare when considered in a global setting.

Additionally, results from this model can provide direct input to a variety of emerging concepts of inclusive wealth or genuine savings. Recognising that GDP is a very limited definition of human wellbeing, several approaches have emerged that seek to expand this definition to include a more comprehensive set of factors (see for instance Polasky et al. 2015 for a review). Although this report emphasises changes in GDP, the GTAP model can also be used to generate key non-monetary output metrics that have been used in many expanded definitions of national wellbeing. One challenge that the inclusive wealth literature has faced is that it considers a very limited subset of ecosystem services, typically limited to goods that still flow through markets (such as mining). Our model expands the set of ecosystem services that could be included in this type of model, allowing for a more comprehensive definition of inclusive wealth.

A critical aspect of this work is that each scenario produces enough food. In each of our scenarios, discussed in more depth below, the world is able to feed the global human population; this is a core assumption in the integrated assessment modelling work that defined each scenario (through the IPBES SSP work). On the one hand, this means that the level of conservation value we obtain in all our scenarios will be lower than plans that only include conservation objectives. On the other hand, it means that our scenarios are more relevant to policy-making insofar as they explicitly include production of the many other goods that often are in competition with conservation goals. By constraining our scenarios to still produce enough food, our results are directly applicable to the "triple challenge" framework presented by WWF in the Living Planet Report 2018. The GTAP-InVEST model is a framework that explicitly considers the challenge of simultaneously providing a stable climate, adequate food and space for nature.

Towards meeting the triple challenge, protection of natural land from development is a core component of one of the scenarios we model (the Global Conservation scenario, defined more fully in section 2.1). This scenario includes protection (or rather prevention of loss) of natural land by pushing the expansion of agriculture or developed land elsewhere. Simultaneously, this scenario includes restoration of natural habitats by increasing the amount of natural land-cover in areas that are least suitable for agricultural or developed land expansion.

1.4 Caveats and limitations

Although the GTAP-InVEST model represents a large step forward in combining economic and ecosystem service models, there remain many caveats and limitations. The foremost of these is that while we did expand the set of ecosystem services considered, we did not include all possible ways that the economy might be affected by ecosystem services. For this reason, along with other choices discussed elsewhere, the values we find represent very conservative estimates of the full impact of natural capital loss. To underscore this point, see Box 1.4, which shows which ecosystem services are included in our report versus which were included in the Millennium Ecosystem Assessment (2005). Additionally, our model does not consider dynamic effects on climate change from the different patterns of land-use change we define in each scenario. This would require a fully dynamic model that also included endogenous climate change (which is well beyond the current state-of-the-art for global, high-resolution modelling). Instead, we use the climate change estimates from Representative Concentration Pathways (RCPs 2.6 and 8.5, which correspond to optimistic and pessimistic projections) as assumed inputs – discussed further below.

Box 1.4: Ecosystem services included in the current Global Futures model compared to other ecosystem services identified in Millennium Ecosystem Assessment

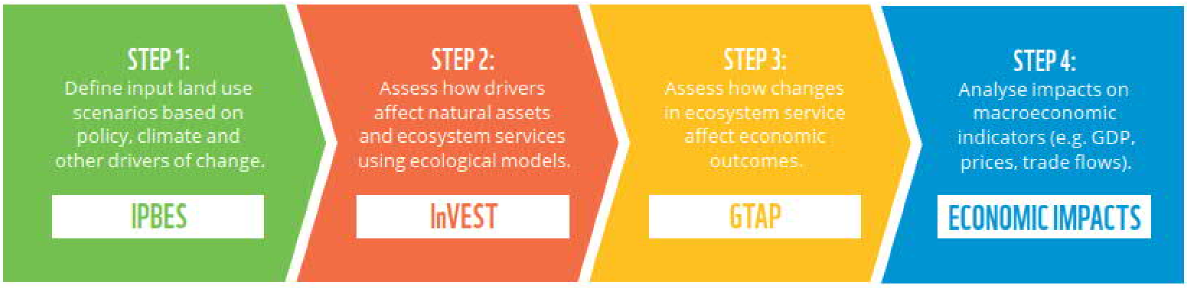
Ecosystem services included in the current model:	Ecosystem services excluded from the current model:
-Pollination -Coastal protection -Water yield -Timber provision -Carbon storage (climate regulation) -Marine fish provision	-Food (see note below) -Fibre and fuel -Genetic resources -Biochemical/natural medicines -Pest and disease regulation -Air quality regulation -Erosion regulation -Water purification -Spiritual and religious values -Education and inspiration -Cultural diversity and heritage -Aesthetic values -Sense of place -Primary production (photosynthesis) -Soil formation and retention

It is important to note that our model sought to capture ecosystem services that are not fully described by market prices. For certain ecosystem services, especially food and fibre products (such as cotton), the product is traded on standard economic markets where the price accurately represents the net private benefit of production. For goods such as these, the only value that might not be described is anything external to the private decision of the producer. Pollination is one such good because the majority of the service is provided by nearby public lands. Additionally, any investment by an individual landowner in creating pollination habitat would result in benefits that accrue to many other landowners. This is a classic public-goods situation where the level of investment in the public good occurs at the lower, privately rational level rather than the higher, socially optimal level. The same argument applies to timber provision and marine fish provision insofar as both have a large component that is provisioned from public lands or marine waters.

2 Methods

The basic components of the linked model developed in this work are shown in figure 2.1, which describes the process in four steps. Each box describes the specific models used or results generated, each of which is described in more depth in the following sections. A more comprehensive version of these model linkages is presented in Appendix figure A-2.

Figure 2.1: Steps in the Global Futures modelling framework



Step 1: Define future global development and land-use change scenarios

Scenarios are often used to inform policy decision-making by exploring how different drivers of change or policy interventions might lead to different states of the world. As predicting the future is uncertain, scenarios are often regarded as "potential futures", typically with the aim of providing hypothetical but comprehensive states of the world to inform discussion and analysis.

In the context of this work, scenarios were used to explore how and under what circumstances environmental changes affect economic outcomes at a range of scales (global, national and sector-level). In practice, scenarios drive the whole modelling process, forming the basis on which the effects of different drivers of environmental change (socio-economic, policy, etc.) are assessed (in terms of land-use change and the status of natural assets) and how this affects ecosystem services and, finally, economic outcomes. For the purposes of this research, scenarios were defined as representations of possible future states of the world in 2050 and were delivered in the form of spatial data; specifically, maps of predicted land-use, land-cover (LULC) change, precipitation, and sea-level rise.

We created three scenarios to assess specific analytical questions regarding the effect of environmental change on global economic wellbeing. These scenarios are listed in table 2.1, together with the key analysis questions that each was designed to address. Comparison of the results of modelling runs for each scenario provides a partial story for how global economies and ecosystems might develop differently under different drivers of change, and what they imply for the economy, trade and industry.

Table 2.1. Scenarios used in the Global Futures project

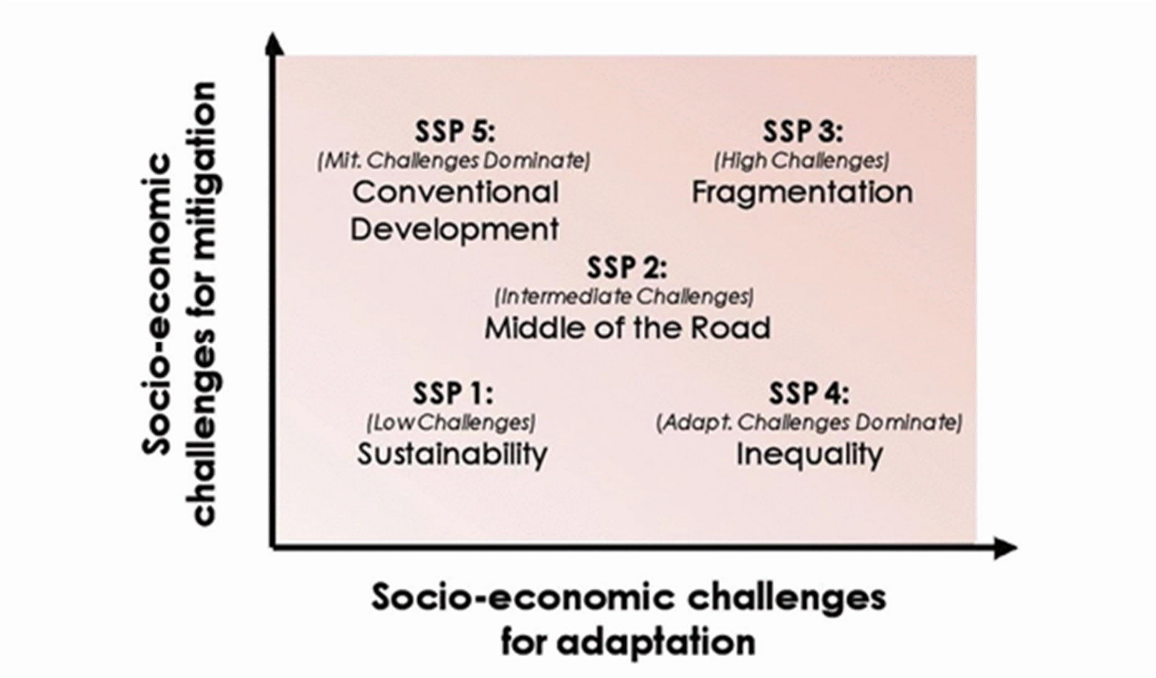
Scenario	Narrative description
Business-as-Usual (BAU)	The world continues to increase fossil-fuel usage to support energy-intensive lifestyles in all parts of the world (including developing countries catching up to developed nations). It assumes high levels of market competition and integration of global markets through trade. Global population peaks in the middle of the 21st century and then declines. Land-use change is widespread and untargeted and climate change is an extreme problem.
Sustainable Pathway (SP)	Society experiences a worldwide shift to more sustainable practices, aimed at keeping within global environmental boundaries. Common-good resources are effectively managed, and education and health advances cause the population to peak sooner across the world. Widespread recognition of the costs of climate change lead to effective global mitigation. Land-use change is more effectively managed globally but is not targeted within countries to avoid further loss of areas that are important for biodiversity and ecosystem services.
Global Conservation (GC)	In addition to international coordination on climate change and land-use (as per the SP scenario), society also implements ambitious global polices to protect and restore natural habitats. It achieves this primarily by targeting land-use change and development to avoid areas that are important for biodiversity and ecosystem services and, in some instances, allowing degraded/converted land to revert to natural habitats.

2.1.1 Approach to scenario development

Scenarios were developed using spatial data from the Land-use Harmonization 2 (LUH2) project (Hurtt et al. in prep), which provides globally consistent, 30km resolution maps of predicted land-use change based on various assumptions of climate change and human development out to the year 2100. This data was created as a part of the World Climate Research Program's Coupled Model Intercomparison Project Phase 6 (CMIP6) to serve as inputs into global environmental and climate models (Eyring et al. 2016). As the ecosystem service models in InVEST are built for LULC data at spatial resolutions of 300m or higher, we created downscaled versions of the LUH2 land-use data using the GLOBIO (Van Asselen and Verburg 2012) and SEALS tools, described in section 2.1.3. This spatial data is used as inputs into our suite of ecosystem service models (see sections 2.2.1 through 2.2.5).

Each scenario in the LUH2 data is based on two fundamental 'building blocks' of global environmental modelling from the Intergovernmental Panel on Climate Change (IPCC): Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). The SSPs were designed to represent ways in which society could adapt to or mitigate climate change – each SSP is a comprehensive set of assumptions regarding socio-economic drivers such as population, GDP growth and specific policy interventions that stem from various integrated assessment models (IAMS) (Riahi et al. 2017). By design, these scenarios produce enough food to meet their respective food demand (which is calculated from other assumptions on population growth and demand characteristics). Figure 2.1.1, taken from O'Neill et al. (2012), illustrates the ways in which five particular SSP scenarios are based on varying levels of socio-economic adaptation and mitigation. Note that the assumptions of policy action (or inaction) in the SSPs are generalisations of more specific policies individual nation states might take.

Figure 2.1.1: The Shared Socioeconomic Pathways (SSP) framework (O'Neill et al. 2012)



RCPs are representations of various greenhouse gas emissions scenarios (van Vuuren et al. 2011), which can be paired with specific SSPs to simulate the consequences of socio-economic drivers on climate change. Whereas SSPs take a more narrative approach to describe how society might act in response to climate change, RCPs provide explicit spatial maps of predicted emissions data. Detailed methods for combining SSPs with RCPs are documented in Kim et al. (2018).

Table 2.1.1.1 summarises the combinations of SSP and RCP used in our selected LUH2 scenarios for the year 2050, alongside the additional downscaling methods applied to achieve LULC data suitable for use in InVEST.

Table 2.1.1.1. Selection of SSP, RCP, and downscaling method for each scenario

Scenario	SSP	RCP	Downscaling method
Business-as-Usual (BAU)	SSP5 (Fossil fuelled development)	RCP 8.5 (GHG emissions continue to rise through the 21st century)	GLOBIO (300m)
Sustainable Pathway (SP)	SSP1 (Sustainability)	RCP 2.6 (GHG emissions peak between 2010–2020)	GLOBIO (300m)
Global Conservation (GC)	SSP 1 (Sustainability)	RCP 2.6 (GHG emissions peak between 2010–2020)	SEALS (300m) implementing conservation policies listed in table 2.1.2

Table 2.1.1.2 reports the total area of key land-cover types in each scenario. Note that the changes outlined do not necessarily reflect changes in environmental quality (or condition). This is because the optimisation routine behind the GC scenario often will trade high ecosystem service grid-cells for low service cells within the same land-use type (leading to zero net change). However, these results still show the basic dynamic at play in the GC scenario whereby there is a slight increase in forest land (1.2 million ha) compared to very large losses of forest in BAU and SP (-30.99 million ha and -32.2 million ha respectively).

The primary element driving these improvements in GC is that by placing expansion of agriculture and urban land in areas with lower ecosystem services value (as specified by the rules in table 2.1.2), we achieve higher protection of natural land while still meeting the same food security and development constraints. Although the net change in land-use and land-cover is similar between scenarios, the distribution is very different. This can be seen in the last column in table 2.1.1.2 which shows dramatic differences in carbon storage between scenarios, indicating that the loss of forests in the BAU scenario, for instance, is in much higher quality (higher carbon storage) locations.

Table 2.1.1.2. Global changes in land-use, land-cover patterns in each scenario with carbon storage

Scenario	Change in cropland (million ha)	Change in forest (million ha)	Change in grassland (million ha)	Change in non-forest natural (million ha)	Change in urban (million ha)	Change in other (million ha)	Change in carbon storage (billion tonnes)
Business-as-Usual (BAU)	30.15	-30.99	5.19	-35.66	6.80	24.51	-3.69
Sustainable Pathway (SP)	-1.73	-32.20	-21.90	18.59	5.79	31.44	-0.29
Global Conservation (GC)	1.09	1.20	-0.77	-0.94	0.51	-1.09	1.48

We used these same combinations of SSP and RCP to acquire spatial data on predicted changes in precipitation and sea-level rise for 2050, which served as inputs to the InVEST water yield and coastal protection models, respectively. Data on projected monthly precipitation rates (mm) based on RCP were provided by WorldClim at a 30 arc-second (~1km) resolution based on the HadGEM2-ES General Circulation Model (Hijmans et al. 2005). Spatially explicit sea-level rise projections were available by RCP for the period 1986–2005 to 2081–2100 from the IPCC (Church et al. 2013). While this did not quite match the study period of this research, it was the best available data and provides an accurate representation of sea-level rise risk.

Similarly, we based our models of marine fisheries on the same combinations of SSP and RCP. Our model of choice, FISH-MIP (see section 2.2.5), takes as input a combination of RCP and fishing restrictions, which map easily onto our given scenarios.

2.1.2 Detailed description of scenarios

Business-as-Usual (BAU)

The SSPs do not explicitly designate one of the scenarios as being "business-as-usual" due to the large variety of BAU paths considered. For the purposes of this project, we assumed a BAU scenario driven by extensive land-use and climate change as represented by SSP5 (fossil-fuelled development) (Kriegler et al. 2017). We chose not to use SSP2, which is often the scenario chosen as BAU, so that we could assess a world that includes continued high rates of fossil fuel use (which is closer to SSP5).

As summarised by Popp et al. (2017), this SSP is guided by:

"…the economic success of industrialized and emerging economies […] this world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Land-use change is incompletely regulated, i.e. tropical deforestation continues, although at slowly declining rates over time. Crop yields are rapidly increasing. Unhealthy diets with high animal shares and high waste prevail. Barriers to international trade are strongly reduced, and strong globalization leads to high levels of international trade. In SSP5, all land-use emissions are priced at the level of carbon prices in the energy sector. But in contrast to SSP1, international cooperation for climate change mitigation is delayed due to a transition phase to a uniform carbon price until 2040."

To account for climate change, this scenario uses RCP 8.5 (GHG emissions continue to rise through the 21st century). In this scenario radiative forcing stabilises at $8.5 W/m^2$ in 2100, which corresponds to approximately 1370ppm CO_2. This scenario assumes no specific climate mitigation target and serves as a business-as-usual, climate-change intensive emissions projection (Riahi et al. 2011).

When selecting LUH2 databased on the combination of SSP and RCP, we also had to select the baseline IAM used to generate the spatial data. As SSP5 relies on the REMIND-MAgPIE, we chose the LUH2 dataset that modelled SSP5 and RCP 8.5 using REMIND-MAgPIE. Corresponding data on precipitation and sea-level rise was selected based on RCP 8.5. For FISH-MIP modelling, RCP 8.5 with no fishing restrictions was selected.

See Appendix figure A-3.1 for an illustration of the specific LULC map used for this scenario, which is the main input to the InVEST models.

Sustainable Pathway (SP)

This scenario describes a future in which the world shifts towards a more sustainable and inclusive development that seeks to stay within global environmental boundaries and tackle climate change. It is based on SSP1 (Sustainability) (van Vuuren et al. 2017) and mirrors the 'sustainable development' scenario used in the IPBES Global Assessment report (from Rosa et al. 2017).

As summarised by Popp et al. (2017), SSP1 represents a world that:

"...shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Land-use is strongly regulated, e.g. tropical deforestation rates are strongly reduced. Crop yields are rapidly increasing in low- and medium-income regions, leading to a faster catching-up with high income countries. Healthy diets with low animal-calorie shares and low waste prevail. In an open, globalized economy, food is traded internationally. In SSP1, international cooperation for climate change mitigation starts early (after 2020). All land-use emissions are priced at the level of carbon prices in the energy sector."

However, this scenario is limited in terms of policy ambition. For example, sustainability goals are based solely on global aggregate behaviour, through different assumptions of global policy (primarily climate policy), population growth, or other such factors. It also falls short on the protection and restoration of nature, in that it does not handle land-conservation strategies such as protected areas, alternate management strategies, payments for ecosystem services, sustainability standards, etc. in a spatially explicit manner.

To simulate the climate impacts of global sustainability policy we coupled SSP1 with climate change projections based on RCP 2.6. This pathway is an optimistic projection of climate change characterised by a peak radiative forcing of $3W/m^2$ with declines before 2100 and corresponds approximately with the goals set out for limiting warming to well below 2 degrees, as in the Paris accord. This corresponds with a peak of around 490ppm CO_2 and reduced methane emissions.

Given that the SP scenario is based on SSP1, which uses IMAGE as its baseline IAM, we selected the LUH2 data that modelled SSP1 and RCP 2.6 using the IMAGE model. As with any IAM, summarising the modelling process can be quite complex, but from the perspective of this project the key aspects of IMAGE are that it includes forest management, agricultural economy, land-use allocation, livestock systems, energy demand and supply, climate policy, carbon cycling, atmospheric composition and water use (see van Vuuren et al. 2017).

Corresponding data on precipitation and sea-level rise was selected based on RCP 2.6. For FISH-MIP modelling, RCP 2.6 with no fishing restrictions was selected.

See Appendix figure A-3.2 for an illustration of the specific LULC map used for this scenario, which is the main input to the InVEST models.

Global Conservation (GC)

This scenario describes a future in which the world implements a transformational environmental policy agenda. It is based on the same LUH2 data as the SP scenario, with additional constraints on land-use change imposed during the SEALS downscaling process. These constraints were designed to simulate a series of ambitious yet plausible global environmental 'outcomes' (i.e. targets), as set out in table 2.1.2.

Table 2.1.2. Assumptions regarding protection/restoration of nature in GC scenario

Intervention	Description
1	Protected areas were assumed to successfully prevent conversion to agriculture or developed land. We did this by lowering the expansion suitability coefficient in SEALS to an extremely low level in all areas defined as "strict protected areas" (IUCN categories I-IV).
2	Prevented all expansion of non-natural land-use into wetlands (ESACCI classes 160 and 170).
3	Reduced the likelihood of expansion of developed land or agriculture in areas identified as having high ecosystem service value under the baseline (2011) conditions, as identified by Chaplin-Kramer et al. (2019). We did this by multiplying the pollination map from Figure 3 in Chaplin-Kramer et al. (which was an index of 0 to 1) by a coefficient $\beta_p = -100.0$. This was chosen such that an area with very high pollination would have a much lower expansion probability score lowered by -10.0 (see the SEALS methodology section for details on implementation).
4	Reduced the likelihood of expansion in areas with high carbon based on a global run of the InVEST carbon storage model based on the current (2011) landscape. The raw carbon storage values (in tonnes per hectare) were multiplied by the coefficient $\beta_c = -10.0$, thereby lowering the likelihood of expansion proportional to the carbon storage total.
5	Reduced the likelihood of expansion in areas with high biodiversity value. These areas were defined as the total weighted fractional richness of all species, as identified by combining all entries in the PREDICTS database of species extents. We multiplied this 0 to 1 score by $\beta_b = -100.0$ to reduce the probability of expansion in these areas.

The outcomes of this scenario generation method relate to the protection of key ecosystems (e.g. forests, wetlands, rivers, oceans, fish stocks) and key drivers of human development (food and climate/energy). The outcomes are 'achieved' through global policy goals (such as, for example, not allowing agricultural expansion in carbon-rich areas, described in more depth below) based on existing proposals and recommendations from a range of sources, including the IPBES Global Assessment (which includes a range of recommendations; see Rosa et al. 2017). The scenario is deliberately not explicit on the specific policy interventions (e.g. institutional, regulatory, market-based) that would be required to meet these outcomes, as this will be the subject of further research.

These additions to the SEALS model almost eliminated expansion in the areas targeted for preservation. However, because we also chose to exactly match the coarse-level change predictions from LUH2, there was some expansion into areas targeted for preservation in the case where no other land was available. See Appendix figure A-3.3 for an illustration of the specific LULC map used for this scenario, which is the main input to the InVEST model, and see Appendix A-4 for the all of the values used to parameterise the SEALS model. For marine fisheries, we calculated the maximum sustainable yield from the FISH-MIP results and defined the scenario such that effective fishing enforcement was able to achieve exactly these rates. Finally, note that in some locations, cropland is declining in the LUH2 scenarios. In many of these locations, natural land expansion replaced the cropland, which can be interpreted as forest or natural land restoration/enhancement.

It is important to note that the outcome assumptions above do not convey a recommended or appropriate level of policy ambition, as this is for policy-makers and other stakeholders to decide. Rather they serve to provide a basis on which to illustrate the ways in which a more 'transformational' environmental policy agenda could affect economic outcomes, in order to help inform policy-making.

2.1.3 Land-use change modelling and downscaling

The two models linked in this project have very different spatial scales (national/regional trade budgets vs. 300m LULC grid-cells). Thus, the project required new methods to easily and accurately move between scales. Going from a high-resolution scale to a regional scale is relatively simple, primarily by summing the gridded data to larger regions. However, going from coarse-level projections of change – particularly land-use change – to high-resolution landscapes is much more challenging. To address this, we used the GLOBIO model (Van Asselen and Verburg 2012) which can downscale land-use change from the regional or coarse scale (i.e. the 30km scale used in LUH2) to high-resolution data (i.e. the 300m data required by InVEST). The basic approach used in the GLOBIO/CLUMondo simulates changes in land-cover based on exogenous demand (defined here based on the SSP LULC change), biophysical and socioeconomic variables along with land-systems characterisation.

A key research advance included in this project was creating a tool (SEALS) to improve upon existing downscaling methods while providing a framework in which to add additional conservation actions to reflect various policy initiatives. The SEALS model builds on past applications of spatially explicit downscaling and land-use change modelling techniques, specifically those of GLOBIO and CLUMondo (Van Asselen and Verburg 2012; 2013), by solving two previously unresolved methodological challenges. First, the downscaling was not based on defining a priori land-use change rules and instead was based on an in-depth econometric time-series calibration of the model based on historical European Space Agency (ESA) LULC data, land-use suitability models, and a wide variety of additional regressors (see Appendix table A-4.2 for regression coefficients). Second, SEALS can implement land-use change objectives during the downscaling process by incorporating additional policy interventions (e.g. the achievement of conservation targets in the GC scenario, table 2.1.2). For detailed methods behind the SEALS model, including the definition and calibration of the downscaling algorithm, see Appendix A-4.

Step 2: Use InVEST to calculate changes in ecosystem services

The three scenarios outlined above (BAU, SP and GC) create spatial data (see figures A-3.1 through A-3.3) based on the assumptions built into the underlying combinations of SSP, RCP and IAM (e.g. policy actions, global development). We use the spatial data as inputs to the InVEST suite of ecosystem services models, specifically focusing on the pollination, coastal protection, water yield, carbon storage (of which forestry is a subset) and marine fisheries models described in sections 2.2.1 through 2.2.5 below. We chose these models because their outputs could be translated into input variables in the GTAP modelling framework (see sections 2.3.1 through 2.3.7) based on existing literature (see Appendix A-1).

2.2.1 Pollination InVEST methods

A modified version of InVEST's pollinator abundance model was used to estimate the effects of land-use change on pollination 'sufficiency', defined as the amount of pollinator-supporting habitat surrounding agricultural land and used to estimate pollinator-dependent agricultural yields. The methods for running this global model are documented in Kim et al. (2018) and Chaplin-Kramer et al. (2019). To briefly summarise, the original InVEST pollination model predicts pollinator abundance based on the spatial relationships between two limiting resources on the landscape: pollinator nesting habitat (e.g. ground, cavity and stem nesting sites) and floral nectar sources. The original model calculates pollinator abundance by simulating pollinator foraging habits based on these two resources, using typical flight distances for the species or guild of pollinator in question (see Sharp et al. 2018 for more details). The modified model presented here simplifies these steps by assuming pollinators are fully abundant on any natural land-covers (classes 50 to 180). The model then calculates the proportional area of natural land-covers around every instance of agricultural land-cover (classes 10-20) to estimate the relative abundance of pollinators on agricultural land, using a 2km buffer based on work by Kennedy et al. (2013). Using a threshold of 30% natural land-cover based on work by Kremen (2005), pollination sufficiency was calculated as a 0 to 1 index, where 1 indicates fully sufficient pollination and corresponds to agricultural land surrounded by more than 30% natural land-covers within 2km. Sufficiency values between 0 and 1 correspond to agricultural lands surrounded by 0% to 30% natural land-covers, scaling linearly. We do not model changes in land management or increases in agricultural intensity, which may lead these results to be underestimates.

2.2.2 Coastal protection InVEST methods

The InVEST coastal protection model combines six geophysical and biological risk factors: relief (angle of slope), natural habitat, net sea-level change, wind exposure, wave exposure and surge potential depth contour) to calculate a coastline's relative exposure to inundation and erosion. Our modelling of this index of 'coastal vulnerability', expressed as values between 1 (low risk) and 5 (high risk), is based on methods defined in Gornitz et al. (1990) and Hammar-Klose and Thieler (2001). It calculates risk scores for each of the factors listed above and generates vulnerability indices for each 1km section of coastline worldwide. Each section of coastline is assigned a relative risk ranking between 1 (low risk) and 5 (high risk) for each of the six risk factors based on the biophysical input data; the geometric mean of the six risk rankings is the overall coastal vulnerability index.

Global runs of the coastal protection model were first pioneered by Chaplin-Kramer et al. (2019) to support IPBES global ecosystem services and biodiversity modelling. We apply the same approach and input data – modified data on coastal habitat from Freiwald et al. (2017), Spalding et al. (1997), Mccowen et al. (2017), and UNEP-WCMC and Short (2017); sea-level rise data from the IPCC (Church et al. 2013); elevation (USGS 2012); and wind direction and power (Tolman 2009) – to each of our scenarios.

Of the risk factors included in the model, only natural habitat and sea-level rise varied across each scenario of global change. Natural habitat, particularly mangroves and wetlands on or near the coast, plays a critical role in slowing down water movement and lowering storm surge, especially where the other factors (geomorphology, wave exposure) make the coastline already at high risk. To simulate marine habitat cover change (which is not included in the LUH2 LULC data), we assumed any section of coastline that transitioned from a natural terrestrial land-cover (classes 40-180) to a developed terrestrial land-cover (class 190) lost any coastal habitat protections (e.g. mangroves, coral reef) in the transition.

2.2.3 Water yield InVEST methods

The InVEST water yield model evaluates how different components of a landscape, such as soil, evapotranspiration processes and precipitation, interact to contribute to water yield, measured as inputs to a reservoir or stream network. The two primary factors in our scenarios that influence our results are precipitation changes from climate change and land-use change resulting in different evapotranspiration rates (e.g., forests can actually absorb more water than other land-cover types through higher evapotranspiration). Unlike the pollination and coastal protection results, which were based on existing runs completed by the Natural Capital Project team for the IPBES assessment, the water yield model has never previously been run at a global, high-resolution (300m) scale.

The water yield approach is based on seminal work from Budyko and Fu (1981) which assesses pixel-level evapotranspiration rates from land-cover compared to reference evapotranspiration (based on grassland) and considers the available water content. More recent revisions of the model are based on Donohue et al (2012), which specifies how available water content, precipitation, rooting depth, rooting restrictions and plant-available water content affect realised water yield.

To calculate water yield globally, we used LULC parameters defined in Appendix table A-5.1. Plant-available water content was calculated based on soil data from ISRIC and Soilgrids (Hengl et al 2014), while potential evapotranspiration was based on CGIAR's global aridity and Potential Evapotranspiration (PET) database (Zomer et al. 2007; Zomer et al. 2008). LULC and precipitation data for each scenario was provided following methods detailed in Step 1.

2.2.4 Forestry and carbon storage InVEST methods

The InVEST carbon storage and sequestration model works by specifying carbon storage levels present in each of four carbon pools (above-ground, below-ground, soil and dead matter) specific to each LULC class (see the appendix for specific LULC classes used, along with their parameters), based on the downscaled GLOBIO LULC classification scheme. These parameters are drawn from the literature or site-based studies, though typically the values used in the IPCC Tier 1 method are used (Ruesch and Gibbs 2008). The base InVEST model is intended to run for a single ecofloristic region, using carbon pool parameters specific to that region (Sharp et al. 2018). To run this globally, we developed separate carbon-pool tables for each of approximately 125 carbon zones where each carbon zone is defined as the unique combination of ecofloristic region, continent, and whether the forest is a frontier forest as specified by the IPCC (as in Ruesch and Gibbs 2008). To develop these tables, we built on work from Suh et al. (in submission), which recategorised ESA LULC data into seven functional types – we extended the classes considered to include carbon storage values for agriculture. These tables are documented in full in Appendix table A-5.2.

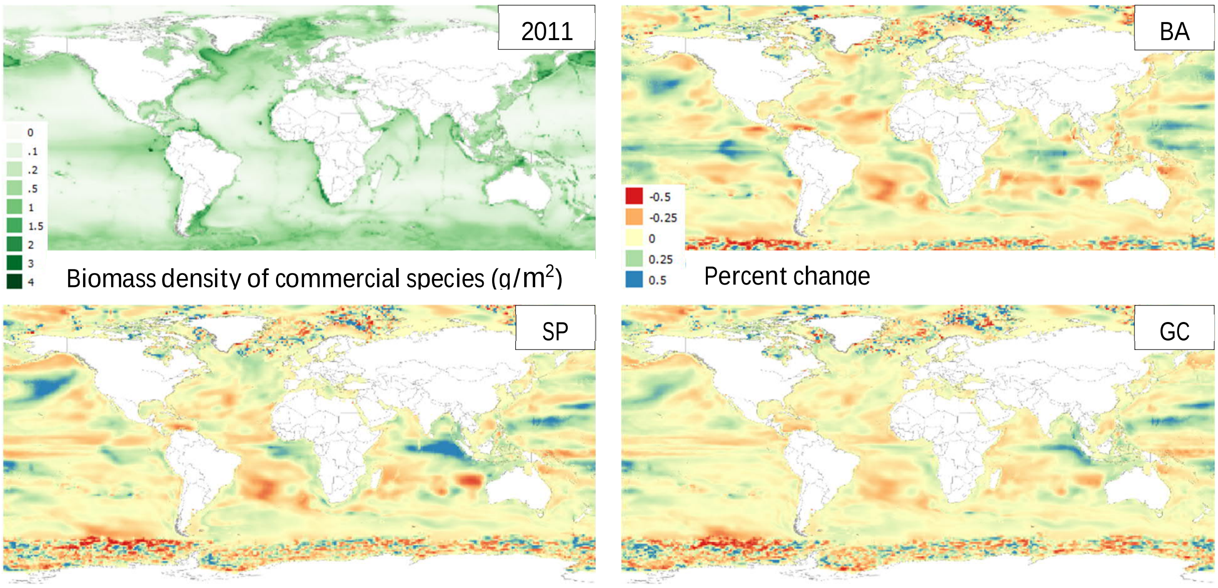
2.2.5 Marine fisheries InVEST methods

Although InVEST has a marine fisheries model, it cannot currently be run globally. Thus, to model the ecosystem changes in marine fisheries, we use outputs from the FISH-MIP program within Intersector Impact Model Intercomparison Project (ISIMIP, isimip.org). In particular, we use results from the EcoOcean and BOATS models, based on the GFDL-ESM2M and IPSL climate reanalysis (following the methods documented in Tittensor et al. 2018). The models we used are global food-web models that incorporate both climate change and human pressures on a global, 0.5 degree grid and outputs results for many (51 in the EcoOcean model) trophic and taxonomic groups with age structure of the populations included. This model run assumed no ocean acidification and excluded diazotrophic fish species (per the FISH-MIP guidelines).

These results are reported in figure 2.2.5, showing the biomass density of commercial species under the baseline 2011 condition and the percentage change from the baseline under our three scenarios. These scenarios are different from the other scenarios used in this report because they are not defined primarily by an LULC map and instead are based on climate and human pressure assumptions. We chose to pair three of the FISH-MIP scenarios with our report scenarios as follows:

- Our BAU scenario uses the FISH-MIP RCP8.5 and SSP5 scenario with BAU levels of fishing
- Our SP scenario uses the FISH-MIP RCP2.6 and SSP1 scenario with BAU levels of fishing
- Our GC scenario uses the FISH-MIP RCP2.6 and SSP1 'no fishing' scenario (which we then use to calculate maximum sustainable yield, see explanation below)

Figure 2.2.5: Biomass density of commercial fishing species (g/m^2) under baseline and future scenarios



To calculate the specific shocks given to GTAP, we extracted the total catch biomass (TCB) variable from the FISH-MIP database (hosted under the ISI-MIP data portal at www.isimip.org), which provide monthly and yearly observations of gridded total biomass of catchable, commercially valued species. For the BAU and SP scenarios, we defined the shock as the percentage change in TCB in each of the GTAP zones (augmented to include their 200 mile nautical claims). For the GC scenario, we chose to reflect improved conservation of sea resources by calculating the maximum sustainable yield implied by the no-fishing scenario from FISH-MIP. Note that current levels of fishing reflect open-access behaviour, which from basic economics (e.g. as described in the fishing discussion in Daly 1998) results in overfishing. Lower stocks from overfishing lead to lower average catch rates from lower reproductive populations. If instead of open-access levels of fishing, the level of fishing permitted was optimally set at the maximum sustainable yield and this was fully enforced, then this would yield higher overall catch rates in the long term than would the open-access level of fishing.

We used the no-fishing scenario from FISH-MIP to calculate what the maximum sustainable yield would be. Extensive literature exists that links the relationship between maximum sustainable yield and carrying capacity. For example, early studies (e.g. Fox 1970) found the relationship to be between 0.3 and 0.4, while later studies revised this downward (Deriso 1987). A recent, high-profile publication from Costello et al. (2016) plotted these values globally for a large database of fisheries catch data. Based on this, we chose to assume that the maximum sustainable yield was 0.2 the size of the carrying capacity, and thus scaled down the 2050 no-fishing TCB values by 0.2 prior to calculating the percentage change.

Overall, shifting to maximum sustainable yields includes a considerable increase in overall catch rates due to proper management of the underlying population.

Step 3: Use ecosystem services changes as inputs to the GTAP model

The third step in our method is to translate the gridded results from InVEST into inputs for the GTAP model. This required converting the spatial outputs of each ecosystem service model into one of the myriad economic shocks built into GTAP (e.g. region-specific reductions in agricultural productivity). Although the GTAP methods are based on calculations specific to regions (rather than grid-cells), we based our biophysical calculations on the downscaled LULC maps because the specific ecosystem services we model have very localised effects (e.g., considering how close natural pollinator habitat is to pollination-dependent cropland).

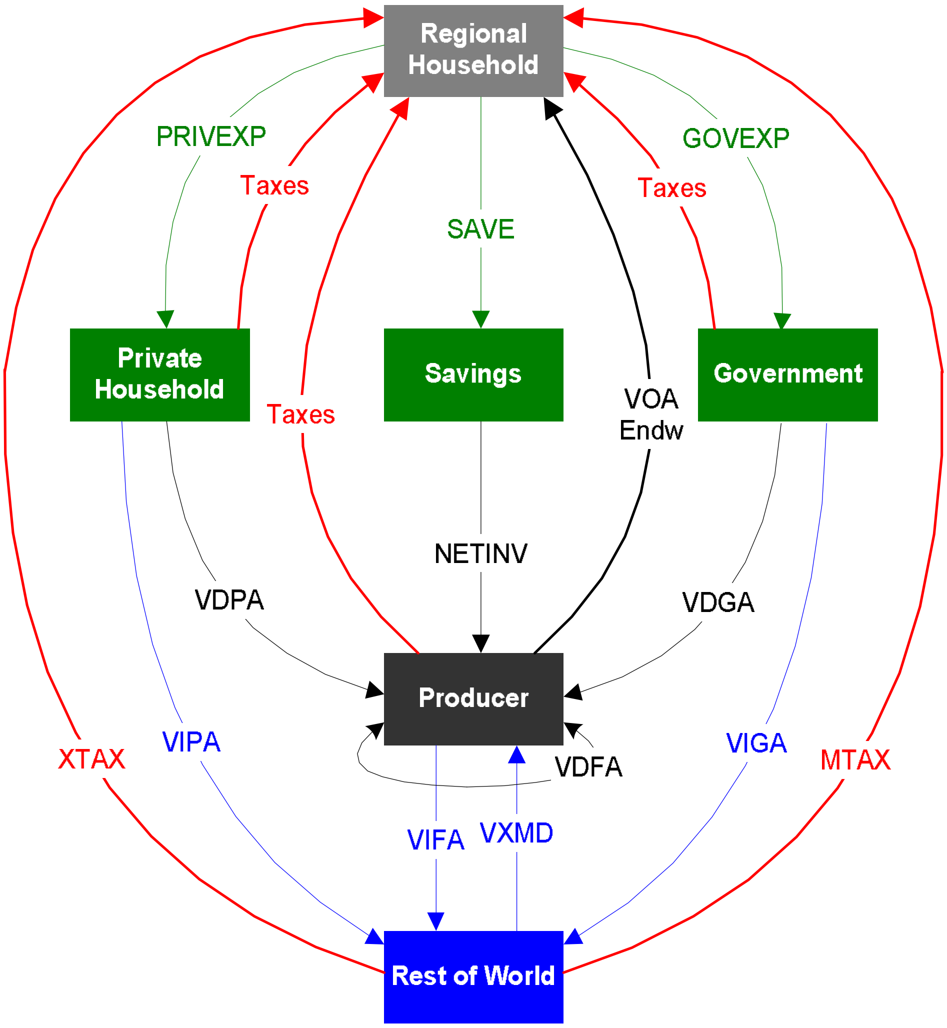
2.3.1 Structure of economic model

2.3.1.1 CGE framework

The GTAP-AEZ model (agro-ecological zones; Plevin et al. 2014) is a multi-commodity, multiregional computable general equilibrium (CGE) model that tracks bilateral trade flows between all countries in the world and explicitly models the consumption and production for all commodities of each national economy. However, unlike the standard model which views land endowments as homogenous and immobile across sectors, the GTAP-AEZ model incorporates heterogeneous land endowments in each region as well as allowing the reallocation of land within the crops sectors and across crops, livestock and forestry sectors (see discussion below). Similar to the standard model, the GTAP-AEZ model is a comparative static CGE model, which means that each simulation shows differences between different possible states of the global economy – with and without policy at the same time period – or with respect to two points in time – current and future period. At the core of the GTAP-AEZ model is an input-output accounting framework wherein all sources and uses of each economic good are accounted for including each input used in production. Figure 2.3.1 is a stylised framework of the GTAP model and summarises the key flows across economic agents in the model.

Consumption framework. The model has a single representative household for each region (regional household). The red lines in figure 2.3.1 represent income flows to the household. The household receives all gross factor payments net of the capital depreciation allowance (VOA – payments of factors of production), plus the receipts from all indirect taxes (including export and import taxes – XTAX, MTAX). Regional income is distributed across three broad categories – private households, government expenditures and savings – by maximising a top-level Cobb-Douglas utility function. Savings is a unitary good while private households and government expenditures utilise sub-level utility functions in order to determine consumption of each domestic (value of domestic purchases of private household and government – VDPA, VDGA – black lines in figure 2.3.1) and imported commodity (value of imported purchases of private household and government – VIPA, VIGA – blue lines in figure 2.3.1).

Figure 2.3.1: Stylised framework of the GTAP model



Sub-level utility function for private households is based on a constant differences of elasticities (CDE) function (Hanoch, 1975). This on the one hand is less demanding than the flexible functional forms, and on the other hand permits calibration of income elasticities and own-price elasticities independently, and importantly is non-homothetic. The sub-utility function for public expenditure is based on a constant elasticity of substitution (CES) utility function (Arrow et al. 1961).

Production framework. Nested CES functions are used for modelling producer behaviour for each region. At the top level of the production framework, producers combine aggregate value-added and intermediate inputs, according to a single CES function. Sub-level CES functions produce aggregated value-added from each primary factor commodity and aggregated intermediate input from each purchased input. Factors of production, or endowments, are of three types: perfectly mobile (e.g. labour and capital), partially mobile or sluggish (e.g. land) and sector-specific factors (natural resources). Each purchased input can be sourced either domestically or internationally and this is modelled using another sub-level CES function (value of domestic and imports of firms – VDFA and VIFA in figure 2.3.1).

Land-use in production. Using the GTAP-AEZ extension of the GTAP model enables fuller incorporation of land as an input to economic activity. In particular, it introduces competition for land resources across crops, pasture and forestry as well as heterogeneous land endowments in each region which are defined by agro-ecological zones (AEZs). The AEZs are defined in terms of 60 day-long length-of-growing periods, of which there are six, each differentiated by climatic zone (tropical, temperate and boreal). These AEZs were populated with crops and forests based on the work of Monfreda et al. (2009) and Sohngen et al. (2009). The GTAP-AEZ model was initially developed to look at land-based climate mitigation and for that purpose was merged with data on non-CO_2 GHG emissions, which are dominated by farming activity (Hertel et al. 2008). However, use of GTAP-AEZ first really took off in the context of the debate over induced land-use change from biofuels (Hertel et al. 2010).

Water-use in production. The GTAP-AEZ model we use incorporates model outputs from the GTAP-BIO-W model (Liu et al. 2014) which is a version of the GTAP-AEZ that adds more detail on water use and consumption. The GTAP-BIO-W introduces water into the GTAP modelling framework at a river basin level in addition to separating crop production into irrigated and rainfed sectors. It can directly report water use in agriculture in each river basin as well as land-use and land-cover at the AEZ level. Unfortunately, the underlying database in the GTAP-BIO-W is outdated (circa Y2000) so we cannot use this model directly. Instead, we use the model to get the implied GDP losses from reduced water availability in agriculture which we then impose in the GTAP-AEZ model using regional productivity shocks.

International trade. The most notable restriction on trade in the GTAP model is that commodity sourcing is at the border: for each product, all domestic agents (i.e. private households, government, producers) in an economy use the same mix of imports from different countries, though each agent chooses its own combination of imported and domestic product. There is also a two-level system of substitution between products from different sources – an import-domestic top-level CES function above an import-import sub-level CES function. Trade flows generate supply and demand for international transport services and this is accounted for in the model. There is also no international trade in primary factors.

Calculation of multiple, simultaneous ecosystem services shocks. Existing research that explicitly connects ecosystem services to a CGE, as discussed above, considers each ecosystem service in isolation. Our approach can do this (and we report single ecosystem service impacts below by running our model on single ecosystem service shocks), though our primary model combines all of the shocks so as to calculate a total impact value. Combining multiple ecosystem services shocks is simply a matter of calculating the cumulative effect of each ecosystem service shock within each grid-cell – for example, a grid-cell containing coastal agriculture that experiences reduced pollinator abundance and reduced coastal protection would see a larger cumulative reduction in agricultural productivity than the effect of either ecosystem service on its own. The gridded data that is used to calculate shocks is aggregated to the regions presented in GTAP-AEZ, which will distribute the shocks across the global economy.

2.3.1.2 Model database

The standard GTAP database version 9 presents globally consistent data on consumption, production and international trade (including transportation and protection data), energy data and CO_2 emissions for 140 regions and 57 commodities for three benchmark years (2004, 2007 and 2011) (see Appendix tables A-6.1 and A-6.2). We modify this database following Baldos and Hertel (2012) and aggregate some regions (from 140 to 137 regions) for use in the GTAP-AEZ model. At its core, the GTAP database is composed of input-output tables statistics, which are contributed by members of the GTAP Network. The GTAP 9 Database includes separate input-output tables for 120 individual countries representing 98% of global GDP and 92% of the world's population. Due to the very large size of the full GTAP database, the associated files are distributed with two alternative aggregation packages (FlexAgg and GTAPAgg), which allow users of the database to tailor sectoral and regional aggregation to their needs. FlexAgg is a command line data aggregation program (Villoria and McDougall 2015) while GTAPAgg is a Windows program with a convenient, graphical user interface that also aggregates the GTAP Database (Horridge 2015). The key elements of the main data file are outlined in Appendix table A-6.3 while Appendix table A-6.4 shows the key model parameters. Key value flows in the database include both input-output flows within each region, bilateral international trade flows, capital stock and savings information, international transport costs, domestic input and output subsidies, export subsidies and import tariffs as well as revenue flows from taxes and tariffs. Most flows are measured at both tax-free and tax-paid prices (i.e. taxes are implicitly accounted for) (Walmsley et al. 2012). Key behavioural parameters provided with the GTAP Database include the source-substitution or Armington elasticities (used to differentiate goods by country or origin), the factor substitution elasticities, the factor transformation elasticities affecting the sluggish factors, the investment parameters, and the parameters governing the consumer demand elasticities. The first three sets of parameters are taken from external sources while the rest are calibrated from the database (Hertel et al. 2016). The standard GTAP database is further processed in order to introduce land-use and land-cover information for each AEZ at the subnational level using the data and methods described in Baldos (2017).

2.3.1.3 Model Implementation

The standard GTAP model is implemented using the GEMPACK (General Equilibrium Modelling PACKage) suite of economic modelling software (Harrison and Pearson 1998). GEMPACK is distributed by The Centre of Policy Studies Knowledgebase at Victoria University, Melbourne, Australia (www.copsmodels.com/gempack.htm). Following the standard for the GEMPACK program, all equations of the GTAP model are recorded not in levels (e.g. million US$) but in percentage change form. Due to non-linearities in formulae and update equations, which result in changes in the underlying shares and price elasticities, the solution requires non-linear methods. The GTAP model can be run via command line as well as the Windows-based RunGTAP tool. RunGTAP is a visual interface to various GEMPACK programs and allows the user to run simulations interactively in a Windows environment using the GTAP general equilibrium model. No previous knowledge of the GEMPACK language or programming skills is necessary to use the program. Results and complementary information for further analysis are also provided in a Windows environment and can be accessed interactively. RunGTAP also has several add-on tools which can be helpful to users. The welfare decomposition tool permits the user to break down the regional equivalent variation metric into its component parts, including changes due to allocative efficiency, terms of trade, improved technology and endowments. The systematic sensitivity analysis tool allows uncertainty analysis in the model shocks and parameters, thereby generating both mean and standard deviations of model output. Finally, the subtotals tool permits further decomposition of changes in the model as sums of the contributions made by the change in each exogenous variable. The subtotals are particularly useful in understanding the key drivers of model outcomes.

All the input files are binary header array (HAR) files, to keep the size of the files small (Harrison and Pearson 1998). The HAR files are designed to work with the GEMPACK program. There is also a GAMS version of the standard GTAP model and software exists for readily converting these HAR files to the General Algebraic Modeling System (GAMS) data exchange file (GDX) format, as well as to CSV files.

2.3.2 Pollination GTAP methods

To connect the outputs from the InVEST pollination model to GTAP, we converted change in pollination sufficiency at a 300m scale into aggregate changes in agricultural production at a national/regional scale, this being a shock available in the GTAP-AEZ model. We followed methods from Chaplin-Kramer et al. (2016), Kim et al. (2018) and Chaplin-Kramer (2019) as the basis for our methods. Specifically, we calculated the proportional change in pollination sufficiency present on each agricultural grid-cell for each scenario. We overlaid this onto data from Monfreda et al. (2008) – which maps 175 crops by hectares harvested – multiplying each grid-cell's harvested hectares value by the proportional change in pollination sufficiency. This results in a map of the "effective hectares" for each crop that remain after accounting for changes in pollinator abundance. For each crop, these values were summed by GTAP region and divided by the total production to get the crop-specific proportional change in effective hectares. Finally, we multiplied the proportional change in effective hectares by the pollination yield dependency ratio – a measure of how dependent a crop yield is on pollinators (see Klein et al. 2007) – which results in the change in production efficiency for each crop.

These steps are summarised in the equation below:

$$e_c = p_c * d_C$$

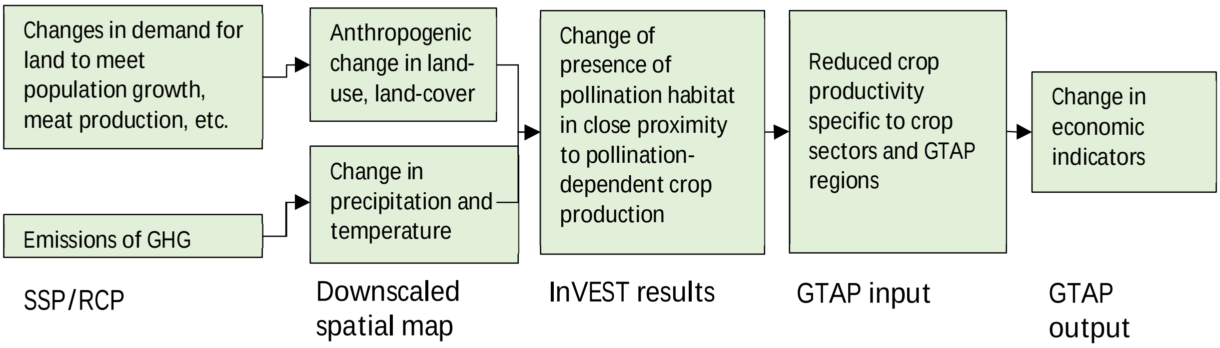
where e_c is the change in production efficiency of crop c, p_c is the proportional change in pollination sufficiency, and d_c is the yield-dependency ratio from Klein et al. (2007).

Our approach is an improvement on the literature on the assessment of economic impacts of global pollination loss. Past studies quantified the contribution of pollination by multiplying the pollination yield dependency ratio by the value of output for each crop (Gallai et al. 2009; Lautenbach et al. 2012). This approach calculates the total value of pollination but does not calculate the change in the value of pollination from a change in land-use or other changes affecting pollinator populations. These papers also fail to account for the economy-wide responses to pollination loss. Bauer and Wing (2010, 2016) utilised the standard GTAP model in order to assess the economic welfare and output value losses of global catastrophic pollination loss within a CGE framework. Our approach improves on the literature by incorporating spatially explicit information on which land areas will experience loss in pollinator habitat and calculates the losses from changes in crop pollination. We also use the GTAP AEZ model which has a more robust modelling of land-use within crops as well as across cropland, pasture and forestry use.

We use the upper bound of each range of yield dependency ratio reported in Klein et al. (2007). For example, if the range of yield dependence is 0-10%, we assumed 10%. In the version of the GTAP model that we are using, there are eight broad crop sector categories (wheat, sugar crops, coarse grains, paddy rice, cotton, fruits and vegetables, oil seeds, and other crops). These eight categories can be mapped back to the detailed crop sectors (see Appendix table A-6.5). Thus, implementation of our 'pollinator loss' simulation requires us to first weight crop-specific dependency ratios by the effective hectares generated from the InVEST model and then aggregate these ratios to the eight broad crop sector categories in the GTAP model. We use value weights in order to aggregate the crop-specific dependency ratios based on the contribution of each crop to the total output value of the broad crop sector category it belongs to. Crop output values are computed using producer price and quantity of crop produced. We use production and producer price data from UN FAO (2019).

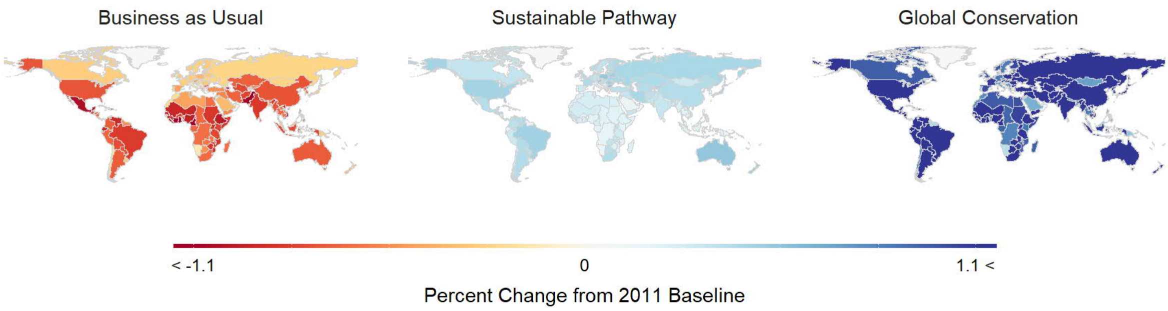
Once aggregated, the computed dependency ratios for each of the eight broad crop sector categories in the GTAP AEZ model are then implemented as negative input-neutral productivity changes for all 137 regions to simulate the effect of a loss in natural pollinators in the current economy. These calculations are summarised as an impact-pathway diagram for pollination in figure 2.3.2.1 while figure 2.3.2.2 summarises the agricultural shocks for each GTAP region.

Figure 2.3.2.1: Impact pathway for pollination



Pollination impact pathway short description: Changes in population and agricultural demand lead to changed patterns of where natural land is adjacent to pollination-dependent crop production. This results in lower natural pollination services benefiting crops based on the crop-species pollination dependence, which we model as a crop- and region-specific shift in productivity for impacted agricultural sectors.

Figure 2.3.2.2: Percentage change in pollinator-dependent agricultural production due to changes in pollination under three 2050 scenarios



2.3.3 Coastal protection GTAP methods

For coastal protection, we assessed how changes in coastline habitat under our different scenarios affected economic activity in each region. Specifically, we considered how changes in coastal protection services would affect GDP and other indicators due to loss of land through inundation and increased flooding risks to infrastructure. Our model aims to include considerably more spatial specificity of sea-level rise costs, leveraging our 300m resolution LULC maps, augmented with additional maps of coastal mangroves, sea marshes, corals and seagrasses. To use these results, we deemed any coastline with a vulnerability index higher than 3.3 “at risk” of coastal flooding – an index of 3.3 generally represents the point at which risks from coastal damages make it economically undesirable to establish permanent improvements on the landscape (Kim et al. 2018). We then recorded the hectares of land present in any grid-cell that became newly categorised as “at risk” in our scenarios.

We estimate the impact on national productivity by calculating the total loss in real GDP in affected coastline for each GTAP region. Here we utilise gridded GDP at purchasing power parity (PPP), converted back into real GDP as used in the GTAP model (~5 minute resolution) from Kummu et al. (2018). These GDP maps were generated using subnational data on GDP PPP per capita as well as grid-cell level population count. However, due to the coarse nature of the Kumma et al. estimates (10km resolution), we assumed that only the first 500m of the grid-cell were lost to inundation, thus assuming that 5% of the total GDP within the coarse grid-cell that is newly at risk from coastal hazards is lost. This GDP loss is aggregated from the grid-cell level to the national level, converted into percentage change in regional GDP which is then implemented as a shock in the GTAP model by adjusting national-level productivity accordingly.

The choice to reduce productivity based on the value of 5% of the grid-cell’s GDP is of course somewhat arbitrary. However, our choice concords well with much of the literature on this topic. Many studies have sought to parameterise the economic losses of sea-level rise, including from Nobel-winning William Nordhaus who produced the Dynamic Integrated Climate–Economy (DICE) model. This model, along with three other climate-specific integrated assessment models, the Regional Integrated model of Climate and Economy (RICE), the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and the Policy Analysis for the Greenhouse Effect (PAGE), provide the most widely used estimates of climate change’s impact on the economy (see Diaz and Moore 2017 for a recent review). Although prominent in the literature, these models take very simplified approaches to identifying sea-level rise damages. The DICE model, for instance, uses a single quadratic equation to relate the change in temperature to a change in GDP, specifically $Damage = 0.00518\,SLR(t) + 0.00306\,SLR(t^2)$, where t is the temperature change given from the climate scenario. The most detailed of the models, FUND, includes more biophysical specificity, but still relies on a small number of parametric relationships that plot lost GDP as a function of climate change intensity. Because these analyses are both very coarse (single global estimates or a small number of regions) and based on generalised damage functions, they are not useful in our task of linking specific LULC changes to increased coastal damages.

Sea-level rise has also been considered in the CGE modelling literature. Most relevant to the current study is Bosello et al. (2007), who created the GTAP-EF model (a variant of the GTAP-Energy model with more sectoral specificity). They used this model to estimate general equilibrium effects of sea-level rise on GDP, though they used relatively dated information on impacts (from 1993) and have very little spatial specificity (only eight global regions). More recent work comes from Hinkel et al. (2010), who developed the Dynamic Interactive Vulnerability Assessment (DIVA) model. The DIVA model considers a subset of the physical factors included within the InVEST coastal protection model, though with considerably coarser resolution (85km coastline segments). The most relevant recent literature on this topic comes from Jevrejeva et al. (2018), who found that the global impact of inundated land was US$1.4 trillion per year (0.25% of global GDP) different between 1.5°C and 2°C of warming by 2100. On the higher end of their impacts, if we follow the RCP8.5 projections, there will be between US$14.3 trillion and US$27.0 trillion of damages per year by 2100. However, they do note that adaptation could reduce this cost by a factor of 10. Finally, Pycroft et al. (2016) analysed the global GDP effect worldwide to be somewhat lower (0.5% in the highest sea-level rise scenario), but noted very large regional disparities with welfare losses ranging from 4% to 12% in vulnerable locations.

Overall, our assumption leads to changes in GDP similar to these other estimates, though of course room for improvement exists by explicitly modelling inundation zones. Our results (discussed in more depth in the results section) show a mean GDP reduction of 0.076% in the SP and GC scenarios, with a considerably larger reduction of 0.305% in BAU. Given that our estimates are for a shorter timeframe than the literature discussed above (2050 vs 2100) we believe that the choice of 5% is justified insofar as it allows us to estimate the more detailed CGE and regional impacts of this shock.

Both above calculations are summarised as an impact-pathway diagram for coastal protection in figure 2.3.3.1 while figure 2.3.3.2 summarises the national productivity shocks for each GTAP region. Note that the expected global real GDP losses due to changes in coastal protection services estimated in this study (between 0.46% and 0.19%) are relatively modest compared to the national level longer-run projections in the literature (see literature review in Appendix A-1 for further justification) because we exclude many non-ecosystem service pathways to impact (such as reduced labour productivity through higher average temperatures).

Figure 2.3.3.1: Impact pathway for coastal protection

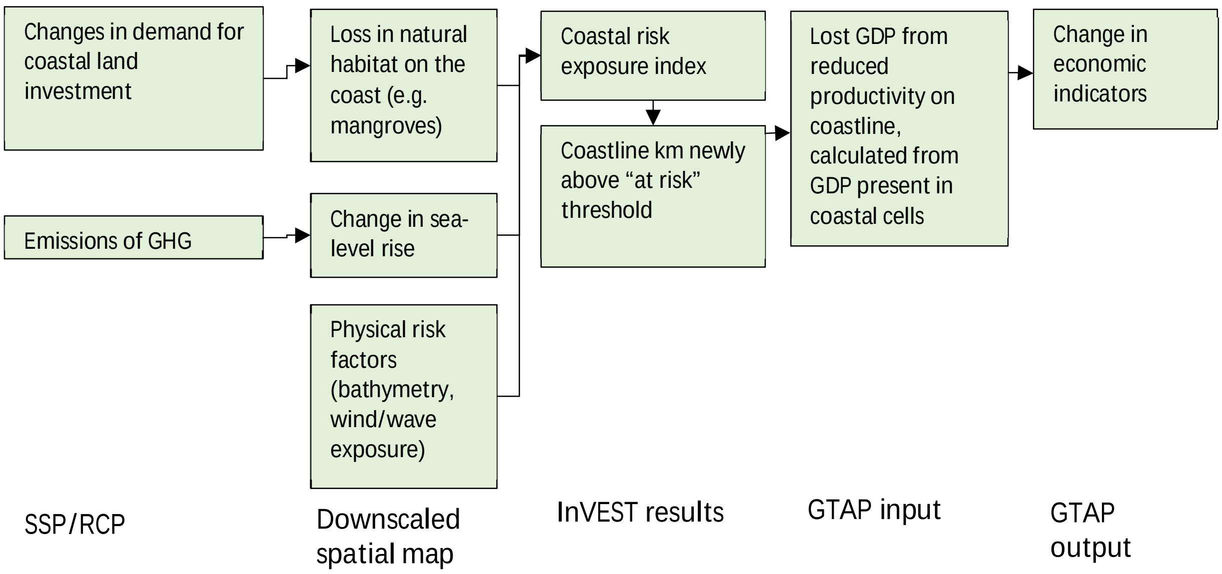
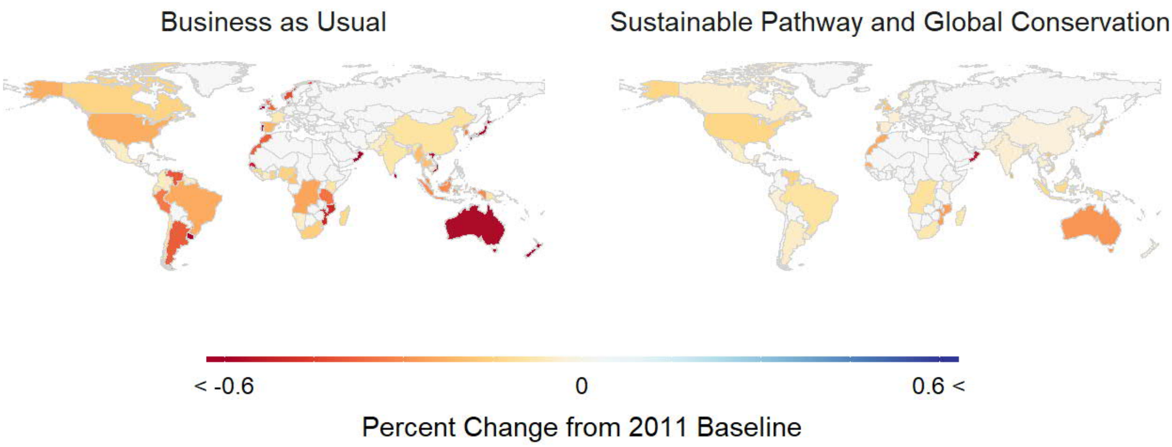


Figure 2.3.3.2: Percentage change in GDP due to changes in coastal protection under three 2050 scenarios



Coastal protection impact pathway short description: Changes in exposure to sea-level rise from reduced natural habitat (of e.g. mangroves and salt marshes) leads to greater coastal exposure and greater inundation of capital and productive assets. We model this as a reduction in national economic activity scaled by the amount of GDP present in the coastal areas newly at risk to climate change.

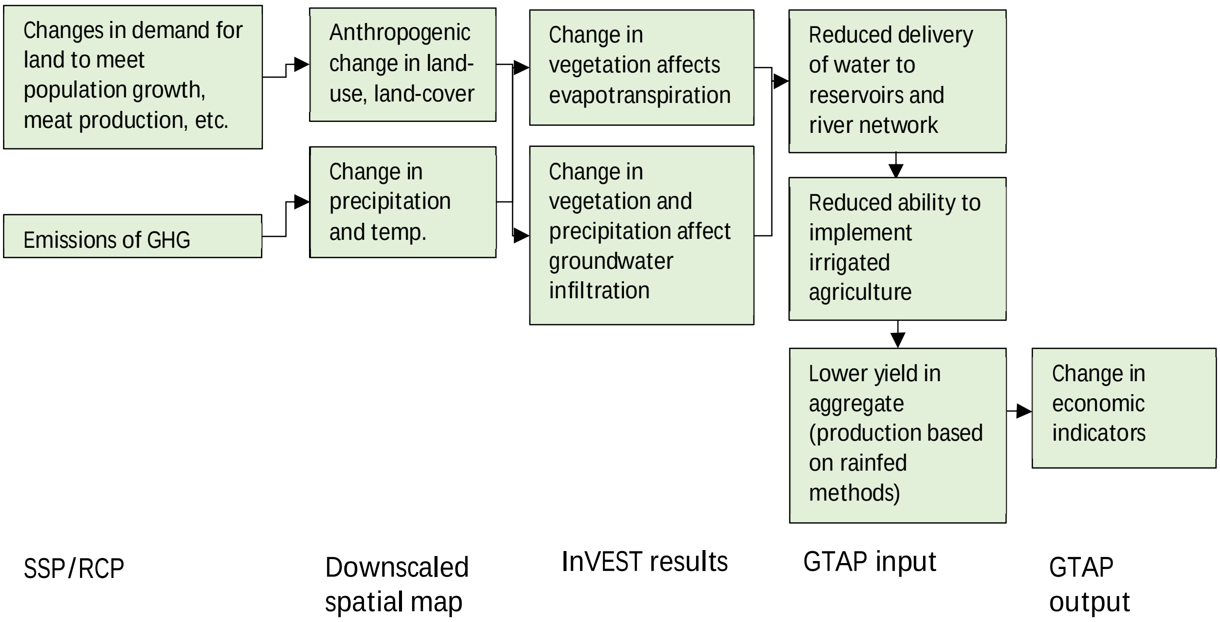
2.3.4 Water yield GTAP methods

Water yield contributes to water availability that contributes to economic activity. Reductions in surface water availability reduce irrigation water for agriculture. We model water for irrigation while also taking into account the increase in future water demand for non-agricultural use as well as changes in water supply due to water yield. In the literature, examination of future water within a CGE framework requires outcomes from global water models (e.g. Liu et al. 2014; 2017) which are specifically designed to consistently capture both water supply and demand given expected climate outcomes as well as socioeconomic trends. However, the information generated from the InVEST model is only on future water supply for each scenario. In this study, several calculations are required in order to calculate the net changes in water availability for irrigation use. First, future demand is taken from present basin-level water demand from Liu et al. (2017) which includes gross irrigation use, domestic use, industrial use and livestock use. In Liu et al. (2017) water demand and use information for year 2011 is generated from the Water Balance Model (Grogan 2016; Wisser et al. 2010) given assumptions on future population and per capita income growth as well as precipitation and temperature. Domestic use, industrial use and livestock use are in turn projected forward using percent changes in grid-level population projections from the SSPs (Kriegler et al. 2010; O'Neill et al. 2014) while keeping water for gross irrigation use constant. Once projected, percentage change in future water demand is calculated. Future water supply is likewise calculated using water supply information from Liu et al. (2017) and percentage changes in water yield information from the InVEST model for each scenario. Water supply from Liu et al. (2017) includes river discharge, reservoir storage and groundwater storage. In this study, percentage changes in river discharge are projected forward using the water yield information from InVEST.

We used the GTAP-AEZ model to estimate the impacts in changes of water yield with agricultural water scarcity estimates extracted from Liu et al. (2014). This paper introduced water into the GTAP modelling framework at a river basin level in addition to separating crop production into irrigated and rainfed sectors. Unfortunately, the latest version of the database used in Liu et al. (2014) was developed for year 2001 only and it is not clear if newer versions of the database that have more regions and for more recent years will be developed soon for the purpose of this project. Also, both gains and reduction in water availability for irrigation have been limited to -40% and +40% in order to avoid numerical issues in the solution method. We used the results from this paper to get the implied real GDP reductions from reduced water availability in agriculture, which we then impose in the GTAP-AEZ model using national-level productivity shocks.

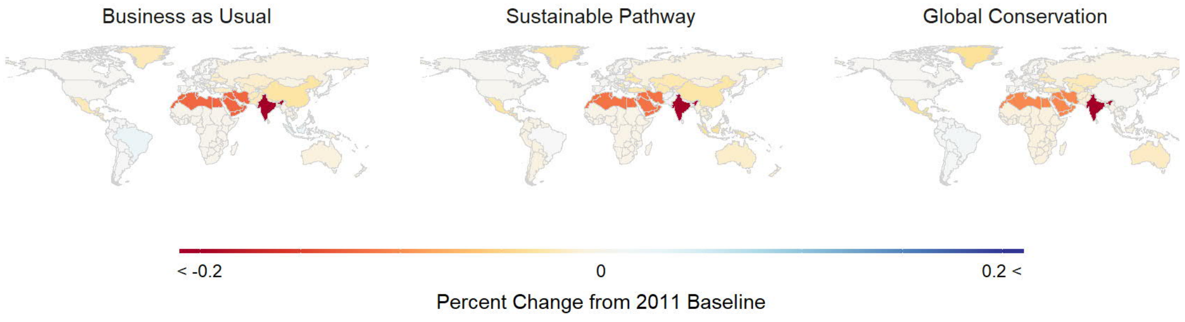
The methods above are summarised as an impact-pathway diagram for water yield in figure 2.3.4.1 while figure 2.3.4.2 summarises the irrigation water availability shock for each GTAP region.

Figure 2.3.4.1: Impact pathway for water yield



Water yield impact pathway short description: Changes in precipitation as well as land-use change affect evapotranspiration and water infiltration rates. In locations where these changes cause supply of water to be less than demand, we model the impact by lowering the yield of agricultural production from the irrigated yield to the lower rainfed yield.

Figure 2.3.4.2: Percentage change in GDP due to changes in water yield under three 2050 scenarios



The reason that these shocks are quite similar in percentages is because the countries most affected by changed water demand, which is high in all scenarios, tend to be larger than the changes in water availability, but upon close inspection the shocks are significantly worse under BAU.

2.3.5 Forestry production GTAP methods

Here we have focused on impacts on timber production from changes in ecosystem services. Based on InVEST (see Section 2.2.4) we identified grid-cells which have forest cover and assumed any change in carbon stock in those cells constituted a commensurate change in timber production in that cell. Specifically, if a grid-cell has more carbon stock, we are assuming that leads to an increase in productivity as more carbon is equivalent to more timber available for the forestry sector to extract. Our model is not a dynamic model, however, and so does not consider the timing of the extraction or the regrowth rate, though we are still able to benefit from the dynamic forestry models involved in the underlying integrated assessment models that generated the SSPs. Here, we rely directly on the InVEST model output of gridded carbon storage changes that result from the new landscapes.

Aggregated to the national level, these changes in forestry sector productivity form a country-level shock that can be applied in the GTAP-AEZ model (Plevin et al. 2014). A technical challenge in modelling these shocks was that in regions that currently have very small forestry sectors and also experience a very large change in forestry cover, the relative size of the shock was very large and prevented a solution from being found. Thus, we set a bound on forest productivity at -10% to 10%, which enabled the model to be solved. This constraint has little to no impact on the results because most countries with any significant forestry had much more reasonable productivity shocks.

The methods above are summarised as an impact-pathway diagram for forestry in figure 2.3.5.1 while figure 2.3.5.2 summarises the forestry sector productivity shocks for each GTAP region.

Figure 2.3.5.1: Impact pathway for forestry production

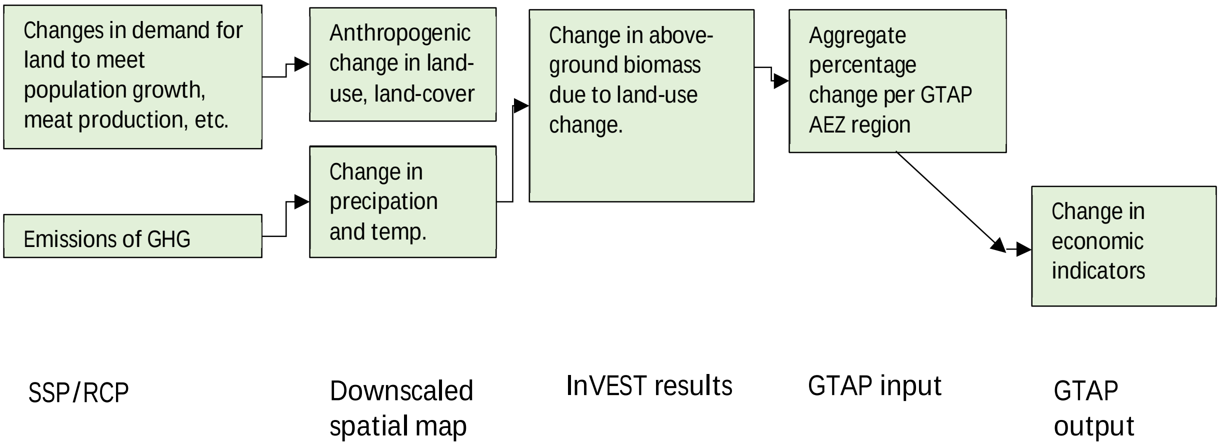
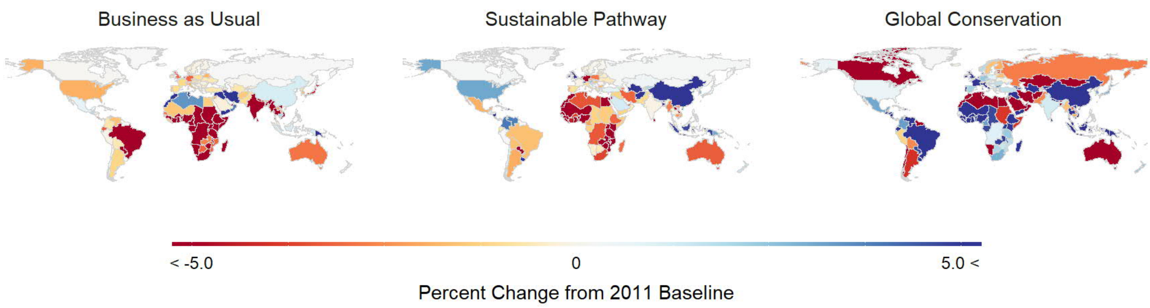


Figure 2.3.5.2: Percentage change in forestry production due to changes in forested habitats under three 2050 scenarios



Forestry impact pathway short description: Reductions in biomass from changed LULC results in less timber being available. We model this as a percentage change in yields equal to the percentage change in carbon storage on lands in forest LULC classes. While many countries gain forest cover under the GC scenario, a number of countries experience significant losses, due to a variety of factors, including climate change and land-use change for other purposes. Thus there are very heterogeneous results across countries.

2.3.6 Carbon storage GTAP methods

We calculated these impacts via the social cost of carbon (SCC) set at US$171 per metric tonne. Several aspects are necessary to understand this choice. When considering how future costs should be considered relative to present-day values, there are (at least) two components to include: first is the “pure rate of time-preference,” which captures the fact that people prefer to consume things sooner rather than later, all else being equal. Second is the discount rate, which combines the pure rate of time-preference with a calculation of substitutability between future economic growth and climate damages. Choosing the pure rate of time-preference is an ethical decision and typical values range from 0.1% (lower end of Stern, 2007) to 3% (upper end of Nordhaus and Boyer, 2000). Many subsequent analyses avoid this ethical choice by presenting a range of estimates for different pure rates of time-preference. For instance, Tol (2009) presents results for 0%, 1% and 3% pure rates of time-preference. This study included a comprehensive review of 232 valuations of the SCC and best values for each rate of time-preference. We chose to use the middle value, 1%, following Figure 2 in Tol (2009).

The second factor, the full discount rate, can vary depending on which decision-maker you are assessing. Following the methods used in Johnson and Hope (2012), we chose to consider the rate based on the "risk-free" rate savers and borrowers use to discount future consumption, which is approximated by long-term, low-risk investment returns (such as treasury notes). This reflects, for instance, the fact that investments in climate mitigation today have an opportunity cost of forgone investments in economic growth in future time periods, which could help offset the harm of climate change. Following work from the Interagency Working Group on the Social Cost of Carbon in the United States, we chose to use their central estimate of this figure at 3%. Finally, given these considerations, we chose to use the mean value of Tol's fitted distribution that summarised his meta-analysis of values, which when converted to 2011 dollars is US$171.

The SCC specifies the marginal increase in damages to the economy from emission of a tonne of carbon, specific to the year in which the carbon was emitted. In typical usage, the SCC captures the total stream of discounted value, so we convert these numbers to annualised figures (see section 2.4.2). Note that we are not implementing carbon storage changes as a shock to regional economic systems in GTAP and instead are calculating the damages post-hoc and re-expressing the damage in comparable terms.

2.3.7 Marine fisheries production GTAP methods

Based on the results obtained in figure 2.2.5, we aggregated by GTAP-AEZ region the percentage change in commercial biomass density and applied it as a country-level productivity shock to the fishing sector. This is summarised as an impact-pathway diagram for marine fisheries in figure 2.3.7.1 while figure 2.3.7.2 summarises the productivity shocks to marine fisheries for each GTAP region.

Figure 2.3.7.1: Impact pathway for marine fisheries production

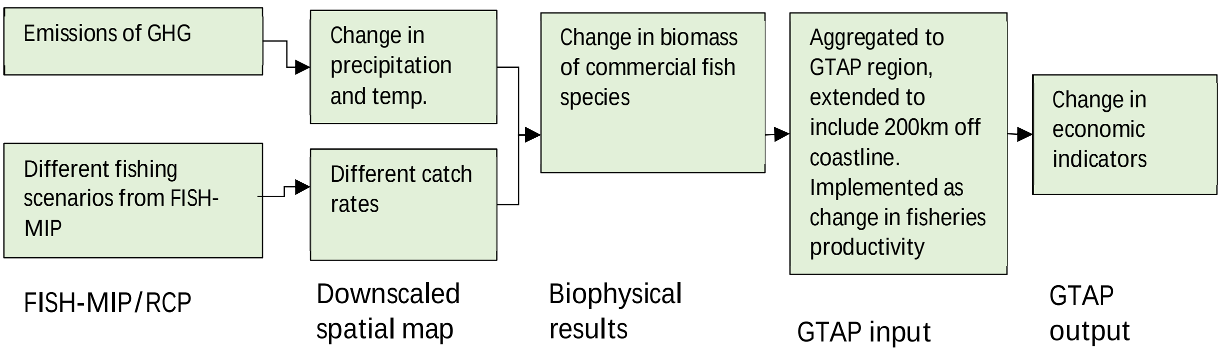
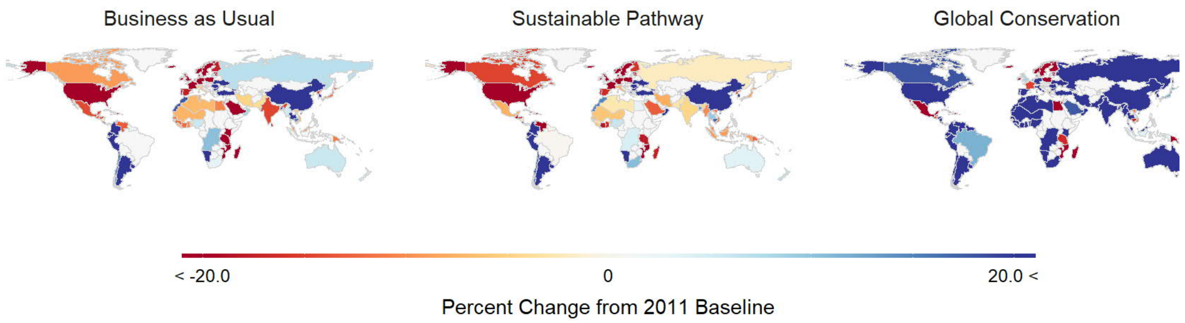


Figure 2.3.7.2: Percentage change in fisheries production due to changes in marine habitats under three 2050 scenarios



Marine fisheries production impact pathway short description: Changes in temperature and level of fishing lead to different catch rates for different GTAP regions, which we model as a percentage productivity change in each region's marine fisheries sector. Under the GC scenario, bringing the level of fishing into line with the level consistent with maximum sustainable yield results in higher catch rates in the long term, hence a much-increased level of productivity.

Step 4: Processing results

The final step in the process is to convert the abundance of output data generated by GTAP into a useful set of macroeconomic indicators and show how each scenario differs in performance. This entails identifying the most important indicators (overall GDP, sectoral supply and prices, trade balance; presented in the reports section below) and calculating any desired time-series scaling (for example, scaling up the impacts by the growth in GDP, population, etc. reported in each scenario so that they reflect the impact of changed ecosystem services scaled to the size of the economy in future years). See the results section for products of this step. To answer questions about the ways economic impacts were distributed globally, we grouped GTAP regions by their corresponding income classification from the World Bank (World Bank 2019). We then compared the income classification groups in terms of impacts on GDP for each ecosystem service. Many additional analyses can be conducted by further processing the results presented in the Supplemental Results spreadsheet provided in conjunction with this report.

2.4.1 Calculating annual GDP impact

The GDP figures presented throughout this report are based on multiplying the percentage change in each scenario by the total size of the 2011 economy. Our method for analysing shocks to the CGE model is a comparative statics approach, meaning that we start with a baseline equilibrium calculated from observed GTAP data, apply a percentage change to specific GTAP variables (described in depth in the next section), and then compare the difference in the new equilibrium from the baseline. The size of the percentage change reflects changes that occur by 2050, though we apply this to the observed structure of the economy from 2011. This means that non-ecosystem-services-based changes to the economy are not considered. A fully dynamic model (as proposed in this report's recommendations) would improve upon this approach by also allowing the structure of the economy to change over time.

2.4.2 Calculating cumulative, discounted GDP impact

To calculate the cumulative impact at the global level, we first computed the annual global GDP without ecosystem service impacts using total changes in global GDP between 2011 and 2050 from the SSP5 scenario. Next, we annualised the 2050 ecosystem service percentage change outputs by assuming the shock grows linearly each year from 0.0 in 2011 to reach the full effect (as defined per scenario in table E.2) at 2050. This annualised shock is then multiplied by the projected overall GDP for each year, following the approach in 2.4.1, to obtain each year's annual impact. GDP for these calculations was defined by the growth rate from the SSP of each scenario presented in the SSP indicators database (O'Neil et al. 2012).

Next, we discounted each year's annual impact according to $dv_t = \frac{av_t}{(1-\rho)^{t-t_0}}$, where dv_t is the discounted annual value in year t, av_t is the undiscounted value in that year, $\rho = 0.03$ is the discount rate that we used, and $t - t_0$ is the number of years past 2011 that year t is. We then sum the full time series of these discounted annual values for each scenario and report the difference from the baseline cumulative GDP. See the Supplemental Results spreadsheet, "Cumulative Calculations" tab, to see the actual calculations or section 2.3.6 for a discussion of how we chose to use a discount rate of 3%.

3 Results

Before proceeding to the detailed results below, it is important to note the proper way to interpret the output of a static GTAP model as presented here. GTAP-AEZ does not presume to holistically predict the economy in 2050 – rather, it uses the baseline year (2011) as a reference against which changes in the world's economy are observed in light of the projected ecosystem services changes in 2050. As such, all economic results presented below are impacts relative to the 2011 economy. That we are predicting them for the year 2050 is reflective of our land-use and climate scenarios, not the economy that we are applying those scenarios to. In short, we tested how landscapes from 2050 would affect the 2011 economy.

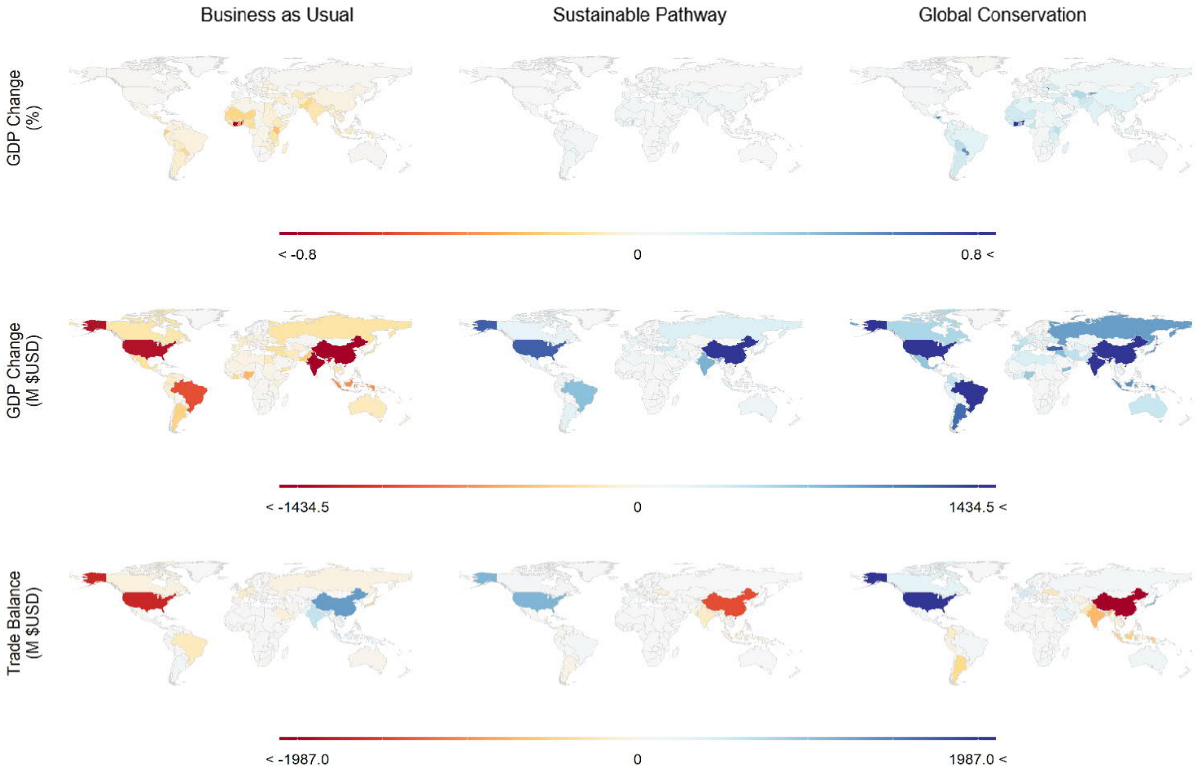
In this section we first present the results for the change in each type of individual ecosystem service in turn. We then present the overall results for the change in all ecosystem services simultaneously.

3.1 Pollination

Globally, the effect of changes in natural habitats on crop pollinators could result in changes in GDP of around -0.021%, 0.016% and 0.058% (or -15.3, 11.8, and 41.7 billion US$) annually under BAU, SP and GC scenarios, respectively, compared to a 2011 baseline. Figure 3.1.1 plots these results globally for the 137 GTAP regions while table 3.1 reports the most impacted regions (by percentage change in GDP).

These are significantly lower than the GDP loss estimates (around US$660 billion, see Appendix A-1) if we follow methods from Bauer and Wing (2016) that use the standard (non-AEZ) GTAP model and ignore spatial information on which land areas will experience loss in pollinator habitat. These differences arise from the significant methodological improvements implemented here: primarily that they only consider total catastrophic loss of pollination (rather than calculating the degree of pollination loss based on changes in habitat).

Figure 3.1.1: Changes in GDP (%, million US$) and trade balance (million US$) from 2011 baseline due to changes in pollination services for three 2050 scenarios



In terms of percentage loss of real GDP due to loss in natural pollinators, regions which are likely to expect severe losses under the BAU scenario include Togo (-1.64%), Cote d'Ivoire (-1.24%) and Benin (-0.49%). Looking at absolute losses in real GDP for the year 2011, large economies such as China (US$-2.9 billion), India (US$-2.2 billion), and the United States (US$-1.4 billion) are expected to face significant losses; emerging economies such as Indonesia (US$-0.7 billion) and Brazil (US$-1.0 billion) are also likely to suffer absolute reductions in real GDP. However, these absolute changes reflect a relatively small percentage of each region's overall GDP (between -0.03% and -0.12%). See Appendix table A-7.1.1 for a full account of macroeconomic impacts.

Notably, many of these losses are dramatically reversed in our SP and GC scenarios. In terms of percentage change, those regions most affected by BAU often benefitted most from the SP and/or GC scenarios, with Togo (0.07% and 1.39%), Cote d'Ivoire (0.16% and 1.35%), and Benin (0.30% and 0.99%) seeing marked increases. Similarly, the same large economies strongly affected by the BAU scenario saw commensurately large increases under SP and/or GC: China (US$3.3 and 10.7 billion), India (US$0.8 and 3.0 billion), and the United States (US$1.2 and 4.6 billion) were all positively affected.

When combined, China, India and the United States produce almost 45% of the world's crop production and comprise 35% of the world's GDP so it is not surprising that these countries generally show large absolute changes in GDP given the pollination shocks that we imposed (FAOSTAT, World Bank WDI). In terms of percent changes, real GDP in Togo, Cote d'Ivoire and Benin is heavily impacted by changes in the pollination productivity impacts. Note that agriculture, forestry and fishing sectors in these countries generally contribute more than 20% of their GDP (WDI). Furthermore, at least 45% of the value of crop production in these countries is produced by the fruits and vegetables, cotton and other crops sectors (Aguilar et al, 2016) which are generally more susceptible to the productivity changes due to pollinator loss relative to other sectors such as coarse grains.

Table 3.1: Regional impacts on GDP due to changes in pollination, ranked by % change in GDP

		BAU		SP		GC	
	Region	%	M US$	%	M US$	%	M US$
Most positive change from BAU to GC	Togo	-1.64	-61.5	0.07	2.5	1.39	52.4
	Cote d'Ivoire	-1.24	-298.8	0.16	39.5	1.35	325.3
	Benin	-0.49	-35.5	0.30	22.1	0.99	72.5
	Rest of Eastern Europe	-0.12	-8.7	0.26	18.0	0.73	51.1
	Ghana	-0.40	-156.9	0.05	18.3	0.44	175.1
Most negatively impacted by BAU	Togo	-1.64	-61.5				
	Cote d'Ivoire	-1.24	-298.8				
	Benin	-0.49	-35.5				
	Ghana	-0.40	-156.9				
	Kenya	-0.26	-90.6	0.05	18.3	0.28	95.4
Most positively impacted by GC	Togo					1.39	52.4
	Cote d'Ivoire					1.35	325.3
	Benin					0.99	72.5
	Rest of Eastern Europe					0.73	51.1
	Honduras	-0.14	-25.1	0.16	27.6	0.65	115.3

The loss in crop pollinators is expected to directly and indirectly affect global commodity supply quantities and prices. World supply of fruits and vegetables, oilseeds and cotton, all of which depend to some degree on pollination services, is expected to decline around -0.11%, -0.15% and -0.16% respectively by 2050 under the BAU scenario. Conversely, supply of these three commodities is expected to increase under both the SP (0.08%, 0.07% and 0.07%) and GC (0.29%, 0.25% and 0.28%) scenarios. For supply, international trade plays an important role due to heterogeneous impacts of pollination losses across regions. With less supply, however, prices of these pollination-dependent commodities in the world market are likely to rise sharply under the BAU scenario (0.96%, 2.06% and 2.89%). Similarly, increases in supply lead to decreases in price under SP (-1.06%, -1.14% and -1.02%) and GC (-3.31%, -4.63% and -3.99%) scenarios, as a result of changes in pollinators only.

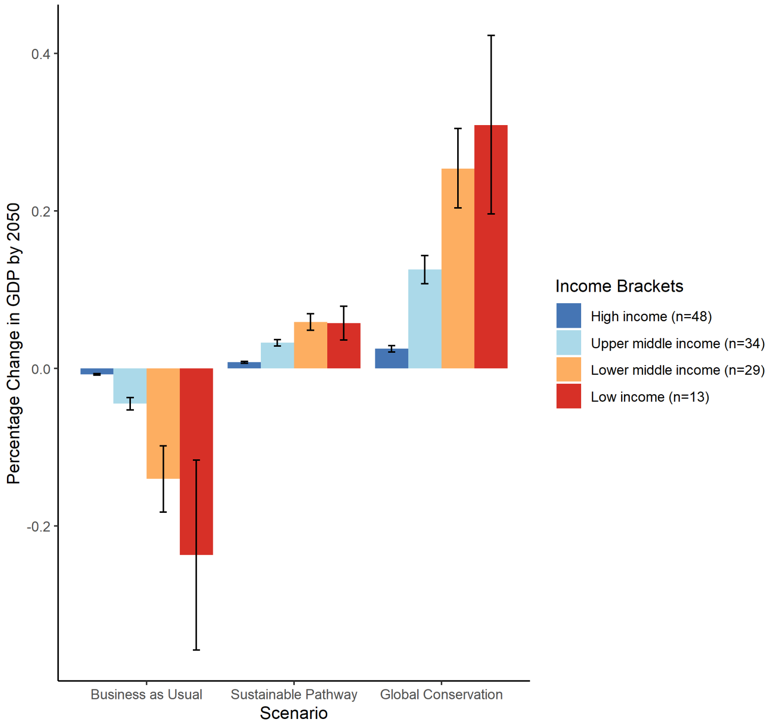
Overall, a key result is evident here that while the SP scenario outperforms the BAU scenario and provides a marginal increase in supply (and subsequent decrease in prices), the GC scenario significantly improves all economic metrics relative to the baseline. In general, this effect arises from the fact that even the SP scenario has considerable agricultural expansion relative to GC, and thus is only able to marginally improve ecosystem service provisioning.

It is important to highlight that sectors which are not directly affected by pollination, such as livestock, processed foods and processed livestock, also experience a reduction in global supply and rise in global prices (see Appendix table A-7.1.2 for a full account of sectoral changes). This is because in economic equilibrium models like GTAP, changes in output and prices for these sectors are affected by changes in the cost of production in the economy in other sectors. In this particular case, we see bidding up of the payments to land and labour resources by pollination-dependent crop sectors causing changes in the other sectors. Moreover, the rising domestic price of pollinator-dependent crops will likely result in greater cost of production for other sectors which use the crops as intermediate inputs in their production (e.g. feed use for livestock production, oilseed inputs in processed food sectors).

For all scenarios, some regions are less affected by changes in pollination services than others due to differences in crop composition as well as projected pollination efficiencies. In some scenarios, gains in productivity are observed due to positive gains in pollination efficiencies. For example, fruits and vegetables sectors in Spain, Italy, South Korea and Australia show notable gains in output across all three scenarios (see Appendix table A-7.1.2 for more detailed sectoral results). Pollination-driven productivity changes for these countries are positive under the SP and GC scenarios and face relatively milder losses in productivity under the BAU scenario. Looking at oilseeds, regions which show notable declines in sectoral outputs across all three scenarios include Puerto Rico, Ethiopia and Austria, although these countries are relatively small producers of oilseeds compared to China, Brazil and the United States.

Figure 3.1.2 shows the average change in GDP for four World Bank income classifications due to changes in pollination services under each scenario. It is clear that low and lower middle-income regions are generally at high risk from pollinator losses and have consequently more to gain from environmental protections.

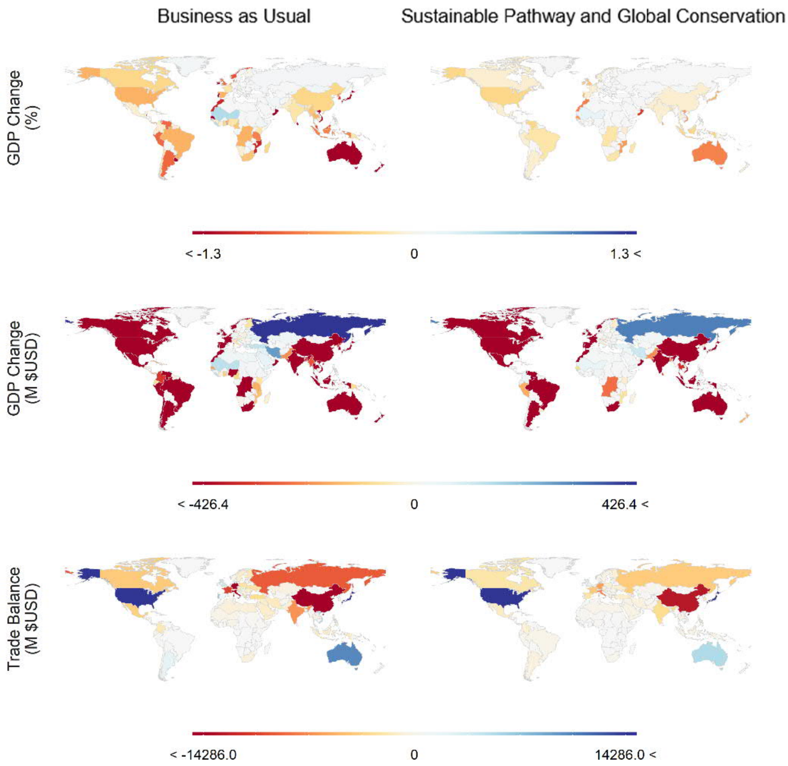
Figure 3.1.2: Average GDP impact (% change) from changes in pollination grouped by regional income classifications for three 2050 scenarios



3.2 Coastal protection

The combination of risks to infrastructure and agriculture in coastal areas under all three scenarios led to significant reductions in GDP both regionally and globally. Reduction in coastal protection services under BAU, SP and GC scenarios, could result in annual real GDP losses of 0.457%, 0.188% and 0.188% (or US$-326.9 billion, US$-134.2 billion and US$-134.2 billion) respectively. Figure 3.2.1 plots there results globally for the 137 GTAP regions while table 3.2 reports the most impacted regions (by percentage change in GDP).

Figure 3.2.1: Changes in GDP (%, million US$) and trade balance (million US$) from 2011 baseline due to changes in coastal protection for three 2050 scenarios



Note that some countries here and elsewhere in the report register no change in some scenarios, and hence are left blank in the table above. This is because under some SSPs, some smaller countries have no change predicted. While unlikely, we chose to stay closely aligned to the SSP projections of land-use change to ensure our results match aggregate distributions from the larger SSP community.

Under the BAU scenario, regions which expect severe losses in percentage of real GDP include Uruguay (-2.60%), Singapore (-2.30%) and New Zealand (-2.30%). The SP and GC scenarios mitigate these regionally specific losses somewhat (-0.10%, 0.01% and -0.10%, respectively), but at a global scale still experience a reduced GDP. Notable losses in absolute real GDP (at least US$-9.9 billion) are observed in large economies in all scenarios, especially for countries which directly face increased coastal risk such as the United States, Japan and the UK (see Appendix table A-7.2 for a full account of macroeconomic impacts).

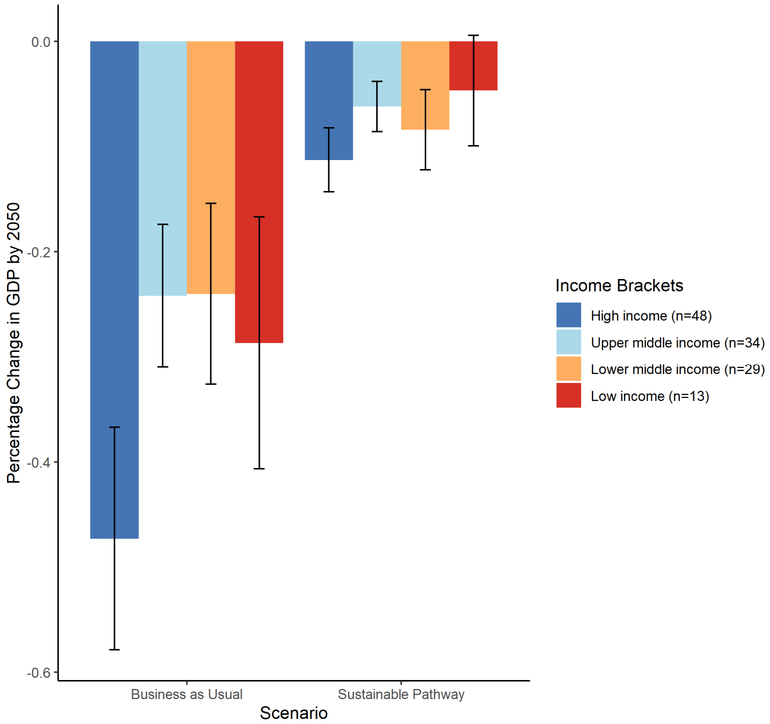
Table 3.2: Regional impacts on GDP due to changes in coastal protection ranked by % change in GDP

		BAU		SP		GC	
	Region	%	M US$	%	M US$	%	M US$
Most positive change from BAU to GC	Uruguay	-2.60	-1228.2	-0.10	-47.2	-0.10	-47.2
	Singapore	-2.30	-6303.5	0.01	14.3	0.01	14.3
	New Zealand	-2.30	-3768.3	-0.10	-163.8	-0.10	-163.8
	Portugal	-1.80	-4281.9	-0.50	-1189.4	-0.50	-1189.4
	Vietnam	-1.90	-2575.2	-0.60	-813.2	-0.60	-813.2
Most negatively impacted by BAU	Uruguay	-2.60	-1228.2				
	Singapore	-2.30	-6303.5				
	New Zealand	-2.30	-3768.3				
	Oman	-2.10	-1469.4	-1.00	-699.7	-1.00	-699.7
	Vietnam	-1.90	-2575.2				
Most positively impacted by GC	Rest of Western Africa	0.48	141.6	0.18	52.6	0.18	52.6
	Nepal	0.29	54.1	0.15	28.2	0.15	28.2
	Togo	-0.90	-33.8	0.08	3.0	0.08	3.0
	Guinea	-0.10	-5.1	0.07	3.7	0.07	3.7
	Ecuador	-0.10	-76.7	0.05	41.7	0.05	41.7

Increased coastal vulnerability is expected to dampen sector-wide productivity in affected countries which in turn causes changes in global commodity supply quantities and prices. Relative to other crops, notable reductions in global supply of cotton occur in each of our scenarios (between -0.10% and -0.23%). Because of supply reductions, the global price of cotton is expected to rise between 0.32% and 0.75% across our scenarios.

Figure 3.2.2 shows the average change in GDP for four World Bank income classifications due to changes in coastal protection services under each scenario. It is clear that high-income regions are at relatively high risk, likely because of GDP losses along affluent coastlines due to inland flooding, but that environmental protections will only mitigate damages without fully reversing them.

Figure 3.2.2: Average GDP impact (% change) from changes in coastal protection grouped by regional income classifications for three 2050 scenarios



3.3 Water yield

The economic impacts of future changes in water yield for irrigation are illustrated in figure 3.3.1. Globally, the losses in real GDP due to reduction in water yield are around 0.026%, 0.024% and 0.019% (or US$18.6 billion, US$17.0 billion and US$13.6 billion) annually under BAU, SP and GC, respectively.

As all scenarios predict reductions in global GDP due to future water scarcity, it follows that most regions experience reductions in GDP. Most notably, India faces a disproportionate reduction in GDP across all scenarios, both in terms of percentage loss of GDP (-0.31% to -0.49%) and real loss of GDP (US$-5.9 billion to US$-9.2 billion). The impacts of each scenario are not uniform, however. For instance, while India loses substantial GDP in each scenario, the threat to China's GDP reduces from a loss of US$-3.1 billion under BAU to a loss of US$-0.3 billion under the GC scenario. Table 3.3 reports the regions most impacted by water scarcity for each scenario.

Overall, these results are driven by the interplay between changing supply and changing demand. In locations that are not water-stressed (where supply is well above demand), changes in water availability have essentially no impact. However, in areas that are near water-stressed, changes in availability have very significant results. This modelling choice reflects that, at least in terms of agricultural production, water availability only has an impact when it changes behaviour around irrigation.

Figure 3.3.1: Changes in GDP (%, million US$) and trade balance (million US$) from 2011 baseline due to changes in water yield for three 2050 scenarios

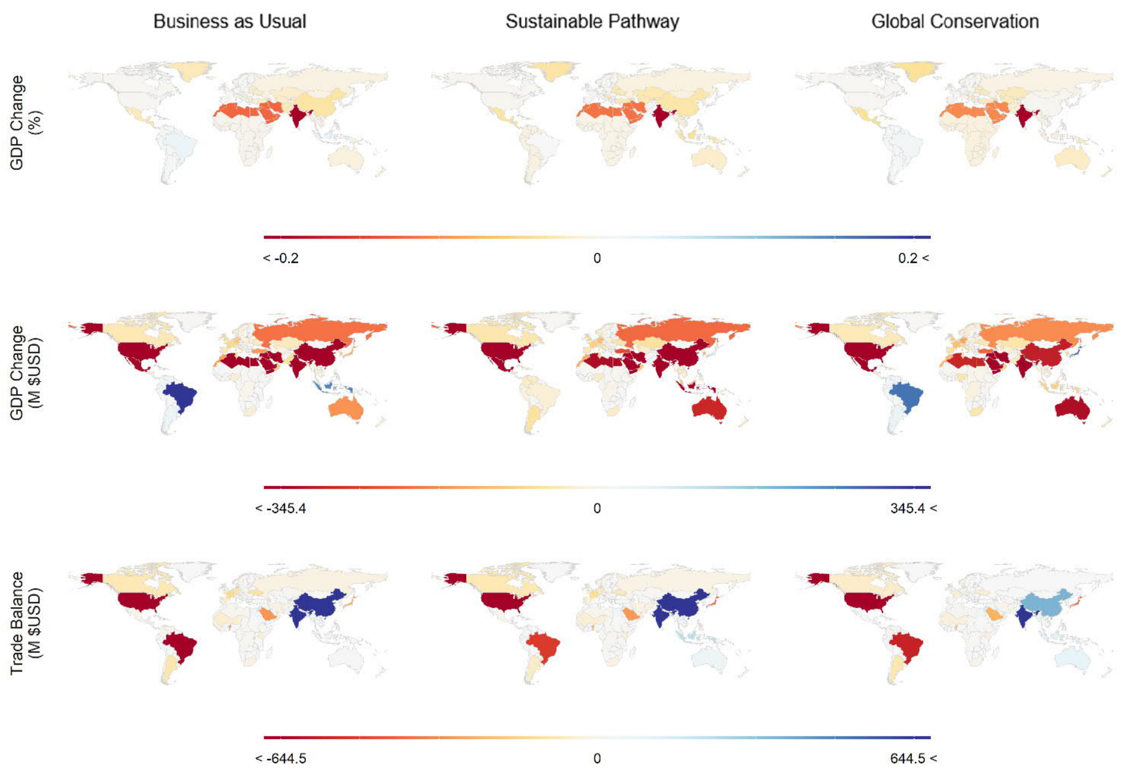


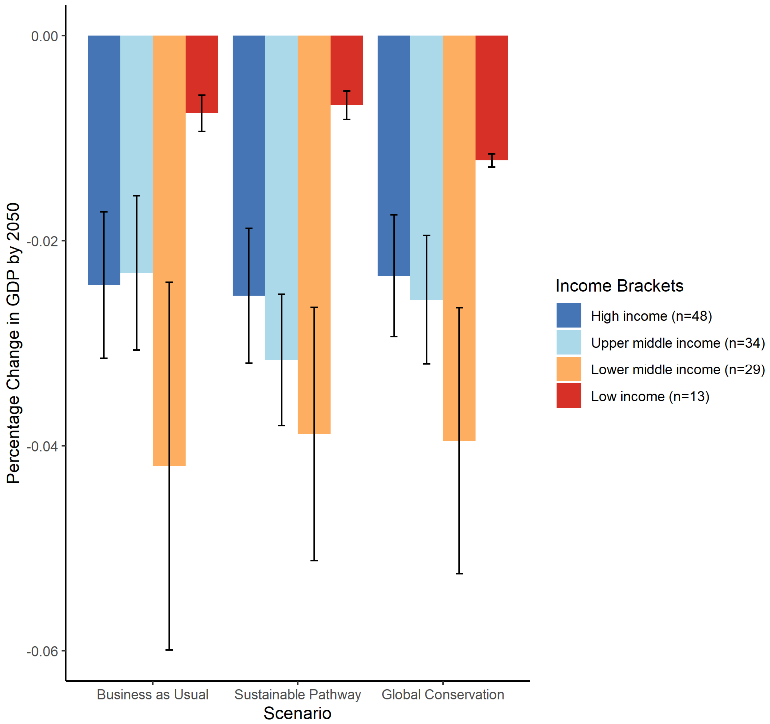
Table 3.3: Regional impacts on GDP due to changes in water yield ranked by % change in GDP

		BAU		SP		GC	
	Region	%	M US$	%	M US$	%	M US$
Most positive change from BAU to GC	India	-0.49	-9150.1	-0.31	-5866.8	-0.35	-6618.5
	China	-0.04	-3110.0	-0.04	-2934.0	0.00	-304.5
	Bahrain	-0.15	-44.1	-0.14	-41.0	-0.13	-36.5
Most negatively impacted by BAU	India	-0.49	-9150.1				
	Bahrain	-0.15	-44.1				
Most positively impacted by GC	Brazil	0.03	690.8	0.00	-22.0	0.01	276.0
	Argentina	0.01	30.3	-0.01	-59.2	0.01	39.1

In terms of agricultural commodities, the global supply of wheat, fruits and vegetables, and sugar crops is most at risk from changes in water yield. Under the BAU scenario, global supply of these commodities is reduced by -0.26%, -0.19% and -0.18% respectively; under the SP and GC scenarios those reductions are limited to around -0.20%, -0.12% to -0.15%, and -0.13% to -0.14%, respectively, as a result of changes in water yield alone. These reductions lead to price increases of between 1.27% and 1.49% for each of these commodities under BAU, 1.12% to 1.30% under SP, and 0.90% to 1.14% under GC.

Figure 3.3.2 shows the average change in GDP for four World Bank income classifications due to changes in water yield under each scenario. The proposed SP and GC scenarios do not significantly impact these aggregated results compared to the BAU. This is because changes in demand for water caused by increased production significantly outweigh changes in supply as a result of ecosystem services provision. Low-income regions are at less risk from the loss of irrigation due to lower water availability across all scenarios. This is because, in general, most of these low-income regions rely more on rainfed agriculture than irrigated farming.

Figure 3.3.2: Average GDP impact (% change) from changes in water yield grouped by regional income classifications for three 2050 scenarios



3.4 Forestry production

Future changes in forestry production in today's economy could result in real GDP changes of around -0.011%, 0.005% and 0.012% (or US$-7.5 billion, US$-3.9 billion and US$-8.4 billion) annually under BAU, SP and GC, respectively. Figure 3.4.1 shows the percentage and absolute changes in real GDP results globally (left and right panels, respectively) while table 3.4 reports the regions most impacted by changes in forestry productivity for each scenario.

Figure 3.4.1: Changes in GDP (%, million US$) and trade balance (million US$) from 2011 baseline due to changes in forestry production for three 2050 scenarios

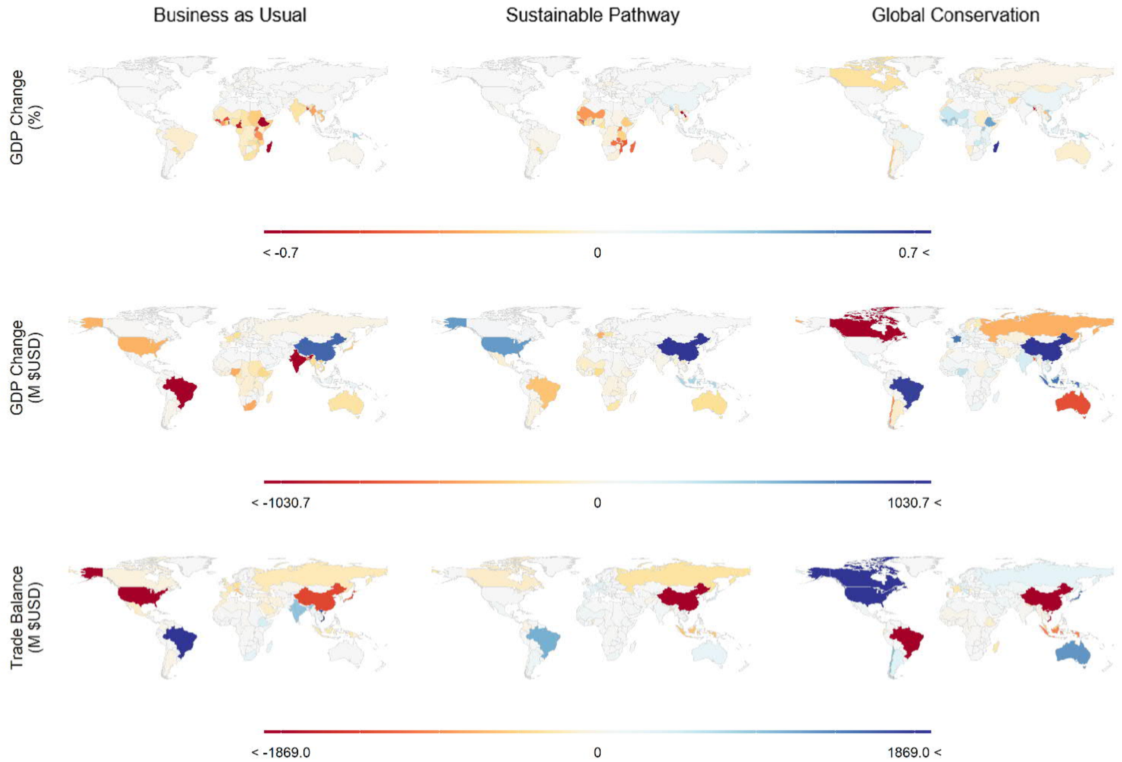


Table 3.4: Regional impacts on GDP due to changes in forestry production ranked by % change in GDP

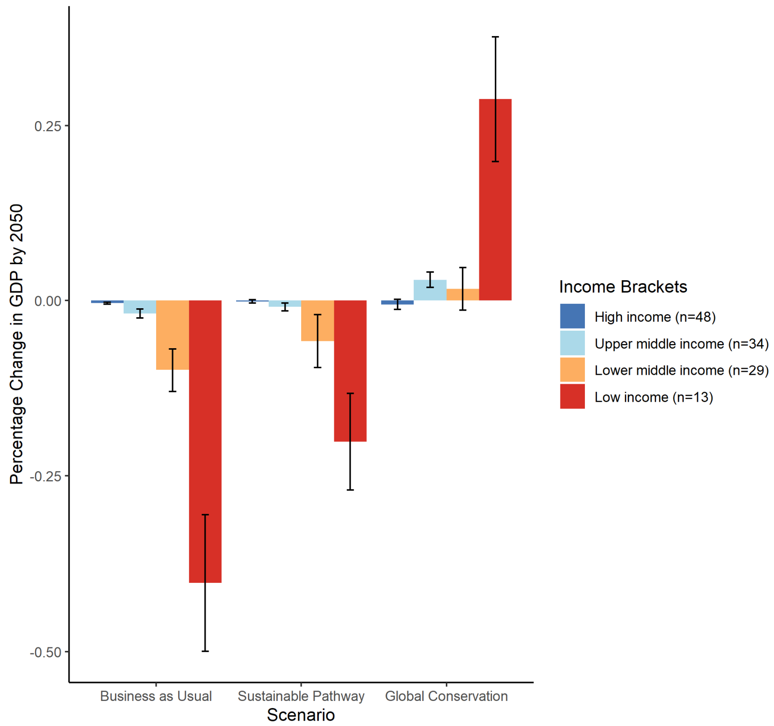
		BAU		SP		GC	
	Region	%	M US$	%	M US$	%	M US$
Most positive change from BAU to GC	Madagascar	-1.31	-128.7	-0.40	-39.8	1.23	120.8
	Ethiopia	-0.74	-233.4	-0.18	-57.0	0.41	129.5
	Togo	-0.61	-22.8	-0.52	-19.6	0.38	14.3
	Guinea	-0.48	-24.5	-0.41	-20.7	0.35	17.6
	Burkina Faso	-0.47	-48.4	-0.15	-15.5	0.32	32.9
Most negatively impacted by BAU	Madagascar	-1.31	-128.7				
	Ethiopia	-0.74	-233.4				
	Togo	-0.61	-22.8				
	Cameroon	-0.59	-150.8	-0.11	-29.0	0.16	40.8
	Bangladesh	-0.54	-598.9	0.33	371.0	-0.64	-715.0
Most positively impacted by GC	Madagascar					1.23	120.8
	Ethiopia					0.41	129.5
	Togo					0.38	14.3
	Guinea					0.35	17.6
	Burkina Faso					0.32	32.9

In terms of forestry production, the regions most at risk in the BAU scenario are also the regions with most to gain from the SP and GC scenarios. Madagascar (-1.31%), Ethiopia (-0.74 %) and Togo (-0.61%) are all set to lose significant percentages of their GDP under the BAU scenario but see significant net gains in the GC scenario (1.23%, 0.41% and 0.38%, respectively). Notably, while the SP scenario mitigates the losses these regions experience compared to BAU, it still prompts GDP losses for these at-risk areas (-0.40%, -0.18% and -0.52%, respectively).

However, forestry productivity varies widely between scenarios for some regions. For example, Bangladesh is set to experience a loss in GDP of -0.54% (US$-598.9 million) under BAU, a gain of 0.33% (US$371.0 million) under SP, and a loss of -0.64% (US$-715.0 million) under GC. As a contrast, China is expected to increase real GDP under each scenario (BAU: US$0.9 billion; SP: US$4.5 billion; GC: US$6.2 billion). The spatial heterogeneity of results is due to different rates of timber production in each country, coupled with variable levels of deforestation happening under the different SSPs. See Appendix table A-7.4.1 for a full account of macroeconomic impacts and Appendix table A-7.4.2 for detailed sector analysis.

Figure 3.4.2 shows the average change in GDP for four World Bank income classifications due to changes in forestry production services under each scenario. It is clear that low-income regions are at severe risk from reduced forestry production under the BAU and SP scenarios and have a significant amount to gain from environmental protections.

Figure 3.4.2: Average GDP impact (% change) from changes in forestry production grouped by regional income classifications for three 2050 scenarios



3.5 Carbon storage

Using the value of US$171 per metric tonne for the SCC (see section 2.3.6 for justification), table 3.5 reports the total impact on GDP for each of our scenarios. Note that the SCC already incorporates potential equilibrium effects in the economy, so these values already take into account the full stream of costs and benefits. Thus, we also report the annualised value of this impact, following the methods in 2.4.2.

Table 3.5: Carbon storage results

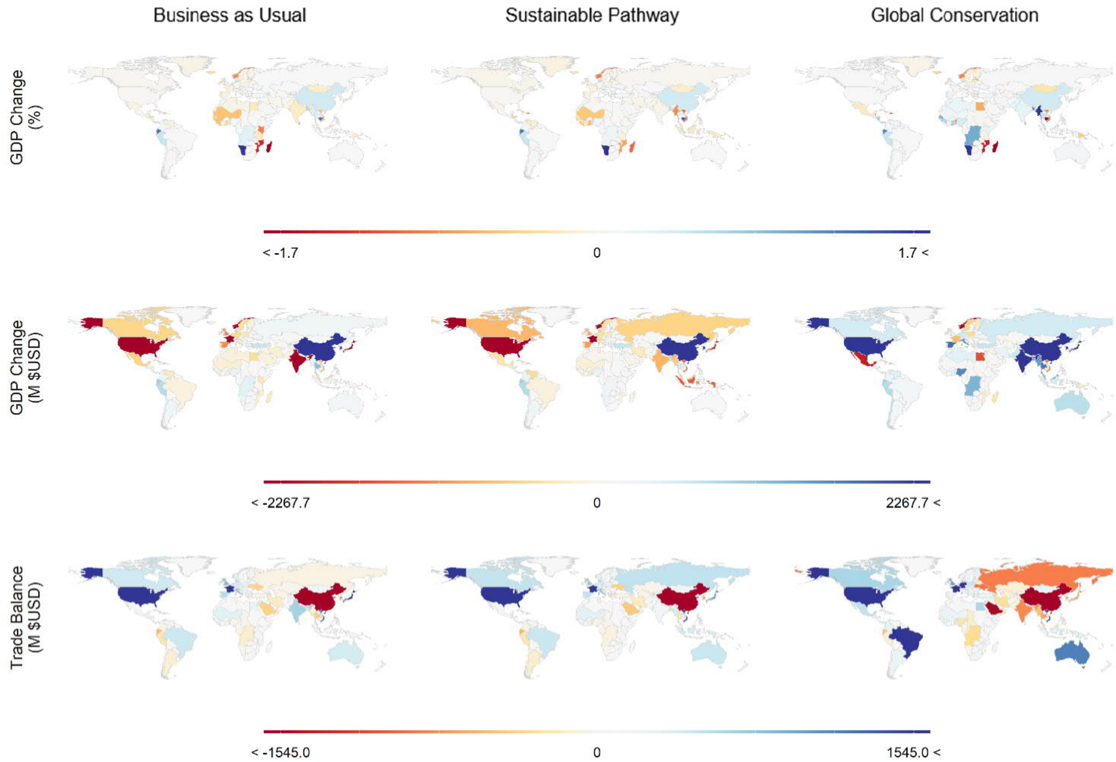
	BAU	SP	GC
Gigatonnes carbon storage difference from 2011 baseline	-3.7	-0.3	1.5
Value using US$171 per metric tonne social cost of carbon	-632,487.6	-49,893.3	253,782.5
Annualised impact value (see section 2.4.2)	-127,678.6	-10,119.6	51,570.0

3.6 Marine fisheries production

Changes in marine fisheries production increases global annual GDP across all three scenarios, with increases of 0.024%, 0.024%, and 0.080% (or US$17.1 billion, US$17.1 billion and US$57.3 billion) annually under BAU, SP and GC respectively. Figure 3.6.1 plots these results globally for the 137 GTAP regions while table 3.6 reports the most impacted regions (by percentage change in GDP).

Overall, under the BAU scenario the global effect on fish stocks and total catch quantity is negative, due mostly to climate change induced increases in ocean temperatures. However, there is very significant spatial heterogeneity in catches with some locations registering large increases as fish populations move and adapt as the climate changes. These increases happen to occur in the marine zones of countries where fisheries are a major component of their economy, thereby causing there to be an overall increase in economic activity even when there is a decrease in global fish stocks. This is a somewhat surprising finding that illustrates the importance of considering how economic systems might mitigate or exacerbate the impacts of environmental changes.

Figure 3.6.1: Changes in GDP (%, million US$) and trade balance (million US$) from 2011 baseline due to changes in marine fisheries production for three 2050 scenarios



The impact of climate- and fishing-driven changes in global fishery stocks varies across the regions used in this analysis. Some regions experience high reductions in GDP regardless of the scenario, both in terms of percentage (e.g. Madagascar: -2.58%, -1.03% and -3.33% under BAU, SP and GC respectively) and in terms of real GDP (e.g. Norway: US$-4.2 billion, US$-4.5 billion and US$-4.5 billion under BAU, SP and GC respectively). Others see reductions in GDP under BAU and SP that are mitigated through the GC scenario, such as the United States (US$-2.6 billion and US$-2.4 billion reduction under BAU and SP, US$2.6 billion increase under GC).

Others still experience the opposite with an increase in GDP under BAU and SP, and a reduction under GC, such as in Cambodia: increases of 1.31% and 1.44% under BAU and SP, and a decrease of -2.24% under GC. As above, this spatial heterogeneity was due to the different conditions in different locations where the FISH-MIP models predicted changes and where economies were more or less dependent on fisheries for their economic activity. For a full account of macroeconomic impacts, see Appendix table A-7.5.1; for more detailed sectoral results see Appendix table A-7.5.2.

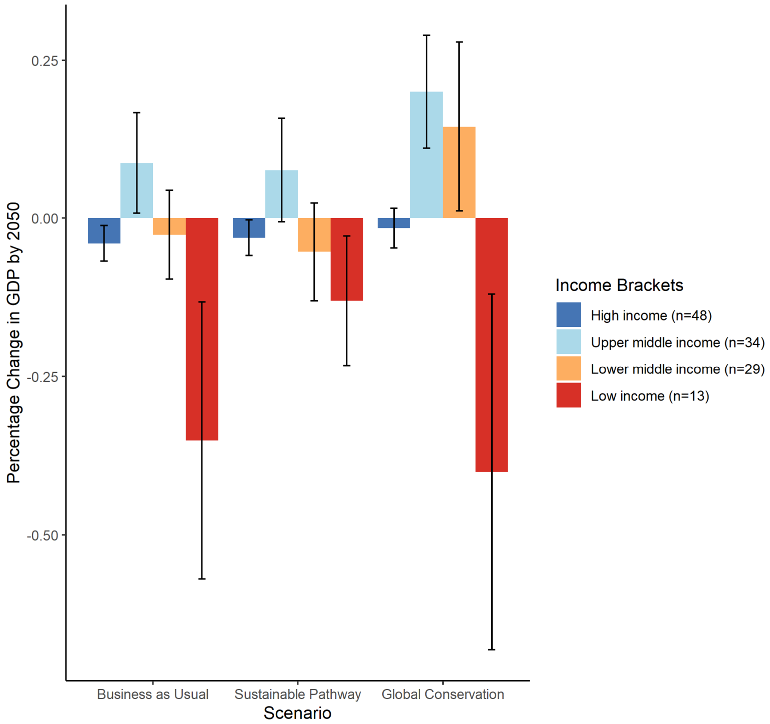
In general, developing coastal countries have the most to gain from the GC scenario as well as the most to lose from the BAU scenario. The regions Rest of Southeast Asia (Myanmar and Timor-Leste) and Rest of Central America (Belize) see the greatest percentage increase in GDP from the BAU to the GC scenario. Madagascar and Mozambique are at the greatest risk from BAU; both are located along the eastern coast of Africa which experiences a disproportionate reduction in fish stocks in our model.

Figure 3.6.2 shows the average change in GDP for four World Bank income classifications due to changes in fishery production under each scenario. It is clear once again that low-income regions are at high risk from changes in global fish stocks, but that the proposed scenarios of environmental protections only serve to improve the GDPs of middle-income regions on average.

Table 3.6: Regional impacts on GDP due to changes in marine fishery production, ranked by % change in GDP

		BAU		SP		GC	
	Region	%	M US$	%	M US$	%	M US$
Most positive change from BAU to GC	Rest of Southeast Asia	0.36	260.5	-0.86	-626.1	2.04	1494.5
	Rest of Central America	-0.31	-4.7	-0.43	-6.4	1.27	18.9
	Sri Lanka	-0.70	-412.1	-0.08	-46.2	0.81	478.2
	Senegal	-0.40	-58.4	-0.23	-33.2	0.94	135.8
	Guinea	-0.57	-28.8	-0.19	-9.5	0.69	34.8
Most negatively impacted by BAU	Madagascar	-2.58	-254.4	-1.03	-101.1	-3.33	-327.9
	Mozambique	-1.39	-174.6	-0.71	-89.3	-1.44	-181.1
	Kenya	-0.90	-310.1	0.00	1.5	0.28	95.7
	Norway	-0.86	-4226.7	-0.92	-4535.4	-0.92	-4517.5
	Sri Lanka	-0.70	-412.1				
Most positively impacted by GC	Rest of Southeast Asia					2.04	1494.5
	Namibia	2.05	255.4	2.05	255.1	1.99	248.1
	Bangladesh	0.70	788.6	0.60	668.7	1.32	1481.8
	Rest of Central America					1.27	18.9
	Ecuador	1.29	994.1	1.30	994.7	1.22	934.9

Figure 3.6.2: Average GDP impact (% change) from changes in marine fishery production grouped by regional income classifications for three 2050 scenarios



3.7 All ecosystem services in combination

When taken in combination, changes in ecosystem services presented above have a significant impact on projected economic outcomes. Global GDP is expected to change by -0.670% and -0.180% (or US$-478.9 billion and US$-128.6 billion) under the BAU and SP scenarios and increase by 0.016% (US$11.3 billion) under the GC scenario (see tables 3.7.1 and 3.7.2 below).

These numbers are likely conservative estimates as we included only pathways for which there was enough evidence to model the ecosystem service and to link it to the economic model. Additionally, note that our estimates are not designed to capture total environmental impact on the economy, but rather the specific contribution that ecosystem services make. This means that many of the effects of climate change, such as reduced labour productivity or changes in agricultural output from increased temperatures, are not included.

Table 3.7.1: Annual percent change in global GDP in 2050 due to changes in all ecosystem services under three scenarios

Ecosystem service	Business-as-Usual	Sustainable Pathway	Global Conservation
Pollination	-0.021	0.016	0.058
Coastal protection	-0.457	-0.188	-0.188
Water yield	-0.026	-0.024	-0.019
Forestry production	-0.011	0.005	0.012
Fish production	0.024	0.024	0.080
Carbon storage	-0.179	-0.014	0.072
All ecosystem services	-0.670	-0.180	0.016

Table 3.7.2: Annual change in GDP by 2050 due to changes in all ecosystem services under three scenarios (million US$, 2011 baseline)

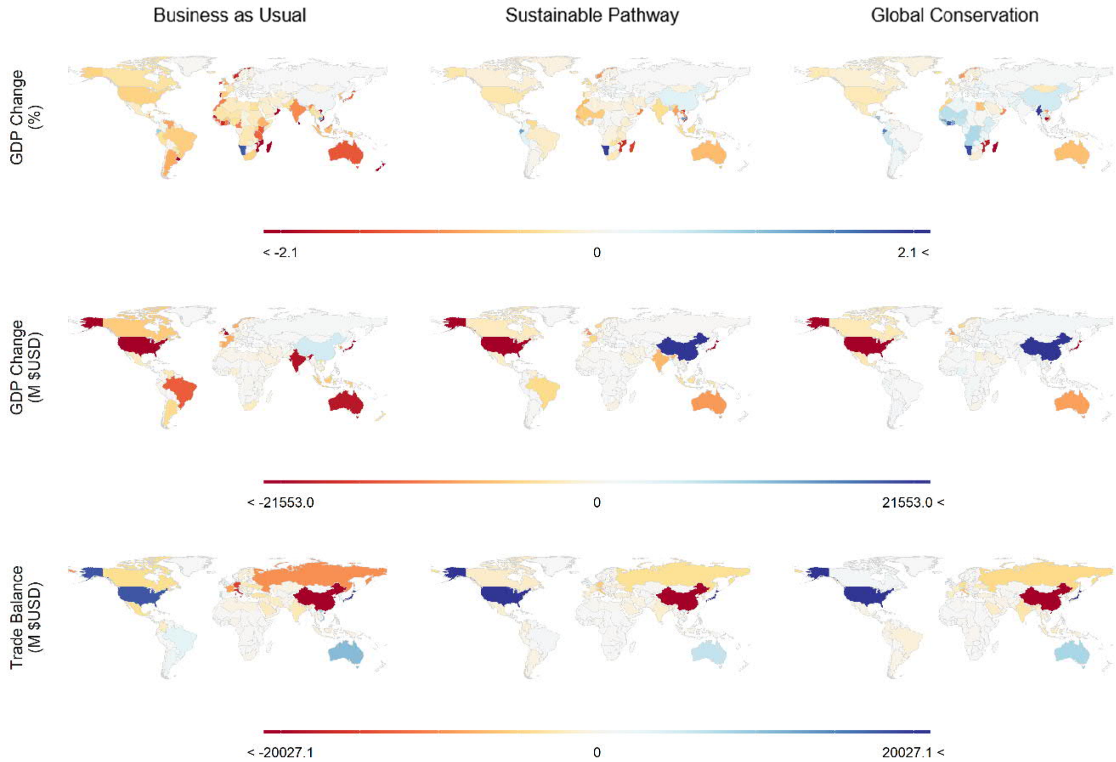
Ecosystem service	Business-as-Usual	Sustainable Pathway	Global Conservation
Pollination	-15,310	11,789	41,727
Coastal protection	-326,854	-134,169	-134,169
Water yield	-18,617	-16,995	-13,565
Forestry production	-7,519	3,856	8,418
Fish production	17,083	17,079	57,337
Carbon storage	-127,679	-10,120	51,570
All ecosystem services	-478,895	-128,560	11,319

Table 3.7.3: Cumulative change in GDP by 2050 due to change in all ecosystem services under three scenarios (million US$, 2011 baseline, 3% discount rate)

	Business-as-Usual	Sustainable Pathway	Global Conservation
All ecosystem services	-9,866,000	-2,646,361	232,923

Figure 3.7.1 also plots changes in GDP (%), changes in GDP in US$ and changes in the trade balance, while table 3.7.4 reports the most impacted regions (by percentage change in GDP).

Figure 3.7.1: Annual changes in GDP (% and million US$) and trade balance (million US$) due to changes in all ecosystem services for three scenarios



When taken together, the ecosystem services modelled in this analysis have a distinct impact on expected GDP. Some regions follow the global trends (BAU and SP reducing GDP while GC increases GDP), such as Togo, Cote d'Ivoire and Sri Lanka: percentage GDP reductions from -1.76% to -3.37% under BAU, -0.14% to -0.64% under SP, and gains from 0.43% to 1.83% under GC. Other regions were highly negatively impacted across all scenarios, such as Madagascar (-4.20%, -1.59% and -2.21% under BAU, SP and GC, respectively), Vietnam (-2.84%, -1.68% and -1.04% under BAU, SP and GC, respectively), and Mozambique (-2.69%, -1.73% and -1.91% under BAU, SP and GC, respectively). Still others such as Namibia (1.87%, 2.05% and 1.93% under BAU, SP and GC, respectively) were positively impacted across all scenarios, although such results were quite rare.

In terms of absolute value of GDP change, there were notable winners and losers among the larger world economies. China consistently experienced increases in real GDP (US$5.3 billion, US$31.7 billion, and US$43.1 billion under BAU, SP and GC, respectively), driven by consistent gains in production from pollinator-dependent agriculture, marine fisheries and forestry under all three scenarios. The United States, Japan and the UK all experienced absolute losses in real GDP under all scenarios. Under BAU, SP and GC, the United States lost US$-82.5 billion, US$-47.6 billion and US$-39.7 billion; Japan lost US$-80.0 billion, US$-30.9 billion and US$-25.7 billion; and the UK lost US$-21.1 billion, US$-10.6 billion and US$-9.3 billion. These losses were driven by various factors for each country, but primarily by changes in coastal vulnerability in coastal regions with high GDP earnings such as the cities of New York and Tokyo.

Table 3.7.4: Regional impacts on GDP due to changes in all ecosystem services, ranked by % change in GDP

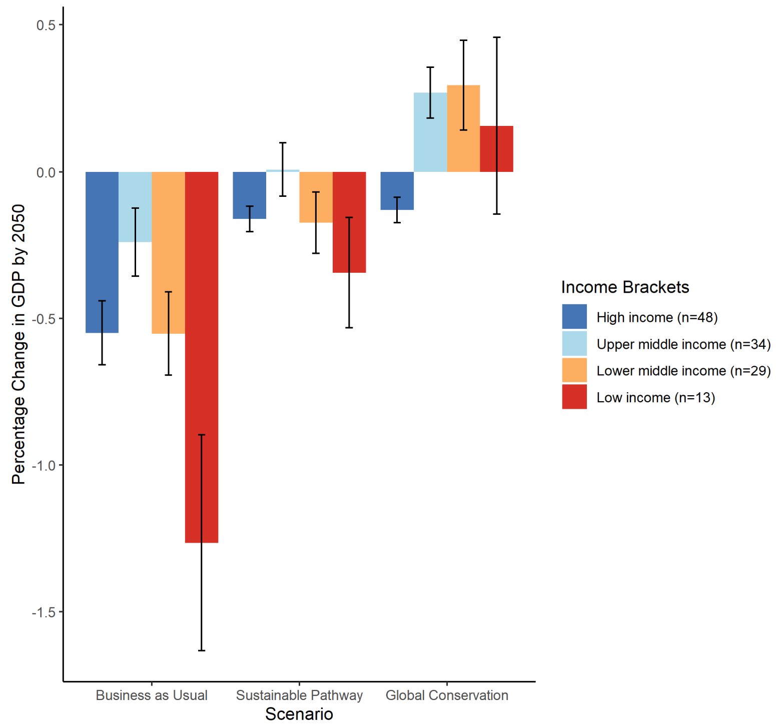
		BAU		SP		GC	
	Region	%	M US$	%	M US$	%	M US$
Most positive change from BAU to GC	Togo	-3.37	-126.6	-0.50	-18.9	1.67	62.9
	Cote d'Ivoire	-1.76	-424.1	-0.14	-32.8	1.83	439.5
	Sri Lanka	-2.48	-1466.3	-0.64	-378.7	0.43	252.7
	Uruguay	-2.54	-1201.3	0.04	20.4	0.14	67.2
	Guinea	-1.24	-63.1	-0.49	-24.7	1.30	65.7
Most negatively impacted by BAU	Madagascar	-4.20	-413.7	-1.59	-157.1	-2.21	-217.4
	Togo	-3.37	-126.6				
	Vietnam	-2.84	-3844.8	-1.68	-2274.4	-1.04	-1403.8
	Mozambique	-2.69	-337.6	-1.73	-217.5	-1.91	-239.4
	Uruguay	-2.54	-1201.3				
Most positively impacted by GC	Rest of Southeast Asia	-0.39	-287.5	-0.92	-673.2	2.06	1509.5
	Namibia	1.87	232.5	2.05	254.8	1.93	240.9
	Cote d'Ivoire					1.83	439.5
	Togo					1.67	62.9
	Ecuador	0.91	700.8	1.34	1027.5	1.57	1202.4

In terms of the global supply of various commodities, all experienced net losses under the BAU and SP scenarios except for the combined category of coal, oil, gas and other mining (0.15% and 0.17%) and forestry (-0.77% under BAU but 0.05% under SP). However, commodities in all sectors experienced increases in supply under the GC scenario except for 'other crops' and 'services' (see table A-6.2 for details of the commodities in these sectors). The most heavily impacted sector across all scenarios was fisheries, ranging from the largest decrease in supply under BAU (-1.14%) to the largest increase under GC (3.20%).

Changes in commodity supply cause commensurate changes in commodity price. All sectors that experienced supply losses under BAU and SP experienced commensurate increases in price, with the notable exception of fisheries which saw price drops of 5.37% under BAU. Similarly, for those sectors with large supply increases under GC, prices dropped. Most notably, fishery prices drop 21.54% under the GC scenario, as do prices for timber (by 6.17%), oilseed crops (by 3.67%), cotton (by 2.39%) and fruits and vegetables (by 1.93%). Additional analysis would be necessary to explain the market mechanisms behind these specific price changes, though they are likely due to substitution away from fishery products as a consumption good due to increased competitiveness of alternatives.

Figure 3.7.2 shows the average change in GDP for the four World Bank income classifications due to changes in all ecosystem services under each scenario. For all regional income groups, environmental protections implemented in SP and GC will serve to improve average GDP compared to the BAU baseline. It is also clear that GDP losses from changes in ecosystem services in the BAU scenario will be most significantly felt by low-income regions.

Figure 3.7.2: Average GDP impact (% change) from changes in all ecosystem services grouped by regional income classifications for three 2050 scenarios



4 Recommendations for future work

This project is a first attempt at an innovative linking of the fields of economic and environmental modelling, and there are several recommendations that could improve on the methods and results presented.

Recommendation 1: Work with emerging networks leveraging this work to create a fully endogenised, fully dynamic version of the current model. Building on progress made in this research, this model would consider impacts flowing in both directions, thereby making the linear model diagram in figure E.1 into a circle. Additionally, this cyclical interaction between the economy and the ecosystem would be recalculated at each time-step to analyse dynamic interactions between the two systems. The University of Minnesota, Purdue University, World Bank, UK Treasury and WWF are exploring opportunities to build this endogenous model and apply it to support a range of global/national policy processes.

Additionally, several independent initiatives have already arisen from this work, catalysed by the initial results presented in the webinars. In particular, a multi-million "network of networks" proposal has been led by Thomas Hertel (member of the core-team on this project), through the National Science Foundation (NSF) of the United States that would bring together key networks over the next five years to fill in the science gaps identified by this (and other, prior) reports, build capacity to run the combined InVEST-GTAP model in a cloud-based super-computing facility (NSF-funded XSEDE network), and improve the relevance of model results. We recommend working with and supporting this network.

Another independent initiative that has arisen is in conjunction with Unilever corporation. With prior experience working with University of Minnesota researchers, they have expressed interest in using InVEST-GTAP combined modelling approaches to assess sustainability of supply-chain choices, attribution of environmental impact globally, and a variety of other questions. We recommend pursuing this connection to identify possible collaborations.

Finally, additional work originating at the University of Minnesota is currently in the process of scoping needs and competitive advantage of creating and funding a new, next generation integrated assessment model (IAMs). This would extend existing IAMs in two key ways: first, it would incorporate a fully general equilibrium economic approach (GTAP), as opposed to the input-output, optimisation-based approaches currently used by most IAMs. Second, it would use recent advances in downscaling and multi-scale modelling to enable much higher resolution projections of key indicators such as land-use change. In particular, the native resolution would be between 30m and 300m, rather than 30,000m currently used in the highest-resolution IAMs. We recommend collaborating further with this endeavour.

Recommendation 2: Develop 'deep-dive' country/region case studies applying the model in specific contexts. One advantage of using the GTAP database is that it can be extended to many other models. This includes regional- or national-level models that contain increased detail about employment, land-use, policy, decision-making structure and/or land ownership, while retaining enough detail in the rest of the world to be able simultaneously to assess broader forces. In particular, the SIMPLE-G global model and/or the SIMPLE-G-US version of that model (Baldos et al. 2019) are good examples of this potential.

Recommendation 3: Continue to add more ecosystem services as global modelling progresses. Specifically, new evidence on sediment retention and soil quality, although not quite ready for this report, will very likely be available globally early 2020. Additionally, new evidence that parameterises the link between soil degradation and reduced yield could be leveraged to specify soil loss-related agricultural productivity shocks.

Recommendation 4: Build upon the potential to design different conservation scenarios (using SEALS) in order to assess different conservation strategies' effectiveness. The current project implemented a single vision of global conservation, but many other possible visions exist. We recommend work is undertaken to explore the potential economic effects of alternative 'packages' of policy goals, targets and/or interventions (e.g. related to LULC, protected areas, resource/energy use, production models, changes in consumption/diet, and economic/trade policy reform).

5 Analysis and discussion of results

This modelling framework developed in this work represents a methodological advance in the field of environment-economy modelling and provides the basis of a tool that can be used by governments, businesses and other actors to help enhance the sustainability of their decision-making. Further work is needed to understand the full range of ways in which changes in ecosystem services affect the economy (and vice versa), and to improve the ways that these linkages are considered in the model. However, the framework created represents a novel and useful approach that we hope will catalyse additional insight and provide a basis to build on in the future.

The results generated so far through this work also have important policy implications. The BAU scenario is harmful to both the value humankind receives through ecosystem services and to the economy, and thus, that we should strenuously avoid following that scenario. In some ways this is not surprising insofar as the BAU scenario represents a large increase in consumer activity, much of which is fuelled through expansion of agricultural and developed land that is undertaken in a way that does not consider how to minimise impacts on the environment.

We anticipate global losses of GDP per annum to be 0.67% by 2050 as a result of the loss of the ecosystem services that we have modelled under the BAU scenario. Even under the current levels of sustainability ambition, as modelled by our SP scenario, we expect annual GDP to be reduced by 0.18%. It is therefore clear that only by pursuing a more transformative global development agenda – including global effort to protect critical ecosystems and optimising land-use for biodiversity and ecosystem services delivery, can we reasonably expect a positive economic outcome, as modelled by the GC scenario with global GDP increased by 0.02% annually by 2050.

These figures lead us to conclude that changes in ecosystem services will have a significant impact on the global economy in monetary values. Calculating the cumulative impact from 2011 to 2050, discounted to 2011 terms, we see a loss of US$9.87 trillion under BAU and US$2.65 trillion under the SP scenario, and a gain of US$0.23 trillion under the GC scenario. These are significant numbers, considerably larger than the total value of liberalising global trade, a comparison highlighted in a preliminary project report produced ahead of the 2019 74th session of the UN General Assembly (Roxburgh et al., 2019).

The GTAP model provides a complex and comprehensive set of results for over 137 regions/countries globally, ranging from predicted supplies and prices of various commodities to changes in trade balance and regional GDP. We do not provide a detailed, country-level analysis here – those interested in that level of result are encouraged to explore the full results. In general, reductions in ecosystem services that directly contribute to the creation of various commodities (i.e. pollinator-dependent crops, timber yields, coastal agricultural products, fish yields) caused commensurate reductions in the supply of those commodities – an effect exacerbated in key production regions for each commodity, in particular China and India which produce roughly 19%, 39% and 36% of the world's oilseeds, fisheries and fruits and vegetables, in 2011 value terms (Aguilar et al., 2016). These reductions in supply cause price increases for these commodities globally.

Beyond a global outlook, this study allows us to ask questions regarding who is most impacted by the protection (or lack thereof) of nature. We grouped all GTAP regions by their corresponding income classification as per the World Bank (World Bank 2019) and compared the average impact of ecosystem services on GDP for all income brackets. From these groupings it is clear that low-income regions are likely to bear the brunt of GDP losses from changes in ecosystem services should we fail to implement environmental protections (as shown in figure 3.7.2). We conclude that implementing the actions in the

GC scenario is a pro-poor development strategy insofar as global equity would be improved by following a GC scenario. As shown in the figure above, under BAU, low-income countries see the largest loss in GDP from lost ecosystem services, yet these same countries stand to gain the most (as a percent) from following the GC scenario. This is driven by developing countries in Sub-Saharan Africa, Central America and Southeast Asia that see improvements in real GDP. These gains come primarily from ameliorating the heavy GDP losses in low-income countries under BAU due to changes in pollination services, forestry and fishery yields. Notably, high-income countries are most threatened by coastal inundation. As we explicitly linked coastal flooding to GDP losses along threatened coastlines, it follows that wealthy countries with high GDP-producing coastal cities (e.g. New York City, Tokyo) would be at the greatest risk from unmitigated sea-level rise.

Another key finding from our results is that the SP scenario still incurs a loss to the economy, but that the GC scenario obtains a gain. This is important because the SP scenario is often considered to represent the current level of sustainability ambition held by the global community, yet we show that it does not result in positive outcomes and can be considerably improved by better consideration of natural capital values in policy and land-use planning. Specifically, pursuing the sustainability goals in the SP scenario results in GDP losses of US$2.6 trillion from 2011 to 2050. However, by pursuing the targeted environmental changes set out in our GC scenario, the world can experience gains in GDP of US$232 billion over the same period. Both scenarios, however, are much better than the US$9.87 trillion of losses incurred over this period under BAU.

We also show that it is possible to simultaneously increase the value of ecosystem services and provide increased levels of food under the GC scenario. This conclusion arises because the GC scenario (and to a lesser extent, the SP scenario) is able to increase the value of ecosystem services while still providing the land necessary for agricultural production to take place. It was possible to engineer this win-win by strategically locating expansion of agriculture and developed land to areas that have lower conservation value.

Together, these should be a key message delivered to stakeholders at forthcoming global conservation meetings: we can and should aim higher and attain a positive global future for the environment, economy and human well-being.

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Appendices

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A-1: Literature review

Note: pieces of this review were used directly in the main text above.

In this section, we review the existing literature on the macroeconomic impacts of ecosystem services to help inform the experimental design. Specifically, we focus our review on studies which analysed ecosystem service outcomes using computational general equilibrium (CGE) models. Most ecosystem services impact pathways can be linked directly to key sectors of the national economy which tend to either gain or lose from changes in these services. However, there are also indirect macroeconomic leakage effects due to the existing sectoral linkages within the national economy and across international markets. These indirect effects can only be captured within a general equilibrium framework which has explicit price and value linkages across sectors and markets as well as substitution possibilities for both consumers and producers.

In general, we find very few studies which explicitly focus on quantifying the macroeconomic impacts of ecosystem services outcomes within a CGE framework. We find some evidence for crop pollination (Bauer and Wing 2010; 2016), for restrictions/reduction in agricultural land expansion to preserve biodiversity (Delzeit et al. 2017; Pelikan et al. 2015) and to increase forest carbon sequestration (Dixon et al. 2016; Golub et al. 2009; Tabeau et al. 2017), and for flooding and availability of water in the agricultural sector (Berrittella et al. 2007; Calzadilla et al. 2011; Liu et al. 2017; Roson and Damania 2017; Taheripour et al. 2018; van Vuuren et al. 2015).

To supplement this, we also extended our review to studies which focused on impact pathways which are loosely similar to the ecosystem services impact pathways that we are exploring. These include studies which apply CGE models to examine the macroeconomic impacts of changes in tourism flows (Berrittella et al. 2006; Bigano et al. 2008) and as well as output changes in the fisheries sector.

We fail to find specific examples in the CGE literature for ecosystem services impact pathways on improvements in timber harvests and output, increased hydroelectric output from better water resources management and for restrictions of nutrient use in agriculture. For these impact pathways, we rely on expert opinion on how these ecosystem services outcomes will affect the economy.

Evidence on macroeconomic impacts of ecosystem service pathways

Crop pollination loss. Bauer and Wing (2010; 2016) utilised the GTAP model in order to assess the economic impacts of global pollination loss within a CGE framework. Bauer and Wing (2010) reviewed the literature on pollination dependency of agricultural crops as well as the methods used to get the economic value of pollination. The authors argued that back-of-the-envelope calculations of economic benefits are either too limited in scope (e.g. cost of commercial pollination using honeybees, computed value of production lost, willingness-to-pay metrics) or fail to account for the economy-wide response to pollination loss. To address these issues, the authors used the GTAP model. The authors relied on the yield dependence ratios calculated by Klein et al (2008) who reviewed the literature to identify which crops are reliant on animal pollination and by how much. In total, Klein et al. calculated yield dependence ratios for 87 food crops which depend on animal pollination. These dependence ratios are then implemented in the GTAP model as input-neutral productivity shocks for each of four broad crop sectors. The authors estimated that the global economy-wide cost of pollination loss is around US$334 billion. Bauer and Wing (2016) provided a more in-depth analysis of the macroeconomic impacts of crop pollination using a more disaggregated version of the GTAP model. In addition to changes in GDP and sectoral output losses, the authors also reported equivalent variation, which is a measure of economic welfare losses in the whole economy. The authors calculated that the global economic cost from catastrophic pollination loss is around US$420 billion while the global economic welfare loss amounts to approximately US$140 billion.

Restrictions in land-use for ecosystem services and forest carbon sequestration. Because they can capture the complex market interactions within and across countries, CGE models have been used widely in analysing the economic implications of land-use restrictions due to policies aimed at mitigating GHG emissions and at preserving areas with rich biodiversity. Using a dynamic version of the GTAP model which accounts for land heterogeneity as well as non-CO_2 emissions, Golub et al. (2009) examined the impacts of land-based GHG mitigation activities in the global agricultural and forestry sector. Using a global carbon price to curtail GHG emissions and encourage forest carbon sequestration, the authors found that the agricultural sector will be adversely affected by a carbon tax due to the methane emissions from ruminants and paddy rice. On the other hand, the pricing of carbon results in a subsidy to the forestry sector which in turn encourages afforestation as well as intensification of managed timber forests. Dixon et al. (2016) used a dynamic CGE model called MAGNET in order to examine the tensions in agricultural land-use due to the EU Renewable Energy Directive (RED) and the United Nations programme to reduce emissions from deforestation and forest degradation (REDD). The authors used reduction in potential agricultural land availability implied by the REDD scenarios as shifts in the agricultural land supply in each world region. The results of the paper show that REDD policies aimed at agricultural land restrictions will result in an 8% decrease in global agricultural land-use relative to its business-as-usual scenario. Tabeau et al. (2017) also used the MAGNET model in order to analyse the impacts of REDD policies on the global farm and food sector. Similar to Dixon et al. (2016), the afforestation implications of REDD policies are modelled as area decreases in potentially available agricultural land across the world. The authors found significant trade-offs between food security and intensity of protection of potentially cultivable forestlands. This is especially evident in the case of more stringent REDD policies wherein protecting 90% of potentially available agricultural lands could result in an 8% increase in global food prices and a 2% reduction in global production.

There are a few studies which directly examine the trade-offs in food security and biodiversity targets. And similar to the studies above, preservation of land for biodiversity purposes are also modelled as shifts in the agricultural land supply curves. Focusing on the EU, Pelikan et al. (2014) quantified the economic impacts of biodiversity-targeted ecological focus area (EFA) requirements on all farms within the EU. The authors combined the results of an agricultural economic model to get the geospatial changes in the agricultural land-use and then applied these changes to the GTAP model. In total, around 4.5% of currently cultivated land in the EU will have to be taken out of production in order to satisfy the EFA biodiversity requirement. The results of the paper showed strong trade-offs between agricultural land reduction, greater intensification as well as leakage effects leading to increased agricultural production abroad. Delzeit et al. (2017) examined the trade-offs between biodiversity and cropland expansion at the global scale. The authors used the DART-BIO model which is a dynamic CGE model in order to project the global cropland requirements in 2030 with and without restrictions in cropland-use in areas rich with biodiversity. The results show greater global agricultural production at around 3% to 9% versus the future scenario where land restrictions are implemented.

Economy-wide impacts of changes in global tourism flows. CGE models are increasingly used in studies which assess economy-wide impacts of tourism. Berrittella et al. (2006) used the GTAP model to examine the global economic impacts of future changes in tourism flows due to climate change. The authors used estimates of future tourism flows from an econometric model given projections of economic and population growth implied by the Special Report on Emissions Scenarios (SRES) – A1. These changes in tourism flows are then incorporated in the GTAP model as increases in demand for recreational services. Furthermore, the authors assumed that the income spending by the tourists is considered as income transfers across countries. The authors find that changes in tourism flows due to climate change alter GDP across the world by -0.3% to +0.5% in 2050. Bigano et al. (2008) used the GTAP model to assess the implications of both sea-level rise and changes in tourism flows in the coming decades. Changes in future land endowments were taken from an integrated global environmental model while changes in tourism flows were derived from an econometric simulation model. Similar to Berrittella et al. (2006), changes in tourism flows are implemented in the GTAP model as shocks in domestic expenditure for recreational services while income spending by the tourists is considered as income transfers across countries. The authors report that changes in GDP due to sea-level rise and changes in tourism flows vary across regions ranging from -0.53% to 0.05%.

<u>Reductions in catch-rates in fishery sectors.</u> There are a few studies which used CGE models to analyse the fisheries sector. Seung and Waters (2010) built a regional CGE model of Alaska in order to examine the economic effects of changes in seafood demand, reductions in catch rates to encourage fish stock growth as well as increases fuel prices. The authors found that a 10% reduction in total allowable catch for pollock results in a 2.5% decline in fisheries output. Declining seafood demand as well as increased fuel prices also negatively affects the seafood sector output in Alaska. Similarly, Waters and Seung (2010) used a CGE model of Alaska in order to see the economy-wide impacts of a 30% reduction in the pollock allowable catch as well as a 125% increase in fuel price. And similar to their previous work, the reduction in catch rates reduces seafood sectoral output by around 8%.

Evidence on macroeconomic impacts of ecosystem services-like impact pathways

Water scarcity: many studies have developed and used CGE models to study the economic and environmental consequences of climate change, water scarcity and water management. These models, which have been used in various applications, carry several common features including, but not limited to, incorporation of water as an input in the production functions of crop sectors; examination of water issues in a small region of a river basin; use of water supply as an exogenous variable in the models; representation of water as a sluggish endowment with limited mobility; and lack of distinction between surface and ground water in global models. The base CGE model is the GTAP and the water representation has been added in the GTAP-E and GTAP-BIO extensions, resulting the GTAP-W and GTAP-BIO-W models, respectively.

Berrittella et al. (2007) study the role of water resources and the implications of reduced supply of water in water-scarce countries. The authors have worked with the concepts of virtual water, which is the water used in production rather than the water contained in the product, and water export/import, which is the water used to produce exported/imported goods. Under a scenario with restricted water supply, water use increases in the unconstrained regions as trade patterns shift; unconstrained regions produce and export more water-intensive products. If water constraints are higher, welfare gains respond less than proportionally and welfare losses more than proportionally. Shifts in trade patterns are also larger. If water is less mobile, the economy has less ability to adapt, and water constraints have a more negative welfare impact in most regions. An important drawback is no differentiation between the distinct qualities of water supplied; the water intensity coefficient does not capture the whole efficiency of water use.

The differentiation of water supply as well the destination to irrigated areas are important drivers and parameters in a CGE model to capture sectoral and regional heterogeneity. There is evidence that regions with higher irrigation efficiency changes save water, and this pushes other regions to reduce irrigation water use as well, mainly because of lower agricultural production (Calzadilla et al. 2011). Global agriculture could increase by 0.7% when all regions improve irrigation efficiency. However, the high level of aggregation in some regions, or highly heterogeneous countries (e.g. China), could cause some misleading results. Similarly, Taheripour et al. (2018) tried to avoid these drawbacks by considering a CGE model that explicitly traces water by country at the river basin level and by agro-ecological zones (AEZs). A large river basin could serve several AEZs. The authors have focused on rice, wheat, corn, soybean and sugarcane in South Asia. Under unrestricted water supply, the climate shocks increase the demand for irrigation, which could help partially mitigate the impacts of climate change on crops and food production in South Asia. Under water scarcity, the water demand in agricultural and non-agricultural sectors associated with the lack of water infrastructure would block the demand for irrigation, generating severe negative economic impacts and causing major land-use changes.

It is well known that climate change increases the demand for irrigation in many river basins around the world. At the same time, the water supply is expected to fall given economic growth, climate change and competition from different water uses. In this sense, sustainable irrigation water withdrawals arise as a challenge for food security and land-use change at global level. According to Liu et al. (2017) curtailing irrigation raises food prices in less developed countries and causes more carbon emissions from cropland conversion. The authors have used an integrated assessment using the SIMPLE-G model coupled with the Global Water Balance Model (WBM). The adaptation through moving water directly by means of inter-basin hydrological transfers and indirectly through virtual water trade can help resolve divergences in local water demand and supply, and therefore mitigate the pressure of excessive water consumption; relatively faster productivity growth in irrigated agriculture leads to different outcomes of pursuing sustainable irrigation; considerable within-region variation exists in the extent of irrigation vulnerability, land-use change and the associated carbon emissions.

Sea-level rise and flooding: CGE analyses of sea-level rise are usually part of broader integrated assessment exercises and they represent the end-of-pipe economic evaluation step of a soft-linking approach. The generation of scenarios for climate variables, the assessment of the physical impacts and the economic evaluation derive from different modelling exercises, connected in a sequential process. Climate models generate sea-level rise scenarios, which are used as inputs in coastal bottom-up models that generate changes in physical and biophysical indicators, such as loss in land or capital stock, and estimates of protection costs. Physical and biophysical indicators and protection costs are finally translated into shocks of key economic parameters represented in CGE models. The macroeconomic response to these shocks represents the economic assessment of the economy-wide impacts of sea-level rise.

Joshi et al. (2016) have addressed the physical and economic consequences of sea-level rise (SLR) for different regions across the world by combining a CGE model and cost-benefit analysis with a geographical information system tool considering different levels of uncertainties. Physical impacts of SLR specifically on agricultural land area loss, capital loss and people affected are estimated using GIS tools at each coastal segment. These impacts are then incorporated in the CGE model GEMINI-E3 to conduct economic analysis without protection cost. The SLR impacts in the CGE model are (1) loss of cropland area, (2) capital loss, (3) number of people affected and (4) investments in protection measures. These are simulated in GEMINI-E3 to investigate the impacts of SLR on national/regional economies. The simulation results showed that economic impacts due to loss in cropland without protection are low. In contrast, economic impacts of SLR due to loss of capital and number of people affected (change in labour supply and government expenditure on migration) are high when protection measures are not considered.

An extension of the GTAP-E model has been used to address ecosystem services and biodiversity correlated to sea-level rise (Bigano et al. 2008; Bosello et al. 2007). Bigano et al (2008) focused on the economic assessment of two specific climate change impacts: sea-level rise and changes in tourism flows. The sea-level rise is translated as a shock into the model as land losses are linear in the sea-level rise. Some land is lost in terms of productive potential, because of erosion, flooding and saltwater intrusion. However, the impacts associated with changes in tourism are larger than the direct impacts of sea-level rise, the maximum cost of a 25cm sea-level rise is 0.1% of GDP vs. 0.5% of GDP of the affected region.

On the other hand, Bosello et al. (2007) use two stylised scenarios: "no protection", i.e., no defensive expenditure takes place, so that some land is lost in terms of productive potential, because of erosion, flooding and saltwater intrusion; and "full protection", where no land is lost to sea-level rise, but which requires some specific infrastructure investment. The results show higher growth rates for the construction industry wherever new infrastructure is built. The main result is that the economy-wide costs are smaller than direct costs. The maximum cost of 0.25m of sea-level rise when capital loss is accounted for occurs in Japan (0.054%).

Key findings

The overall results of our literature review confirm that existing research on the linkages of ecosystem services to macroeconomic effects is very sparse. Among what does exist, there are two general categories of connections: welfare impacts and production efficiency impacts. The review conducted here focuses on the latter, as this is most relevant to modifying inputs of GTAP. However, the former is relatively better-documented in the literature, though it does not affect macroeconomic outputs (except insofar as aggregate welfare production is an output itself of macroeconomic models). We interpreted the focus of this project to be primarily focused on linking the ecosystem services results to macroeconomic variables, but because this is such a large component of existing literature and of the direct impact on human wellbeing, we report on both types of connections throughout the rest of this report. See Appendix figure A-2 for a modified version of our model-linkage diagram that includes explicit calculation of welfare changes.

Among the documented connections between ecosystem services and macroeconomic indicators, most analyses looked at how particular drivers of global change (e.g. climate, land-use change, demographics, consumption patterns) are reflected in macroeconomic models, and how, in turn, these affect the provision of ecosystem services. The CGE applications reviewed above primarily address how a shock to the economy from a change in the natural world would affect economic indicators primarily from a sector-specific point of view (rather than considering a full set of shocks on multiple sectors simultaneously). However, integrated modelling approaches do assess this type of integrated linkage, such as those reported by the scenarios technical support unit of IPBES and in a variety of efforts centred on defining systems of national accounts (SNAs) that include natural capital or inclusion of broader conceptions of "wealth" in macroeconomic variables. These have focused on macroeconomic impacts from erosion reduction, pollination, water availability, nutrient retention, recreation and tourism, and climate regulation (similar to findings in, e.g., Alkemade et al. 2009; Maes et al 2012; Schulp et al 2012).

Apart from the effect that ecosystem services have directly on the production efficiency of specific sectors, the literature is in relative agreement that a major linkage between ecosystem services and CGEs will be in the form of competition for land availability as a shared input (see Stevenson et al. 2013).

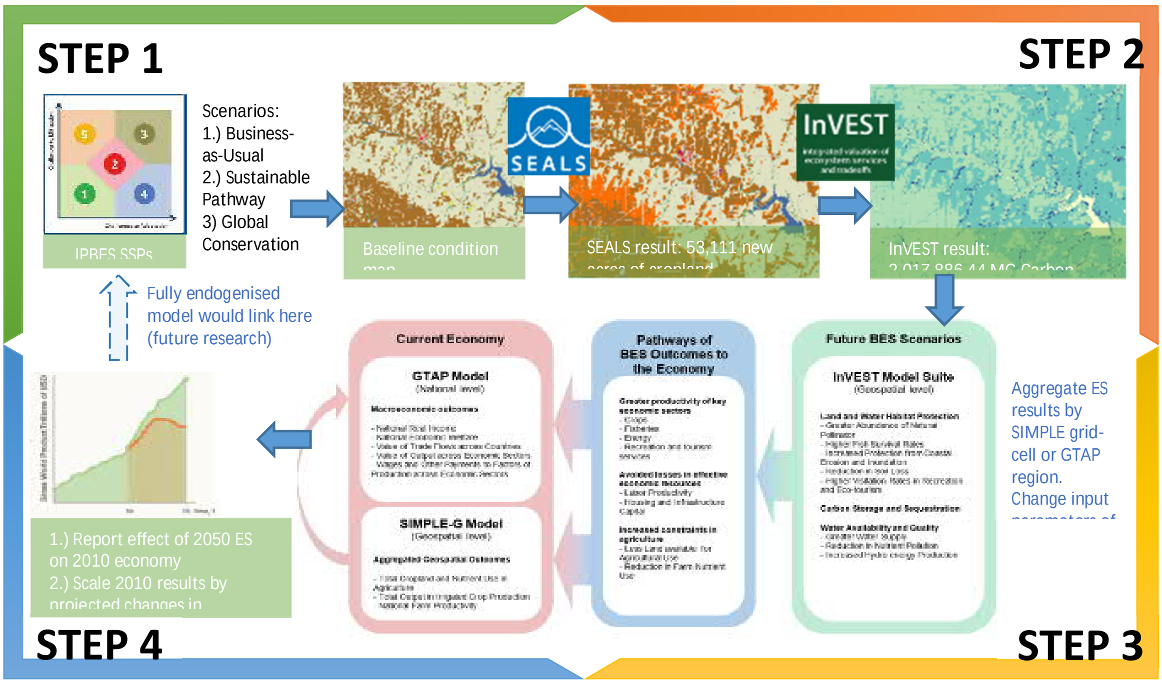
We find that this particular linkage will likely drive many of the impact pathways when we link ecosystem services outputs from InVEST to the specific input parameters to SIMPLE/GTAP.

We conclude that there is no ready-to-use approach that calculates macroeconomic outcomes of potential future scenarios of natural capital. Instead, new modelling work will be necessary that links ecosystem services to CGE models in a way able to 1) consider sufficiently detailed future scenarios of ecosystem services shocks that are spatially explicit and globally consistent, 2) consider a sufficiently broad set of ecosystem services impacts, and 3) include detailed modelling of ecosystem services provision (rather than simple per-hectare valuations). The remainder of this report and this project will seek to fill in the missing gaps necessary to create this type of a model.

A-2: Detailed model linkages

Because the set of models used and linkages made are quite complex, we present a second model-connections schematic in figure A.2 to augment the one presented in figure 2.1. This figure illustrates the same four steps, but now includes details on how the models are actually linked.

Figure A.2: Detailed schematic of the GTAP-InVEST model linkages



A-3: Spatial data for scenarios

Figure A-3.1: Business-as-Usual scenario land-use, land-cover map

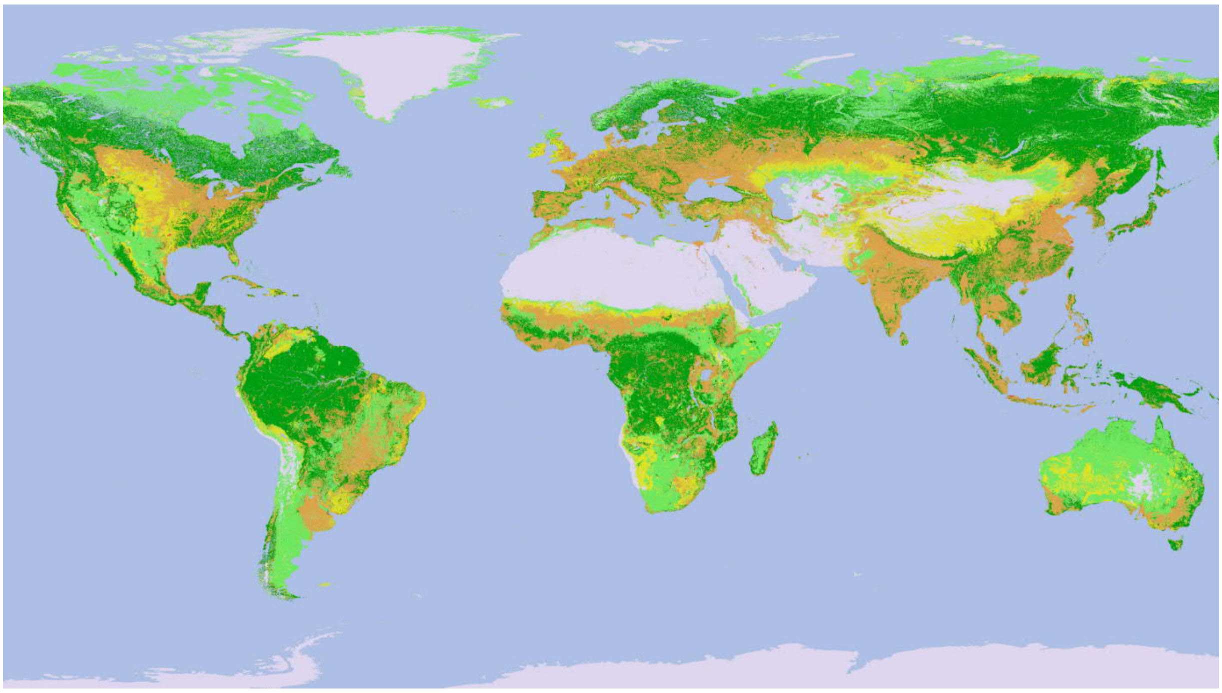


Figure A-3.2: Sustainable Pathway scenario land-use, land-cover map

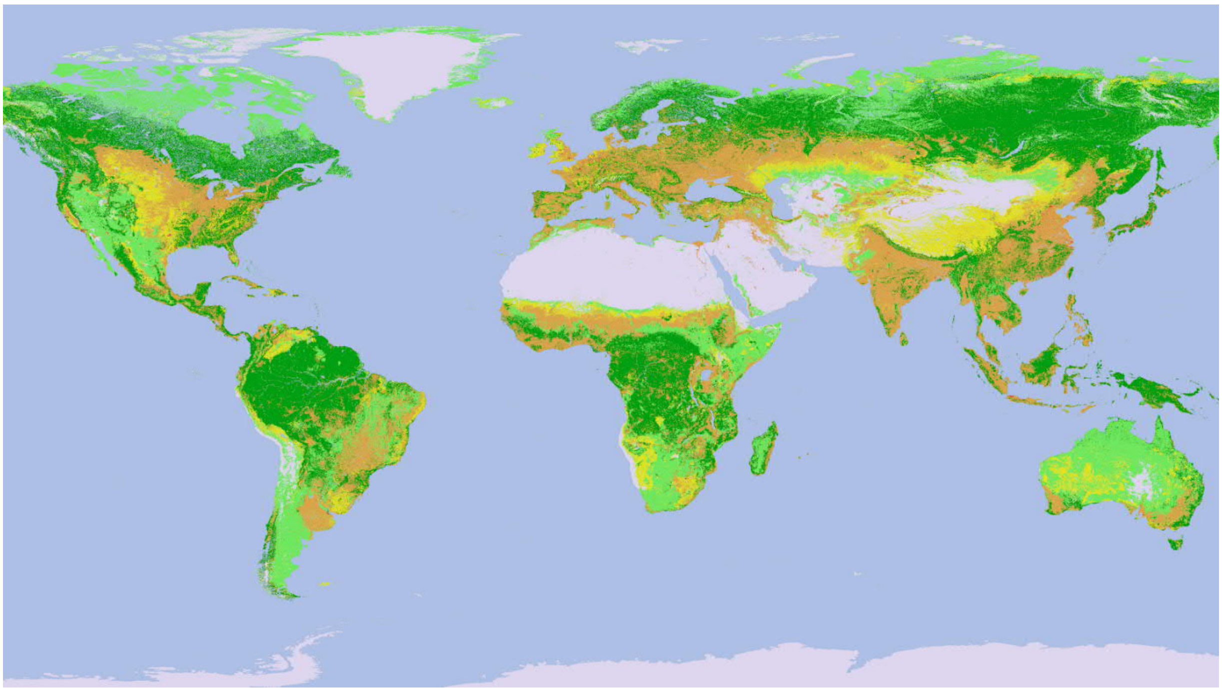
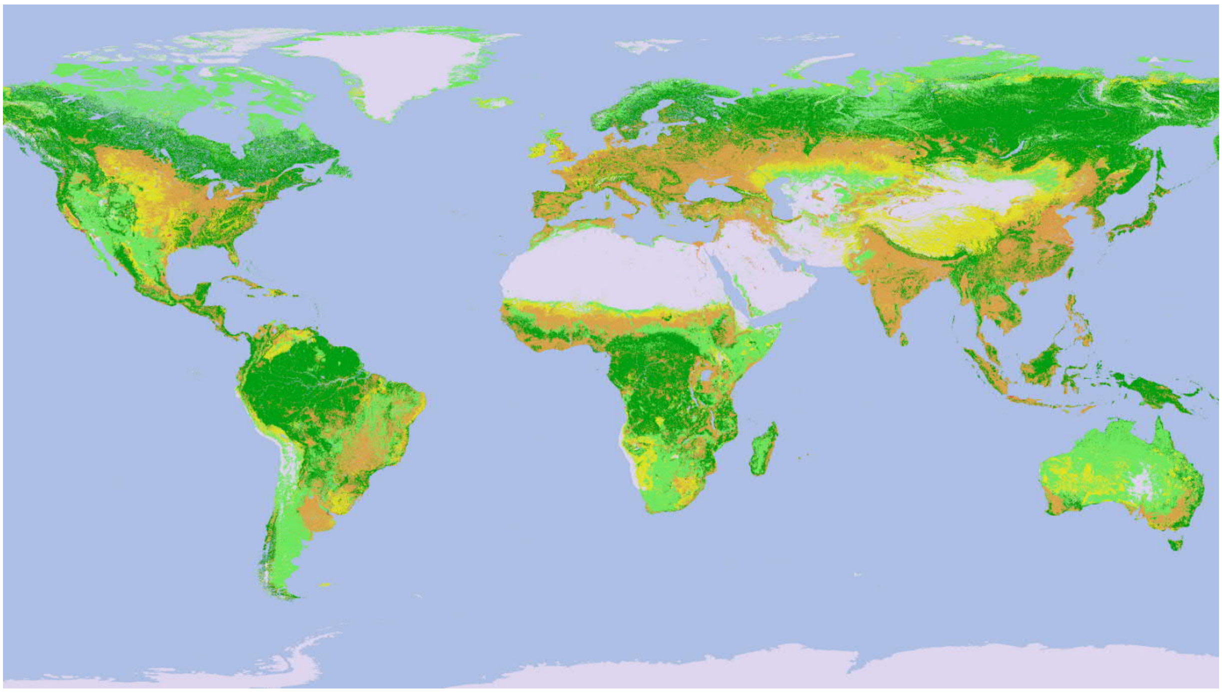


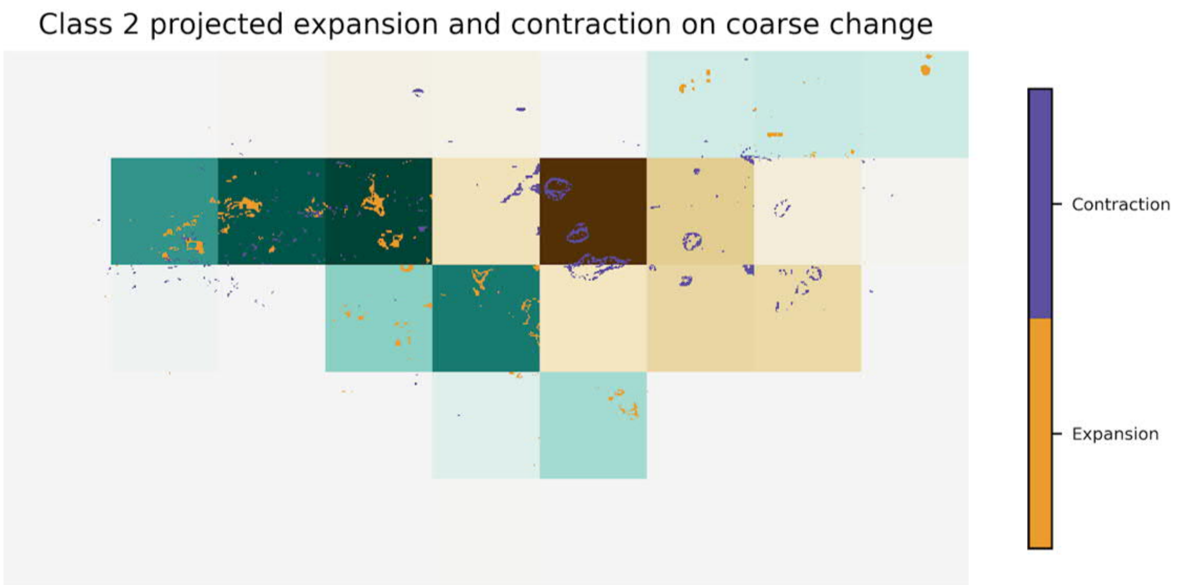
Figure A-3.3: Global Conservation scenario land-use, land-cover map



A-4: SEALS downscaling methodology

The IPBES assessment and other global efforts have produced higher quality data about land-use change dynamics. The main output of this effort is reported by the Land-Use Harmonization 2 (LUH2), which provides yearly measures of land-use change for 13 classes under each of 6 SSP scenarios used by IPBES. This data, however, is at very coarse (30km) resolution and cannot be used in InVEST ecosystem service tools. The primary goal of SEALS was to create a replicable and empirically calibrated algorithm that allocates changes in LULC to resolutions applicable to ecosystem service models. Figure A-4.1 illustrates how SEALS applies this algorithm to apply LULC changes from a coarse resolution (LUH2 prediction of agricultural land-use change in brown [decreases] and green [increases]) to a high resolution (specific locations for expansion [orange] and contraction [blue]). Initially SEALS modelled the expansion of single land-use types, such as maize expansion (Suh et al., in review). For this project, we expanded the functionality to consider all land-use changes simultaneously.

Figure A-4.1: Expansion and contraction of agricultural land in Krasnodar, Russia from input LUH2 data (coarse resolution) and in SEALS output (high resolution).



Allocation algorithm

SEALS uses a simplified LULC classification scheme that is a hierarchically defined subset of the ESA classes (table A-4.1). The simplification was used because many relationships were not statistically different among similar class specifications (e.g. between deciduous broadleaf and deciduous needle-leaf forests).

Table A-4.1: ESA LULC simplification scheme

SEALS LULC types	id	Combined ESA LULC types
Urban	1	190
Cropland	2	10, 11, 12, 20, 30
Pasture/Grassland	3	130
Forest	4	40, 50, 60, 61, 62, 70, 71, 72, 80, 81, 82, 90, 100
Non-forest vegetation	5	110, 120, 121, 122, 140
Water	6	210
Barren or Other	7	150, 151, 152, 153, 160, 170, 180, 190, 200, 201, 202, 210, 220
No data	255	

SEALS allocates land-use change by identifying the net change of each LULC class required in each coarse region, identifying a net change vector N where each entry represents the net change for the i-th land-use type in the coarse cell. The allocation algorithm then takes a n by i matrix of coefficients for how each n-th spatial input affects the probability of i-th expansion in each grid-cell. An example of the table and specification of the functional forms is given in table A-4.2. The coefficients actually used are obtained by iteratively solving the allocation algorithm to search for the parameters that minimise the difference between observed change and projected change.

SEALS allocation algorithm

1. For each i LULC class that might expand and for each c-th coarse-resolution projection zone, we have a net hectarage change of n_c.
2. Define the starting condition of the landscape based on the current 300m resolution LULC map $L_{x,t}$.
3. Define the spatial allocation algorithm $S(n_c, L_{x,t}, p_{xi}, a_{xij}, e) = L_{x,t+1}$ that takes the net hectarage change and an existing LULC map ($L_{x,t}$) and produces a LULC map for a future time based on three factors:
    1. p_{xi} The physical suitability of cell x to be converted into class i
    2. a_{xij} The effect on suitability of being converted to class i in cell x based on the relative adjacency impact of class j
    3. e A 0-1 map that defines which grid-cells are eligible (e.g. prevent expansion into cities).
4. Combine 3.1 - 3.3 with n_c to define the Change-weighted suitability map C.
5. Rank all values in C (note, this is where much of the computation time happens) into a map of conversion order R (lower values denote earlier conversion).
6. Starting with the first conversion in R, convert to the target LULC class and reduce the remaining amount of conversion necessary in n_c by the amount converted. Continue until $n_c = 0$ in all coarse-region projections.

Table A-4.2: Regression coefficients for each possible change in LULC classification in SEALS

spatial_regressor_name	Type	class_1	class_2	class_3	class_4	class_5
class_1_constraint	Multiplicative	0	0	0	0	0
class_2_constraint	Multiplicative	1	0	1	1	1
class_3_constraint	Multiplicative	1	1	0	1	1
class_4_constraint	Multiplicative	1	1	1	0	1
class_5_constraint	Multiplicative	1	1	1	1	0
class_6_constraint	Multiplicative	0	0	0	0	0
class_7_constraint	Multiplicative	1	1	1	1	1
class_1_binary	Additive	0	-0.032222222	0.013888889	-0.013888889	-0.016666667
class_2_binary	Additive	-0.027777778	0	0.016666667	0.011111111	0.004333333
class_3_binary	Additive	0.005555556	0.018888889	0	0.041666667	-0.026111111
class_4_binary	Additive	-0.019444444	-0.016666667	-0.002666667	0	0.033444444
class_5_binary	Additive	0.01	0.144444444	0.060111111	0.02	0
class_6_binary	Additive	0	0	0	0	0
class_7_binary	Additive	-1.119444444	0.001666667	0.126666667	0.061111111	-0.023333333
class_1_gaussian_1	gaussian_parametric_1	1.713888889	-1122.233444	-11.13055556	0.041666667	-1122.241667
class_2_gaussian_1	gaussian_parametric_1	0.105555556	0.333444444	0.022222222	0	-11.24444444
class_3_gaussian_1	gaussian_parametric_1	0.054444444	0.005444444	0.38	0.018222222	0.085555556
class_4_gaussian_1	gaussian_parametric_1	-0.122222222	1111.065556	-0.011	0.276666667	-0.022233333
class_5_gaussian_1	gaussian_parametric_1	0.010888889	0	0.019444444	-0.122222222	0.466666667
class_6_gaussian_1	gaussian_parametric_1	0.036555556	-112.2027778	-112.24	-1.105555556	-1133.322333
class_7_gaussian_1	gaussian_parametric_1	-0.127777778	-112.2555556	-1112.144444	-1111.133333	0.005555556
class_1_gaussian_5	gaussian_parametric_1	-0.072222222	-11.52222222	-111.2638889	-0.093333333	-0.087777778
class_2_gaussian_5	gaussian_parametric_1	0.068888889	0.162333333	-0.016666667	0.122222222	0.065555556
class_3_gaussian_5	gaussian_parametric_1	0.100222222	-0.025	0.431111111	-0.026677778	-0.041666667
class_4_gaussian_5	gaussian_parametric_1	0.133222222	0.367777778	0.076333333	0.281777778	0.113333333
class_5_gaussian_5	gaussian_parametric_1	0	-0.073111111	0.024444444	-0.005555556	0.152777778
class_6_gaussian_5	gaussian_parametric_1	0.091666667	0.005	-1111.105444	-1.092777778	-0.002222222
class_7_gaussian_5	gaussian_parametric_1	0.045555556	0.15	-1111.077778	-0.008333333	-110.89
class_1_gaussian_30	gaussian_parametric_1	-0.066666667	-0.073333333	0.077777778	-0.026111111	0
class_2_gaussian_30	gaussian_parametric_1	0.011111111	0.034888889	-0.081666667	-0.016666667	-0.037777778
class_3_gaussian_30	gaussian_parametric_1	-0.017222222	-0.006	0.308333333	0.009444444	0.024333333
class_4_gaussian_30	gaussian_parametric_1	-0.016111111	0.155555556	0.108888889	0.056777778	0.153444444

spatial_regressor_name	Type	class_1	class_2	class_3	class_4	class_5
class_5_gaussian_30	gaussian_parametric_1	0.005555556	-0.021111111	0.137222222	0.143444444	0.105555556
class_6_gaussian_30	gaussian_parametric_1	-0.021111111	0.036555556	0.152444444	0	0.055555556
class_7_gaussian_30	gaussian_parametric_1	0.025	1109.978889	0.204444444	-1.080555556	-0.034555556
soil_organic_content_1m_30s	Additive	0.027777778	-0.15	110.9777778	-111.14	-0.027777778
bio_12	Additive	11.11944444	-0.994444444	1.14	-1.075	11.00444444
alt	Additive	-0.104444444	0.085	-0.024888889	-0.037788889	0.01
bio_1	Additive	-0.022111111	0.044444444	-0.011111111	-0.01	-0.001111111
minutes_to_market_30s	Additive	0.016122222	0.21	0.005555556	1111.077778	-0.034333333
pop_30s	Additive	0	0	0	0	0
bulk_density_1m_30s	Additive	1.15	1.122222222	-0.016666667	22.18444444	-11.1
CEC_1m_30s	Additive	0	-0.016666667	0	111.0722222	0
clay_percent_1m_30s	Additive	-0.051111111	0.02	-0.186111111	-0.046222222	1.084333333
ph_1m_30s	Additive	0	0.1	0	0	0
sand_percent_1m_30s	Additive	0.034444444	0.018333333	-0.037777778	-0.048888889	-0.001111111
silt_percent_1m_30s	Additive	-0.012777778	-0.165	0	-0.059011111	-0.146111111
protected_area	Additive	-100	-100	0	0	0
wetlands	Additive	-100	-100	0	0	0
pollination_nc	Additive	-100	-100	0	0	0
carbon	Additive	-10	-10	0	0	0
biodiv	Additive	-100	-100	0	0	0

Calibration

A key component in SEALS is that it downscales according to observed relationships present in time-series input data. Specifically, SEALS uses a spatial allocation approach that has been calibrated on ESA's 1992-2015 time series using an iterative gaussian L1-loss function minimisation approach. The approach is documented in figure A-4.2 as per the following algorithm:

1. Define a baseline condition (figure A-4.2a, year 2000 for this example).
2. Define a projection year in the set of observed years after the baseline year (figure A-4.2b, 2010) and calculate the net-change between the two years for each coarse resolution (30km) grid-cell. This defines the amount of change in each LULC class that our allocation algorithm will predict.
3. Allocate the net change of each LULC class using only the baseline map and a spatial allocation algorithm, S(p1), where p1 is the parameter set used in the allocation and is initially set to an arbitrary value.
4. Calculate how accurate the projected LULC map for 2011 (figure A-4.2c) is compared to the observed 2011 LULC map. Specifically, calculate the difference score, which is the summation of 5 L1-difference functions, one for each LULC transition, that calculates how different (in terms of gaussian-blurred distance) each class is in the projected map compared to the observed map.

This generates a score for the quality of fit for the current set of parameters (figure A-4.2d). See figure A-4.3 for a detailed illustration of this calculation for one of the LULC classes.

5. Iteratively for each parameter in p1_i, increase the parameter by X% (initially 10), rerun step 4 with the new parameter, observe the new similarity score, then decrease it by 10% and rerun.
6. After calculating the change in fit from each parameter increase and decrease in step 5, identify which change had the greatest improvement in the similarity score. Update the parameter set to include the single best change, and then repeat steps 3-6 until no additional improvements can be made.

Figure A-4.2: Calibration of SEALS to observed LULC changes

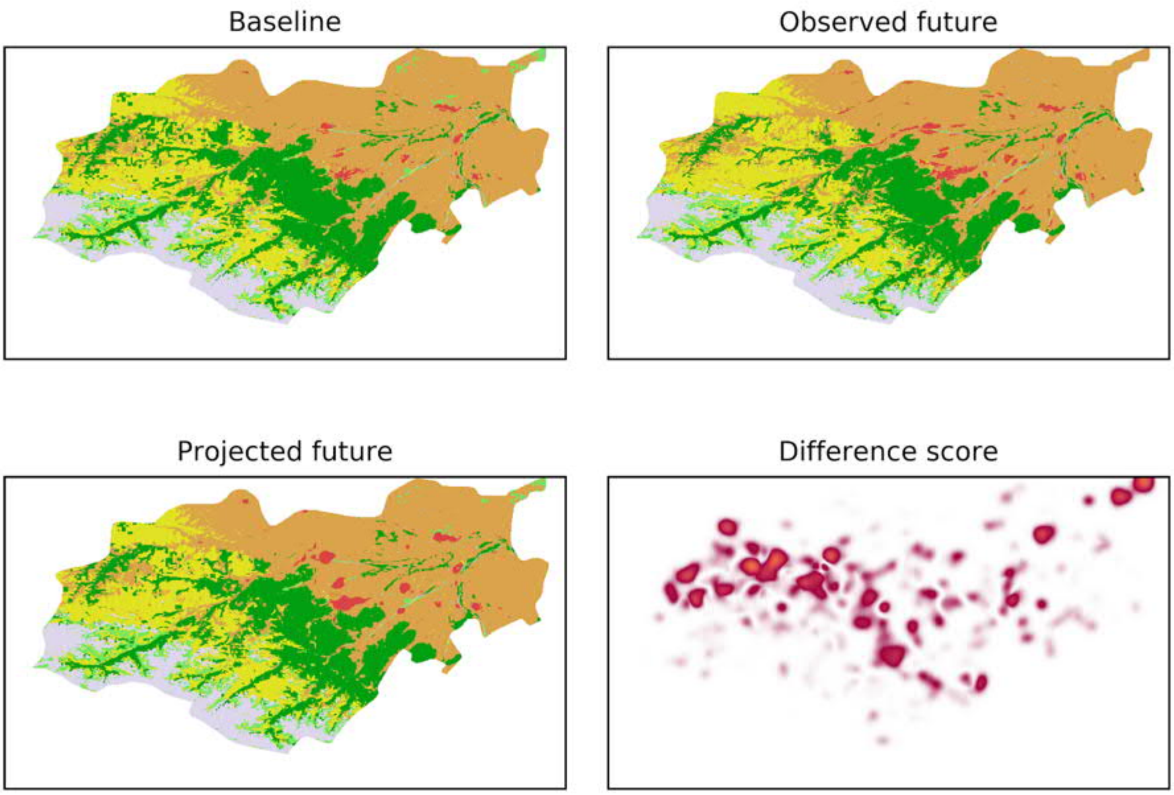
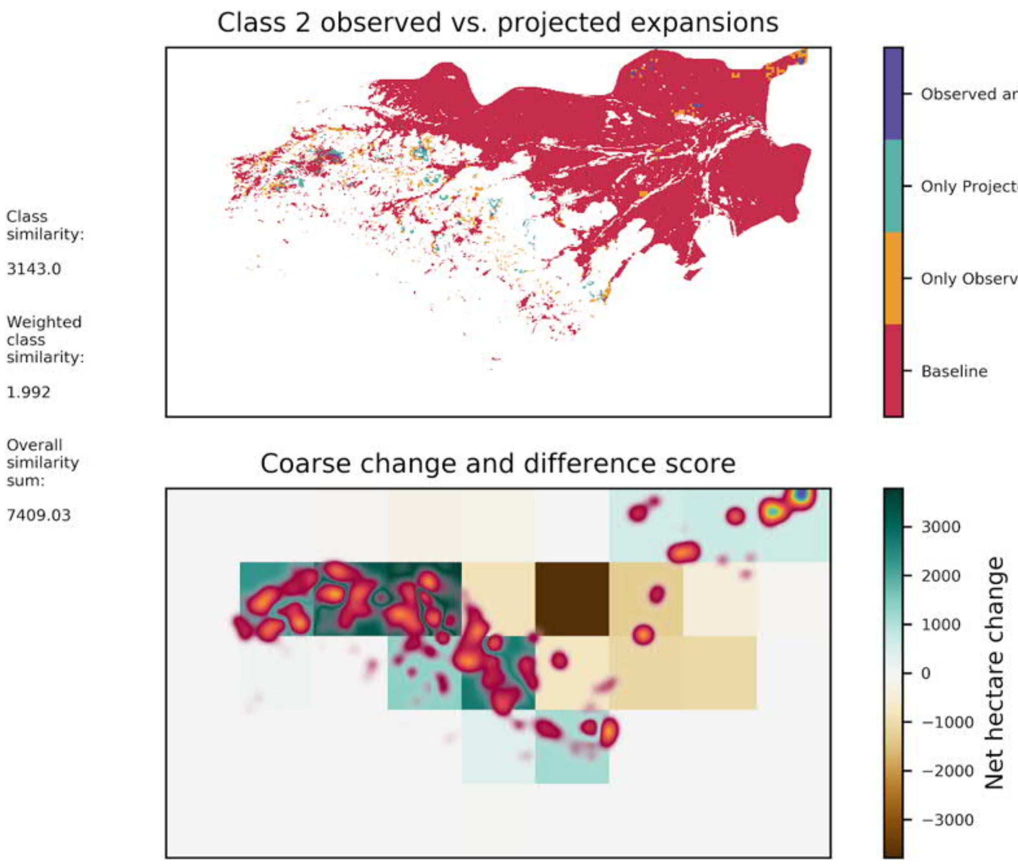


Figure A-4.3: Assessment of prediction quality-of-fit for 1 LULC class



Results

SEALS results in global, high-resolution maps that have exactly the same LUC as the LUH2 set when aggregated to that scale (thereby maintaining interoperability with existing modelling endeavours), while providing an empirical calibration to define the allocation method. The figures below show the results of SEALS, which were then used as the primary input that changes in the InVEST runs. Figure A-4.4 shows the global mapping of SEALS output.

Figure A-4.4: Global results of SEALS downscaling

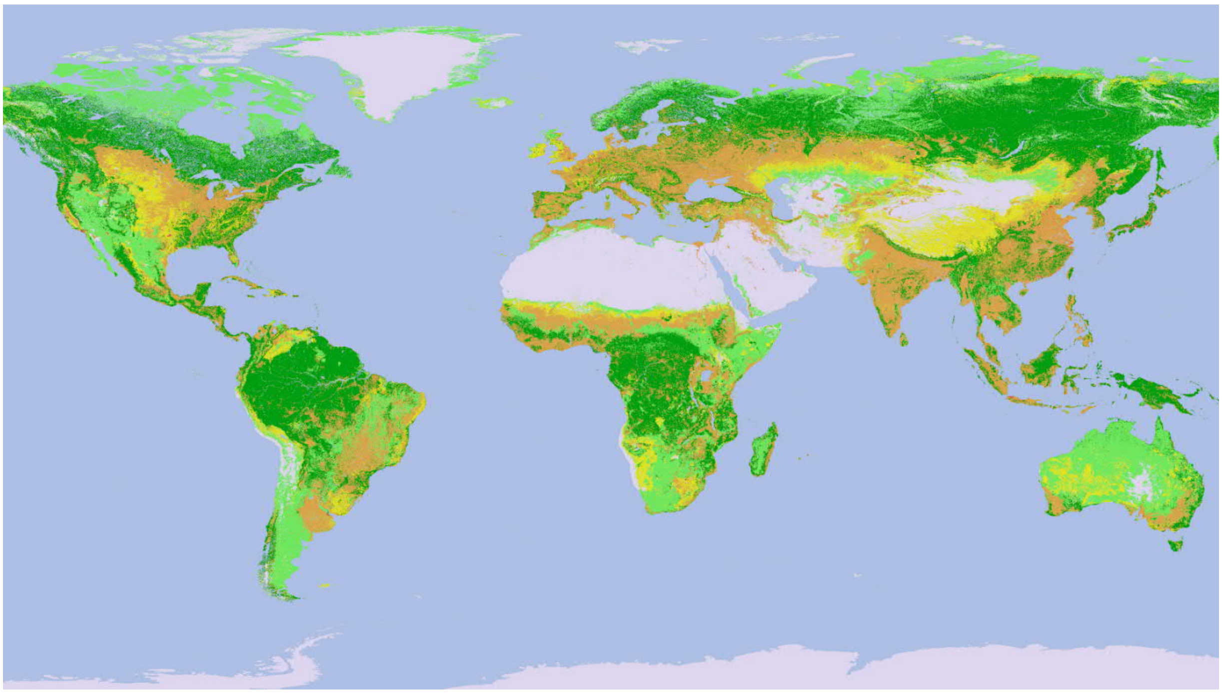
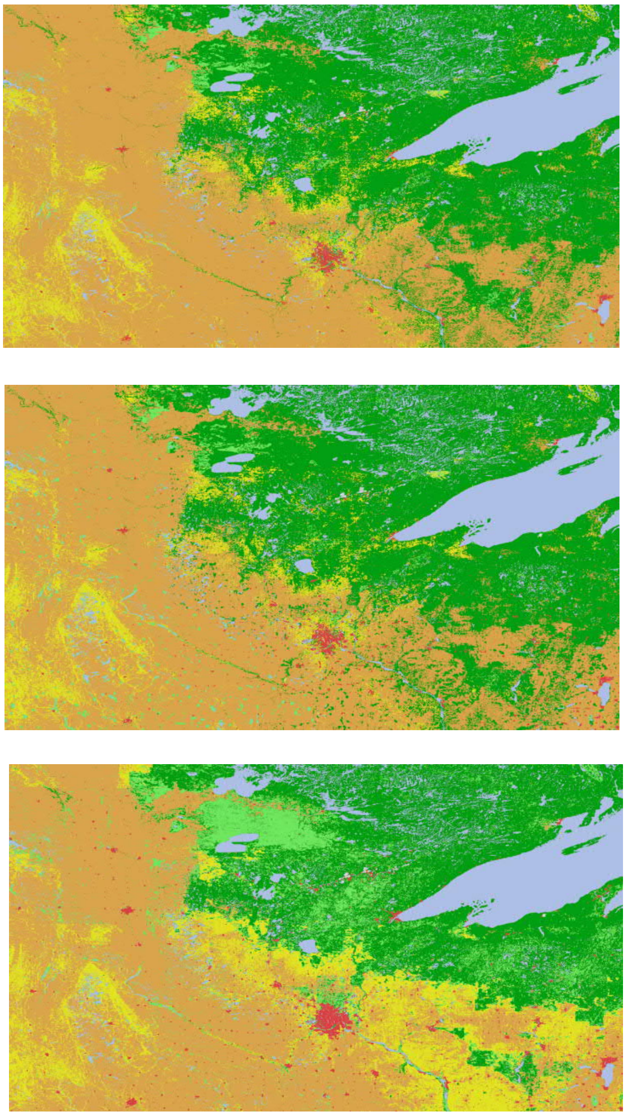


Figure A-4.5: Comparison of ESA 2015 (top), SEALS (middle) and Globio (bottom) in Minnesota



Current limitations

Due to the computationally heavy nature of calibration, the calibration was only done on a subset of the input data. We chose to stick exactly with the LUH2 data. This had some downsides, such as locating massive agricultural expansion in the northern Sahara. In locations where the change projected by LUH2 is well outside any observed changes, the calibration is not effective and visible artifacting is present in these locations. In these locations, no allocation method based on the sparse observed data is likely to produce realistic outputs unless in the underlying input LUH2 data is modified. We chose not to modify the input LUH2 data in these locations in order to stay consistent with existing approaches, though other applications of this data may benefit from versions that modify the input data. Future research directions should include dynamic updating between the coarse and fine resolutions to resolve the underlying problem.

It is also important to note that the modelling outputs (including LULC change maps, InVEST outputs, and GTAP outputs) are not meant to be accurate predictions of future change, rather they are illustrations of possible future outcomes given the assumptions used. Furthermore, the modelling approaches used in this project are a first step in exploring how the integration of ecosystem service models (InVEST) and economic models (GTAP) can be connected to help explore the implications of large-scale implementation of global conservation goals, and will be further refined over time.

A-5: Ecosystem services modelling parameters

Parameter tables for the water yield and carbon sequestration InVEST models. Previously published methods and parameter values were used for pollination (Kim et al. 2018; Chaplin-Kramer et al. 2019) and coastal protection (Freiwald et a. 2017; Spalding et al. 1997; Mccowen et al. 2017; UNEP-WCMC and Short 2017; Church et al. 2013; USGS 2012; Tolman 2009).

Table A-5.1. InVEST water yield parameter values

LULC_desc	lucode	root_depth	cover_rank	Kc
Ndv	0	0	0	0
crop_rainfed	10	1000	0.39	0.65
crop_rainfed_herb	11	1500	0.445	0.575
crop_rainfed_tree	12	2250	0.65	0.825
Palm oil plantation	18	3500	0.79	0.7
crop_irrigated	20	1000	0.39	0.65
crop_natural_mosaic	30	1833.333	0.543333334	0.675
natural_crop_mosaic	40	2666.667	0.696666667	0.7
tree_broadleaved_evergreen	50	3500	0.92	1
tree_broadleaved_deciduous_closed_to_open_15	60	3500	0.91	1
tree_broadleaved_deciduous_closed_40	61	3500	0.91	1
tree_broadleaved_deciduous_open_15_40	62	3500	0.91	1
tree_needleleaved_evergreen_closed_to_open_15	70	3500	0.92	1
tree_needleleaved_evergreen_closed_to_open_15_extended	71	3500	0.92	1
tree_needleleaved_evergreen_open_15_40	72	3500	0.92	1
tree_needleleaved_deciduous_closed_to_open_15	80	3500	0.91	1
tree_needleleaved_deciduous_closed_40	81	3500	0.91	1
tree_needleleaved_deciduous_open_15_40	82	3500	0.91	1
tree_mixed_type	90	3500	0.91	1
mosaic_tree_and_shrub_50_herbaceous_cover_50	100	2750	0.705	0.75
mosaic_herbaceous_cover_50_tree_and_shrub_50	110	2750	0.705	0.75
Shrubland	120	2000	0.5	0.5
evergreen_shrubland	121	2000	0.5	0.5
deciduous_shrubland	122	2000	0.5	0.5
Grassland	130	2000	0.3	0.65
lichens_and_mosses	140	2000	0.3	0.65
sparse_vegetation_tree_shrub_herbaceous_cover_15	150	1175	0.3235	0.365
sparse_tree_15	151	1175	0.3235	0.365
sparse_shrub_15	152	1175	0.3235	0.365
sparse_herbaceous_cover_15	153	1175	0.3235	0.365
tree_cover_flooded_fresh_or_brakish_water	160	3500	0.91	1
tree_cover_flooded_saline_water	170	3500	0.91	1
shrub_or_herbaceous_cover_flooded_fresh_saline_brakish_water	180	2000	0.5	0.5

LULC_desc	lucode	root_depth	cover_rank	Kc
urban_areas	190	0	0.1	0.29
bare_areas	200	500	0.16	0.2
consolidated_bare_areas	201	500	0.16	0.2
unconsolidated_bare_areas	202	500	0.16	0.2
water_bodies	210	10	0	1
permanent_snow_and_ice	220	0	0	0.4

A-6: GTAP-AEZ model parameters and inputs

Table A-6.1: Regional classifications used in GTAP-AEZ

GTAP Code	Region	GTAP Code	Region
aus	Australia	pol	Poland
nzl	New Zealand	prt	Portugal
xoc	Rest of Oceania	svk	Slovakia
chn	China	svn	Slovenia
jpn	Japan	esp	Spain
kor	South Korea	swe	Sweden
mng	Mongolia	gbr	United Kingdom
xea	Rest of East Asia	che	Switzerland
khm	Cambodia	nor	Norway
idn	Indonesia	xef	Rest of EFTA
lao	Laos	alb	Albania
mys	Malaysia	bgr	Bulgaria
phl	Philippines	blr	Belarus
sgp	Singapore	hrv	Croatia
tha	Thailand	rou	Romania
vnm	Vietnam	rus	Russian Federation
xse	Rest of Southeast Asia	ukr	Ukraine
bgd	Bangladesh	xee	Rest of Eastern Europe
ind	India	xer	Rest of Europe
npl	Nepal	kaz	Kazakhstan
pak	Pakistan	kgz	Kyrgyzstan
lka	Sri Lanka	xsu	Rest of Former Soviet Union
xsa	Rest of South Asia	arm	Armenia
can	Canada	aze	Azerbaijan
usa	United States of America	geo	Georgia
mex	Mexico	bhr	Bahrain
xna	Rest of North America	irn	Iran
arg	Argentina	isr	Israel
bol	Bolivia	jor	Jordan
bra	Brazil	kwt	Kuwait
chl	Chile	omn	Oman
col	Colombia	qat	Qatar
ecu	Ecuador	sau	Saudi Arabia
pry	Paraguay	tur	Turkey
per	Peru	are	United Arab Emirates
ury	Uruguay	xws	Rest of Western Asia

GTAP Code	Region	GTAP Code	Region
ven	Venezuela	egy	Egypt
xsm	Rest of South America	mar	Morocco
cri	Costa Rica	tun	Tunisia
gtm	Guatemala	xnf	Rest of North Africa
hnd	Honduras	ben	Benin
nic	Nicaragua	bfa	Burkina Faso
pan	Panama	cmr	Cameroon
slv	El Salvador	civ	Cote dIvoire
xca	Rest of Central America	gha	Ghana
dom	Dominican Republic	gin	Guinea
jam	Jamaica	nga	Nigeria
pri	Puerto Rico	sen	Senegal
tto	Trinidad and Tobago	tgo	Togo
xcb	Caribbean	xwf	Rest of Western Africa
aut	Austria	xcf	Central Africa
bel	Belgium	xac	South Central Africa
cyp	Cyprus	eth	Ethiopia
cze	Czech Republic	ken	Kenya
dnk	Denmark	mdg	Madagascar
est	Estonia	mwi	Malawi
fin	Finland	mus	Mauritius
fra	France	moz	Mozambique
deu	Germany	rwa	Rwanda
grc	Greece	tza	Tanzania
hun	Hungary	uga	Uganda
irl	Ireland	zmb	Zambia
ita	Italy	zwe	Zimbabwe
lva	Latvia	xec	Rest of Eastern Africa
ltu	Lithuania	bwa	Botswana
lux	Luxembourg	nam	Namibia
mlt	Malta	zaf	South Africa
nld	Netherlands	xsc	Rest of South African
		xtw	Rest of the World

Table A-6.2: Sectors used in GTAP-AEZ database

GTAP Code	GTAP Description
pdr	Paddy Rice: rice, husked and unhusked
wht	Wheat: wheat and meslin
crsgrns	Other Grains: maize (corn), barley, rye, oats, other cereals
fruitveg	Veg & Fruit: vegetables, fruitvegetables, fruit and nuts, potatoes, cassava, truffles,
oilsds	Oil Seeds: oil seeds and oleaginous fruit; soy beans, copra
sugarcrops	Cane & Beet: sugar cane and sugar beet
cotton	Plant Fibres: cotton, flax, hemp, sisal and other raw vegetable materials used in textiles
othercrps	Other Crops: live plants; cut flowers and flower buds; flower seeds and fruit seeds; vegetable seeds, beverage and spice crops, unmanufactured tobacco, cereal straw and husks, unprepared, whether or not chopped, ground, pressed or in the form of pellets; swedes, mangolds, fodder roots, hay, lucerne (alfalfa), clover, sainfoin, forage kale, lupines, vetches and similar forage products, whether or not in the form of pellets, plants and parts of plants used primarily in perfumery, in pharmacy, or for insecticidal, fungicidal or similar purposes, sugar beet seed and seeds of forage plants, other raw vegetable materials
Livestock	Cattle: cattle, sheep, goats, horses, asses, mules, and hinnies; and semen thereof
	Other Animal Products: swine, poultry and other live animals; eggs, in shell (fresh or cooked), natural honey, snails (fresh or preserved) except sea snails; frogs' legs, edible products of animal origin n.e.c., hides, skins and furskins, raw , insect waxes and spermaceti, whether or not refined or coloured
	Raw milk
	Wool: wool, silk, and other raw animal materials used in textile
Nres	Forestry: forestry, logging and related service activities
	Fishing: hunting, trapping and game propagation including related service activities, fishing, fish farms; service activities incidental to fishing
	Coal: mining and agglomeration of hard coal, lignite and peat
	Oil: extraction of crude petroleum and natural gas (part), service activities incidental to oil and gas extraction excluding surveying (part)
	Gas: extraction of crude petroleum and natural gas (part), service activities incidental to oil and gas extraction excluding surveying (part)
	Other Mining: mining of metal ores, uranium, gems. other mining and quarrying
PrLstk	Cattle Meat: fresh or chilled meat and edible offal of cattle, sheep, goats, horses, asses, mules, and hinnies. raw fats or grease from any animal or bird.
	Other Meat: pig meat and offal. preserves and preparations of meat, meat offal or blood, flours, meals and pellets of meat or inedible meat offal; greaves
PrFood	Vegetable Oils: crude and refined oils of soya-bean, maize (corn),olive, sesame, ground-nut, olive, sunflower-seed, safflower, cotton-seed, rape, colza and canola, mustard, coconut palm, palm kernel, castor, tung jojoba, babassu and linseed, perhaps partly or wholly hydrogenated,inter-esterified, re-esterified or elaidinised. Also margarine and similar preparations, animal or vegetable waxes, fats and oils and their fractions, cotton linters, oil-cake and other solid residues resulting from the extraction of vegetable fats or oils; flours and meals of oil seeds or oleaginous fruits, except those of mustard; degras and other residues resulting from the treatment of fatty substances or animal or vegetable waxes.
	Milk: dairy products
	Processed Rice: rice, semi- or wholly milled
	Sugar
	Other Food: prepared and preserved fish or vegetables, fruit juices and vegetable juices, prepared and preserved fruit and nuts, all cereal flours, groats, meal and pellets of wheat, cereal groats, meal and pellets n.e.c., other cereal grain products (including corn flakes), other vegetable flours and meals, mixes and doughs for the preparation of bakers' wares, starches and starch products; sugars and sugar syrups n.e.c., preparations used in animal feeding, bakery products, cocoa, chocolate and sugar confectionery, macaroni, noodles, couscous and similar farinaceous products, food products n.e.c.
	Beverages and Tobacco products
Mnfcing	Textiles: textiles and man-made fibres
	Wearing Apparel: Clothing, dressing and dyeing of fur
	Leather: tanning and dressing of leather; luggage, handbags, saddlery, harness and footwear
	Lumber: wood and products of wood and cork, except furniture; articles of straw and plaiting materials
	Paper & Paper Products: includes publishing, printing and reproduction of recorded media
	Petroleum & Coke: coke oven products, refined petroleum products, processing of nuclear fuel
	Chemical Rubber Products: basic chemicals, other chemical products, rubber and plastics products
	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete
	Iron & Steel: basic production and casting
	Non-Ferrous Metals: production and casting of copper, aluminium, zinc, lead, gold, and silver
	Fabricated Metal Products: Sheet metal products, but not machinery and equipment
	Motor Motor vehicles and parts: cars, lorries, trailers and semi-trailers
	Other Transport Equipment: Manufacture of other transport equipment
	Electronic Equipment: office, accounting and computing machinery, radio, television and communication equipment and apparatus
	Other Machinery & Equipment: electrical machinery and apparatus n.e.c., medical, precision and optical instruments, watches and clocks
	Other Manufacturing: includes recycling

GTAP Code	GTAP Description
Services	Electricity: production, collection and distribution
	Gas Distribution: distribution of gaseous fuels through mains; steam and hot water supply
	Water: collection, purification and distribution
	Construction: building houses factories offices and roads
	Trade: all retail sales; wholesale trade and commission trade; hotels and restaurants; repairs of motor vehicles and personal and household goods; retail sale of automotive fuel
	Other Transport: road, rail ; pipelines, auxiliary transport activities; travel agencies
	Water transport
	Air transport
	Communications: post and telecommunications
	Other Financial Intermediation: includes auxiliary activities but not insurance and pension funding (see next)
	Insurance: includes pension funding, except compulsory social security
	Other Business Services: real estate, renting and business activities
	Recreation & Other Services: recreational, cultural and sporting activities, other service activities; private households with employed persons (servants)
	Other Services (Government): public administration and defense; compulsory social security, education, health and social work, sewage and refuse disposal, sanitation and similar activities, activities of membership organizations n.e.c., extra-territorial organizations and bodies
	Dwellings: ownership of dwellings (imputed rents of houses occupied by owners)

Table A-6.3: Data available for each region in the GTAP-AEZ database

Name	Description
ADRV	Protection - Anti-Dumping Duty
DPSM	Sum of Distribution Parameters in Household Demand System
EVFA	Endowments - Firms' Purchases at Agents' Prices
EVOA	Endowments - Output at Agents' Prices
FBEP	Factor-Based Subsidies
FTRV	gross factor employment tax revenue
ISEP	Intermediate Input Subsidies
MFRV	Protection - MFA Export Subsidy Equivalent
OSEP	Ordinary Output Subsidies
POP	Population
PURV	Protection - Price Undertaking Export Subsidy Equivalent
SAVE	Savings - Net Expenditure at Agents' Prices
TFRV	Protection - Ordinary Import Duty
TFRVSA	Import tariff Rev by type of tariffs paid
TVOM	sales of domestic product, at market prices
VDEP	Capital Stock - Value of Depreciation
VDFA	Intermediates - Firms' Domestic Purchases at Agents' Prices
VDFM	Intermediates - Firms' Domestic Purchases at Market Prices
VDGA	Intermediates - Government Domestic Purchases at Agents' Prices
VDGM	Intermediates - Government Domestic Purchases at Market Prices
VDPA	Intermediates - Household Domestic Purchases at Agents' Prices
VDPM	Intermediates - Household Domestic Purchases at Market Prices
VFM	Endowments - Firms' Purchases at Market Prices
VIFA	Intermediates - Firms' Imports at Agents' Prices
VIFM	Intermediates - Firms' Imports at Market Prices
VIGA	Intermediates - Government Imports at Agents' Prices
VIGM	Intermediates - Government Imports at Market Prices
VIMS	Trade - Bilateral Imports at Market Prices
VIPA	Intermediates - Household Imports at Agents' Prices

Name	Description
VIPM	Intermediates - Household Imports at Market Prices
VIWS	Trade - Bilateral Imports at World Prices
VKB	Capital Stock - Value at Beginning-of-Period
VRRV	Protection - VER Export Subsidy Equivalent
VST	Trade - Exports for International Transportation, Market Prices
VTWR	Margins on International Trade
VXMD	Trade - Bilateral Exports at Market Prices
VXWD	Trade - Bilateral Exports at World Prices
XTRV	Protection - Ordinary Export Subsidy

Table A-6.4: Key parameters in the GTAP-AEZ database

Name	Description
ESUBD	Armington CES for domestic/imported allocation
ESUBM	Armington CES for regional allocation of imports
ESUBT	Elasticity of intermediate input substitution
ESUBVA	CES between primary factors in production
ETRAE	CET between sectors for sluggish primary factors
RORFLEX	Expected rate of return flexibility parameter
SUBPAR	CDE substitution parameter
INCPAR	CDE expansion parameter

Table A-6.5: Mapping of crops from Klein et al. 2007 to GTAP-AEZ crop sectors

FAO Crops	GTAP Crops	Mapping to Klien et al (2007)
Almonds	Fruits&Vegetables	Almond
Apples	Fruits&Vegetables	Apple
Apricots	Fruits&Vegetables	Apricot
Asparagus	Fruits&Vegetables	Asparagus
Avocados	Fruits&Vegetables	Avocado
BambaraBeans	Fruits&Vegetables	Bambara bean, Bambara groundnut, Earth pea
Bananas	Fruits&Vegetables	Banana, Plantain
Plantains	Fruits&Vegetables	Banana, Plantain
Barley	Coarse Grains	Barley
BeansDry	Fruits&Vegetables	Bean dry like Kidney bean, Haricot bean, Lima bean, Azuki bean, Mungo bean, String bean
BrdBeansDry	Fruits&Vegetables	Bean dry like Kidney bean, Haricot bean, Lima bean, Azuki bean, Mungo bean, String bean
BeanGreen	Fruits&Vegetables	Bean dry like Kidney bean, Haricot bean, Lima bean, Azuki bean, Mungo bean, String bean
StringBeans	Fruits&Vegetables	Bean dry like Kidney bean, Haricot bean, Lima bean, Azuki bean, Mungo bean, String bean
Grpfrt_Pmlos	Fruits&Vegetables	Bergamot, Chinotto, Citron, Clementine, Grapefruit, Kumquat, Lemon, Lime, Mandarine, Orange, Pomelo, Tangerine
Lmn_Lme	Fruits&Vegetables	Bergamot, Chinotto, Citron, Clementine, Grapefruit, Kumquat, Lemon, Lime, Mandarine, Orange, Pomelo, Tangerine
Oranges	Fruits&Vegetables	Bergamot, Chinotto, Citron, Clementine, Grapefruit, Kumquat, Lemon, Lime, Mandarine, Orange, Pomelo, Tangerine
TngMndClmnt	Fruits&Vegetables	Bergamot, Chinotto, Citron, Clementine, Grapefruit, Kumquat, Lemon, Lime, Mandarine, Orange, Pomelo, Tangerine
Currants	Fruits&Vegetables	Black currant, Red currant
BrazilNuts	Fruits&Vegetables	Brazil nut, Para nut, Cream nut
BrdBeanGreen	Fruits&Vegetables	Broad Bean, Faba bean, Field bean, Horse bean
Buckwheat	Coarse Grains	Buckwheat
Cabbage4Fddr	Other Crops	Cabbage, Cauliflower
Cabbages	Fruits&Vegetables	Cabbage, Cauliflower
Cauliflower	Fruits&Vegetables	Cabbage, Cauliflower

Cntlp_othMln	Fruits&Vegetables	Cantaloupe, Melon
Ntmg_Mc_Crdm	Other Crops	Cardamom, Mace, Nutmeg
Carrots4Fddr	Other Crops	Carrot
Carrots	Fruits&Vegetables	Carrot
Cashewapple	Fruits&Vegetables	Cashew nut, and Cashew-apple
CashewNuts	Fruits&Vegetables	Cashew nut, and Cashew-apple
Cassava	Fruits&Vegetables	Cassava
Chestnuts	Fruits&Vegetables	Chestnut
ChickPeas	Fruits&Vegetables	Chick pea, Bengal gram, Garbanzo bean
ChicoryRoots	Fruits&Vegetables	Chicory root
Pepper	Other Crops	Chile pepper, Red pepper, Bell pepper, Green pepper, Allspice, Pimento
Pimento	Other Crops	Chile pepper, Red pepper, Bell pepper, Green pepper, Allspice, Pimento
Chll_PpprGrn	Fruits&Vegetables	Chile pepper, Red pepper, Bell pepper, Green pepper, Allspice, Pimento
CocoaBeans	Other Crops	Cocoa
Coconuts	Oilseeds	Coconut
CoffeeGreen	Other Crops	Coffee
KrtNtSheant	Oilseeds	Cola nut, Kola nut
Kolanuts	Fruits&Vegetables	Cola nut, Kola nut
SeedCotton	Cotton	Cotton seed
CowPeasDry	Fruits&Vegetables	Cowpea, Blackeye pea, Blackeye bean
Berriesnes	Fruits&Vegetables	Cranberry, Blueberry
Blueberries	Fruits&Vegetables	Cranberry, Blueberry
Cranberries	Fruits&Vegetables	Cranberry, Blueberry
Ccmbr_Ghrkn	Fruits&Vegetables	Cucumber, Gherkin
Dates	Fruits&Vegetables	Date palm
Eggplants	Fruits&Vegetables	Eggplant, Aubergine
Figs	Fruits&Vegetables	Fig
Garlic	Fruits&Vegetables	Garlic
GrnOlsd4Fddr	Other Crops	Groundnut, Peanut
GrndntWShll	Oilseeds	Groundnut, Peanut
KiwiFruit	Fruits&Vegetables	Kiwifruit
Lentils	Fruits&Vegetables	Lentil
Lettuce	Fruits&Vegetables	Lettuce
Linseed	Oilseeds	Linseed, Flax
FlaxFibr_Tow	Cotton	Linseed, Flax
Maize	Coarse Grains	Maize, Green corn, Sweet corn
PopCorn	Coarse Grains	Maize, Green corn, Sweet corn
Maize4FrgSlg	Other Crops	Maize, Green corn, Sweet corn
GrnCornMaize	Fruits&Vegetables	Maize, Green corn, Sweet corn
Mangoes	Fruits&Vegetables	Mango
Millet	Coarse Grains	Millet
MixedGrain	Coarse Grains	Mixed Grain
MustardSeed	Oilseeds	Mustard Seed
Oats	Coarse Grains	Oat
OilPalmFruit	Oilseeds	Oil palm fruit
Okra	Fruits&Vegetables	Okra, Gumbo
Olives	Oilseeds	Olive
OnionDry	Fruits&Vegetables	Onion, Shallot, Welsh onion
OnionShlltGn	Fruits&Vegetables	Onion, Shallot, Welsh onion
Papayas	Fruits&Vegetables	Papaya
PeasDry	Fruits&Vegetables	Pea, dry and green like Garden pea, Field pea
PeasGreen	Fruits&Vegetables	Pea, dry and green like Garden pea, Field pea
Peach_Nctrn	Fruits&Vegetables	Peach, Nectarine
Pears	Fruits&Vegetables	Pear
Persimmons	Fruits&Vegetables	Persimmon
PigeonPeas	Fruits&Vegetables	Pigeon pea, Cajan pea, Congo bean
Pineapples	Fruits&Vegetables	Pineapple

Plums	Fruits&Vegetables	Plum
Potatoes	Fruits&Vegetables	Potato
PmpknSqshGrd	Fruits&Vegetables	Pumpkin, Squash, Gourd, Marrow, Zucchini
Quinoa	Coarse Grains	Quinoa
Oilseedsnes	Oilseeds	Rapeseed, Oilseed rape, Canola
Rapeseed	Oilseeds	Rapeseed, Oilseed rape, Canola
Raspberries	Fruits&Vegetables	Raspberry, Blackberry, Cloudberry, Northern dewberry, Southern dewberry
PaddyRice	Rice	Rice, Paddy
Rye	Coarse Grains	Rye
RyeGrsFrgSlg	Other Crops	Rye
SesameSeed	Oilseeds	Sesame seed
Sorghum	Coarse Grains	Sorghum
Cherries	Fruits&Vegetables	Sour cherry, Sweet cherry
SourCherries	Fruits&Vegetables	Sour cherry, Sweet cherry
Soybeans	Oilseeds	Soybean
Spinach	Fruits&Vegetables	Spinach
Strawberries	Fruits&Vegetables	Strawberry
SugarBeets	Sugar Crops	Sugar beet
SugarCane	Sugar Crops	Sugar cane
SnflwrSeed	Oilseeds	Sunflower seed
SweetPotato	Fruits&Vegetables	Sweet potato
Grapes	Fruits&Vegetables	Table grape, Vine grape
TaroCocoYam	Fruits&Vegetables	Taro (Coco Yam)
Tomatoes	Fruits&Vegetables	Tomato
Vanilla	Other Crops	Vanilla
Melonseed	Oilseeds	Watermelon
Watermelons	Fruits&Vegetables	Watermelon
Wheat	Wheat	Wheat
Yams	Fruits&Vegetables	Yam

Global Futures is an innovative science-policy partnership between WWF, the Global Trade Analysis Project (founded and hosted by Purdue University) and the Natural Capital Project (co-founded by the University of Minnesota).

Based on a new first-of-its-kind global environment-economy modelling framework, its aim is to generate compelling new quantitative evidence on how and under what circumstances changes in the Earth's natural systems will affect the world's economies, trade and industry. The ambition is that governments, businesses and other actors will use this information in order to support more sustainable decision-making, improving long-term outcomes for nature and people.