Integrated Economic and Ecosystem Services Modeling

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This paper builds on the Global Futures Project (GFP) led by the World Wide Fund for Nature (WWF) and University of Minnesota. The goal of the GFP is to enhance awareness among policy makers of the risks to economic prosperity of global environmental degradation by developing and applying a new, cutting-edge modelling approach. At the core of the approach is the Computable General Equilibrium (CGE) model based on Global Trade Analysis Project (GTAP) data base – 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 is linked to high-resolution global ecosystem service models. We use a version of the GTAP model that has been expanded to agroecological zones (GTAP-AEZ), described in more depth below. 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, such as how it will affect GDP, welfare, value added by sector, trade flows and terms of trade, job shifts between sectors (note that analyzing other job variables, such as unemployment, would require shifting to a labor-specific GTAP model extensions, and is thus out of scope of the current contract), as well as providing a basis for assessing the resilience and security of different scenarios.

Many other CGE models exist with capabilities similar to the GTAP-AEZ model, such as the ENVISAGE family of models used extensively within the World Bank. The choice to use GTAP-AEZ over other model types was primarily made so that we can leverage existing code developed under the GFP (thereby greatly accelerating our work), but also because the specific definition of the GTAP-AEZ model we used was custom-tailored to answer key environmental questions, such as how *demand* for water within a watershed affects the outcome. However, future work could definitely extend the advances under the GTAP-AEZ framework to be incorporated in an ENVISAGE model to extend the potential impact of our work.

At present, the GFP assesses the impacts of changed Ecosystem Services ES on the economy, using the Shared Socio-Economic Pathways (SSPs, see box 1 for more information) as inputs. This has the advantage of ensuring consistency with the broad research community, which is centered on assessing the effects of different SSPs. However, the SSPs are "outcome" scenarios, i.e. they summarize the outcome of a combination of policies and other factors that will result in different stylized representations of how the future may unfold. The SSPs do not define explicitly what specific policies can be adopted to arrive at those outcomes. The work defined in this section of the inception report is intended to enrich the GFP analysis in several ways (organized in two phases of work). The first phase will support the GFP in integrating additional "outcome scenarios" and in finalizing the estimates of impacts of ecosystem loss under a wider range of climate change scenarios while the second phase will develop a new version of the integrated model capable of analyzing new questions, such as:

1. addressing the interaction between the economy and ecosystems in both directions (i.e. economic development leading to changes in ecosystem services; and changes in ecosystem services leading to a response by the economic system);
2. estimating the comparative advantages and disadvantages of alternative, specific policies on environmental and economic variables;
3. estimating consumption-based biodiversity loss.

Each of these will be discussed in more depth in the methodology section below.

Box 1: The Shared Socioeconomic Pathways (adapted from GFP report)

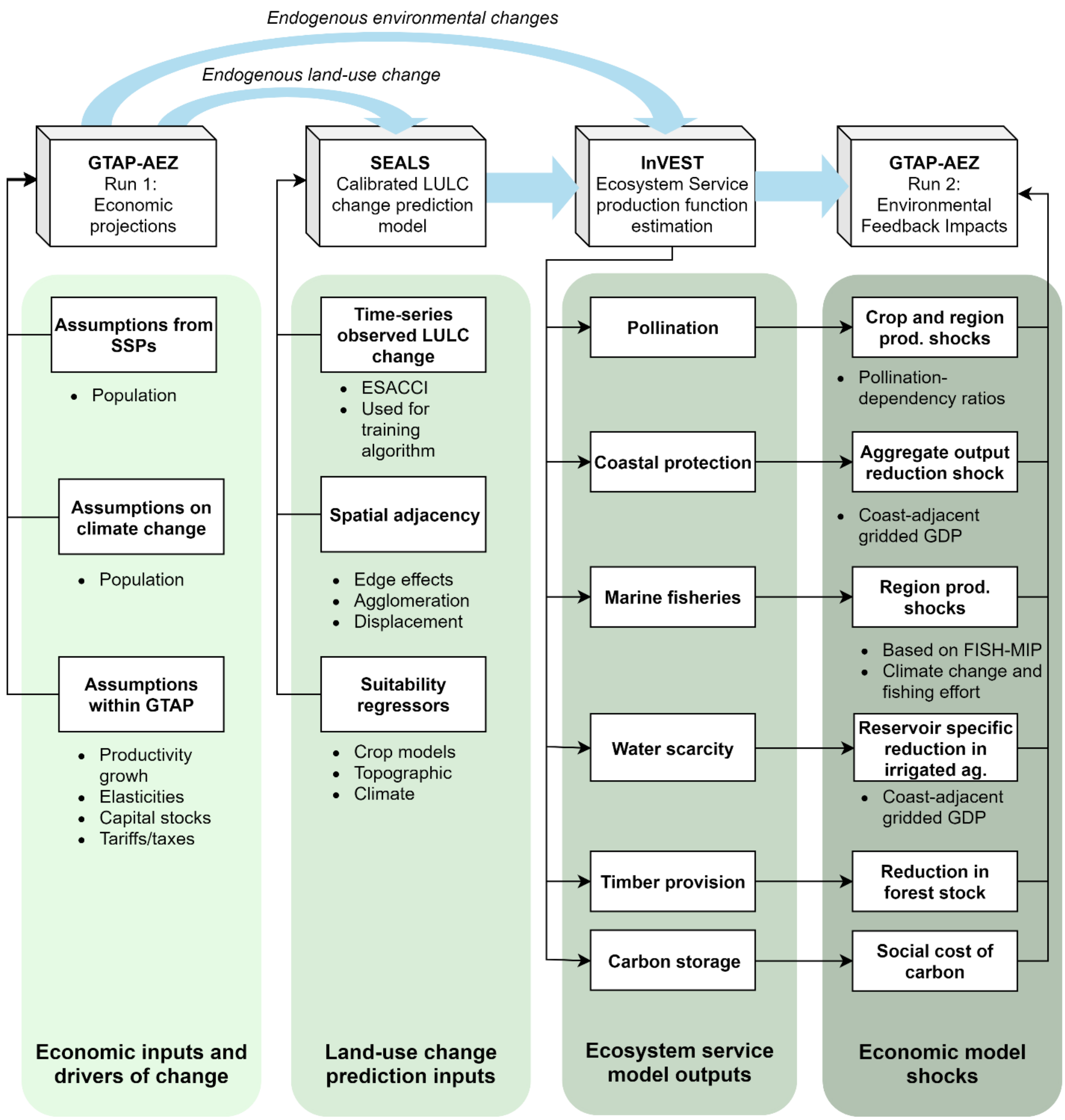
SSPs *(C. Weil, adapted from O'Neill, 2014)*

Figure 1: Graphical depiction of SSPs

Methods

This project includes creation of new methodological approaches along with linking existing modeling tools. The combination of methods used are summarized in figure 2, and described in more depth below.

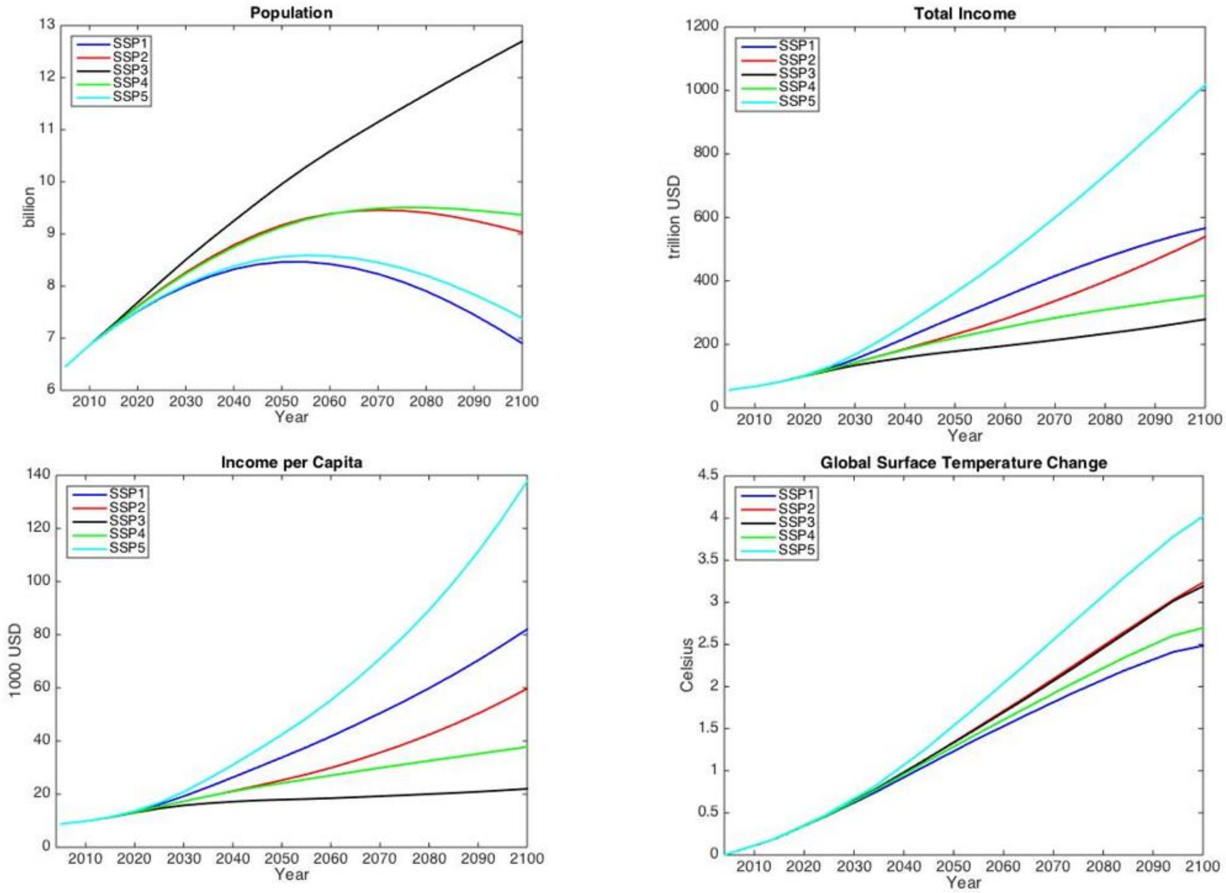
Figure 2: Feedback model methods and linkages



Input Assumptions

As discussed above, the GFP project used the SSPs, and thereby their input assumptions, directly and without modification. This has the advantage of simplicity, transparency and connection to standard practices in global modeling communities. The key assumptions used in the GFP model are represented in figure 3 below, illustrating the trends of population growth, income growth and climate change.

Figure 3: Input assumptions used with GFP from the SSPs



Source: IIASA (2015). SSP Database 2012-2015. Preliminary scenarios. Available https://tntcat.iiasa.ac.at/SspDb

However, relying on these assumptions as exogenous prevents modification in a consistent (non-equilibrium violating) way. Thus, this project replaces the SSPs with a GTAP-based projection of the economy to 2030 that endogenizes many key elements (including income). However, we still take population and climate change projections as exogenous.

GTAP economic methods

The initial version of the GFP model that was produced was based on the standard GTAP with 140 regions model (see appendix 1 for formal description). However, this version of the model does not have water-basin specific information necessary to estimate water demand and also does not have endogenous, spatially explicit competition for land. The second version of the GFP model (that will be produced for the final, October 2019 report) changed the underlying model to be based on the GTAP-AEZ (Agro-Ecological Zone) version from Hertel et al. (2009), updated extensively for this project. Compared to Hertel et al., we increased the administrative-unit resolution (from 19 to 141), subdivided further by the AEZs defined in Hertel et al. to create 843 zones. See figure 4, which plots both the admin-unit boundaries and the AEZs.

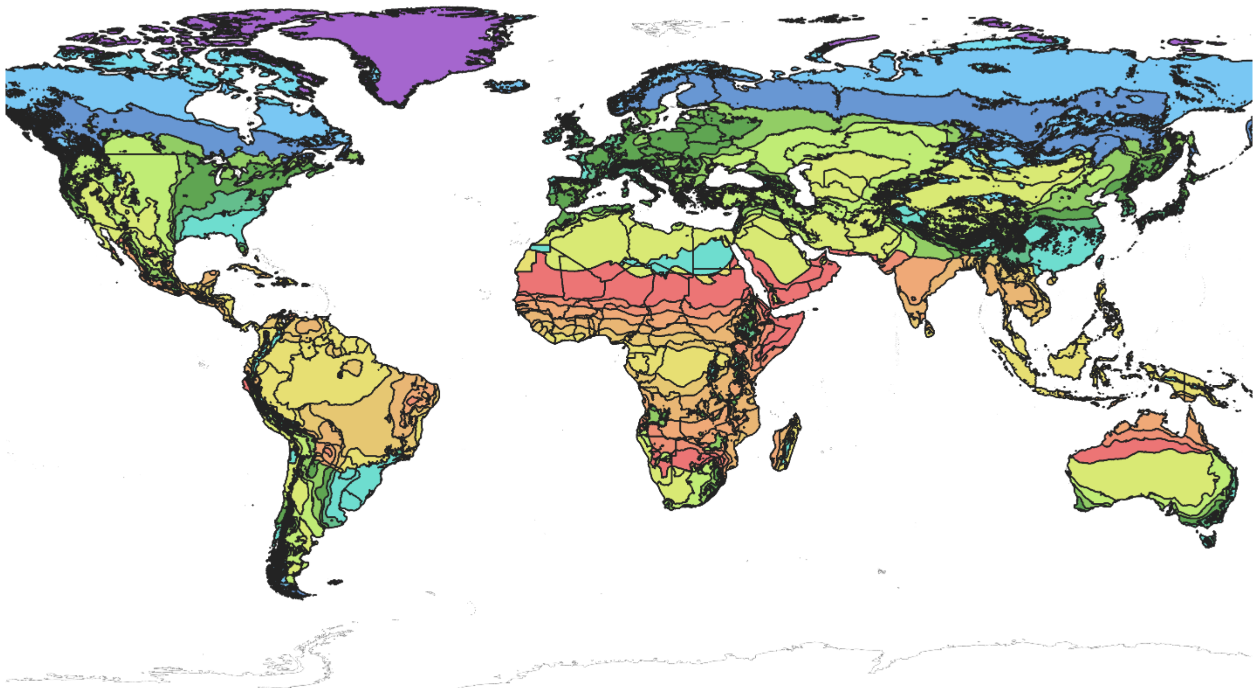


Figure 4: Agroecological Zones and Country Boundaries

The AEZs are defined such that they share common climate, precipitation and moisture conditions, specifying details necessary to parameterize competition between different land-uses. In particular, this redefinition enables is specifying production functions that are different for each product for each AEZ (though note that the price for the product remains the same for the region).

In this formulation, land-supply is modeled using a constant elasticity of transformation revenue function, whereby landowners maximize total returns by allocating their land endowment to different uses, subject to feasibility constraints on which land-use transitions are allowed. Specifically, owners solve:

$$\sum_{l} R_l X_l = R$$

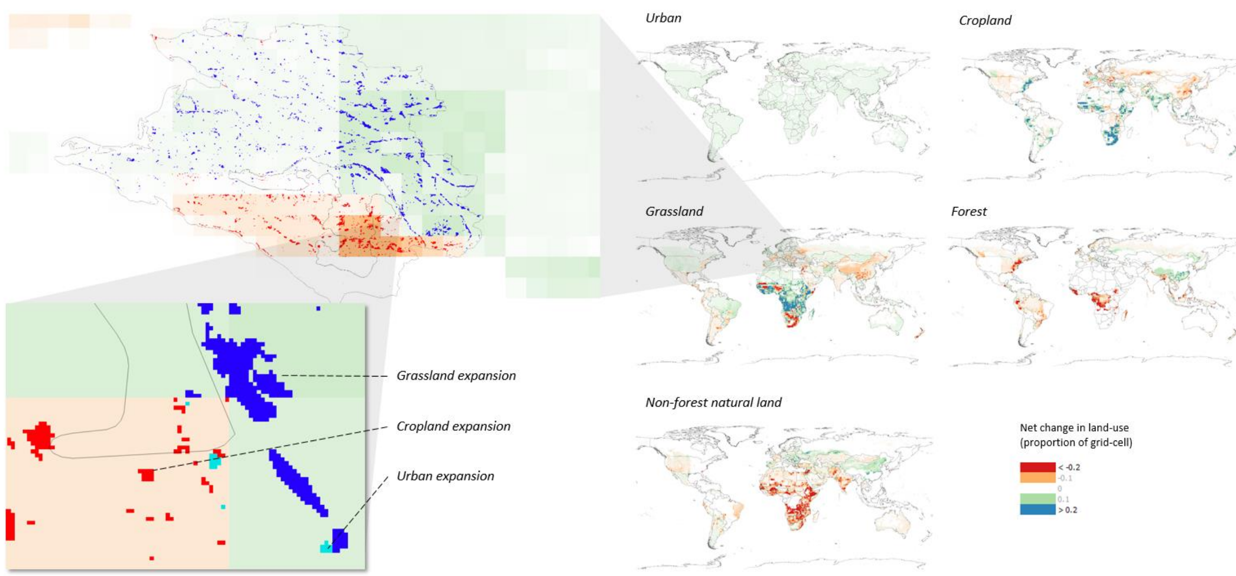
$$s.t. \qquad A = \left(\sum_{l} \theta_l X_l^{\rho} \right)^{\frac{1}{\rho}}$$

where R_l is the rental rate for land in sector l and X_l is the revenue maximizing allocation of land to l. In this, ρ is the constant-elasticity of substitution parameter (taken from GTAP database elasticities), θ_l is the production efficiency of land as an input into production and A is cross-sectoral aggregate production. The AEZ- and sector-specific net hectare change of land-use is the main output of GTAP-AEZ that is used as inputs to the SEALS-InVEST component.

SEALS downscaling methods

In order to use the scenarios described above to answer questions specific to landscape scale indicators, such as “how much forest will be lost to cropland expansion,” or “what is the ecosystem service impact of these changes,” it is necessary to know where within the country the specific changes happen. To enable this, we downscale the scenarios to a fine (10 arc-second, ~300m) resolution using the Spatial Econometric Allocation Landscape Simulator (SEALS), illustrated in figure 5 below (and more fully presented in Appendix 2). In this figure, the five small maps show the medium-scale (15 arc-minute, ~15km) resolution input data from the Land-use Harmonization 2 project while the maps show where the fine-scale change is placed on top of the medium scale resolution data.

Figure 5: Downscaling to 300m resolution



These downscaled maps will be used by CWON component 3.1, which specifies that expansions in cultivated area should be estimated so that it identifies deforestation. This will be used to adjust forest accounts in the wealth of nations as determined by agricultural expansion. By being spatially explicit in this manner, very detailed estimates of e.g. carbon storage lost within the deforestation can also be obtained. The specific scenario to be used for the CWON work will be RCP4.5, SSP2 for 2050 (which represents a middle of the road estimate for both land-use change and climate change.

InVEST ecosystem service methods

Summary of scenarios

We will use two different sets of scenarios in this work. The first, named “outcome scenarios,” are taken from the GFP project directly or are simple extensions of the approach to additional representative concentration pathways (RCPs) of climate change and SSPs. These scenarios will include:

1. Fossil-fuel dependence (based on RCP8.5, SSP5, downscaled to 300m)
2. Sustainable pathway (based on RCP2.6, SSP1, downscaled to 300m)
3. Global Conservation (based on sustainable pathway but implements additional landscape-scale conservation measures and protection of land).

The Global Conservation scenario includes spatially-explicit conservation actions, namely the prevention of agricultural or developed land expansion into protected areas, into locations with high carbon value, into wetlands, focusing ag-expansion in degraded areas, and finally, reducing overfishing by returning areas to maximum sustainable yield. Specifically, each policy goal is represented by a distinct constraint or prioritization method implemented in the SEALS downscaling and scenario generation methodology. In particular, we added five additional inputs to represent an increased prioritization of environmentally valuable conservation land as follows:

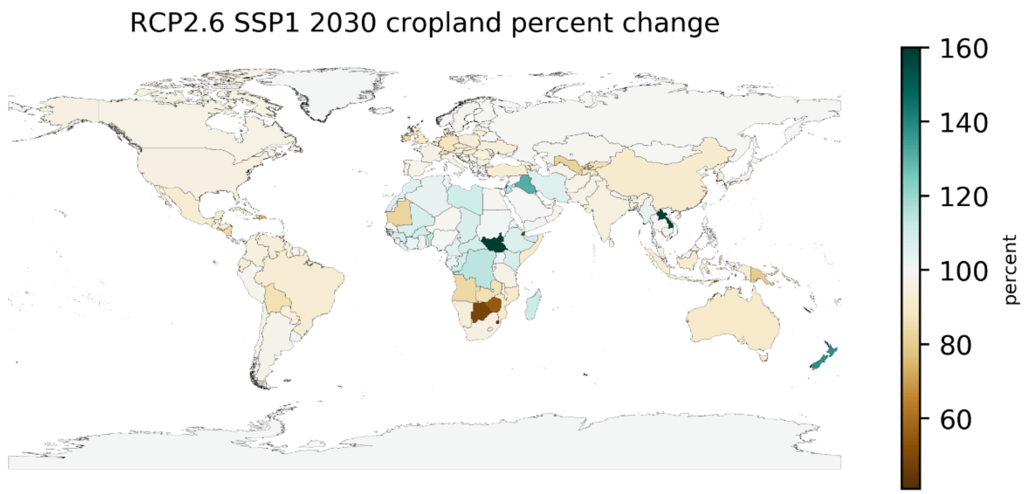
1. Protected areas were assumed to have successful prevention of development from agriculture or developed land. We did this by lowering the expansion suitability coefficient in SEALS to an extremely low level in all areas defined as "strict protected areas," (IUCN categories I-IV).
2. Prevented all expansion of non-natural land-use classed into wetlands (ESACCI classes 160 and 170).
3. Reduced the likelihood of expansion in areas identified as having high ecosystem service value under the baseline (2010) 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 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 (2010) landscape. The raw carbon storage values (in megagrams 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 multipled this 0 to 1 score by $\beta_b = -100.0$ to reduce the probability of expansion in these areas.

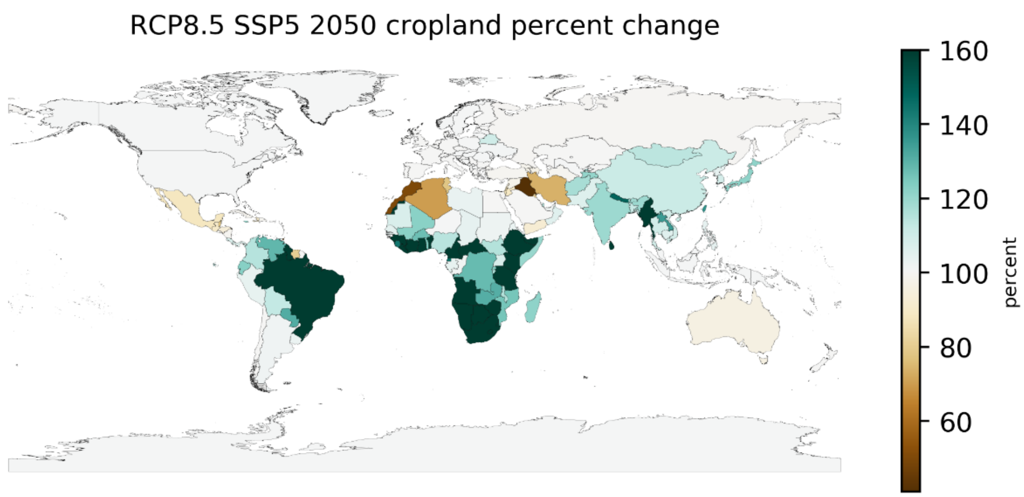
These additions to the SEALS model almost completely eliminated expansion in the areas targeted for preservation. However, because we also chose to exactly match the coarse-level change predictions from LUH2, there was some expansion into areas targeted for preservation in the case where no other land was available.

The scenarios used in the GFP to date have been based on the SSPs and thus much of the coarse-level variation comes directly from the variation in outputs from the IAMs used. Here, we summarize country-level land-use change in these scenarios, reported as percentage change from 2030 or 2050 compared to the baseline year of 2015. We use a simplified schema of land-use classes (to be used throughout the rest of the project) that summarizes to the following 5 classes:

1. Urban
2. Cropland
3. Grassland
4. Forest
5. Non-forest Natural

Two supplementary files are included with this report: a spreadsheet with all country-scenario-year combinations of baseline and percentage change; a vector file (GeoPackage) suitable for mapping; and a directory containing images that plot the changes. The last of these is illustrated in the figure below, which shows percentage change in cropland area under two of our scenarios.





The second set of scenarios, named “policy scenarios,” extend and complement the outcome scenarios described above to analyze not just specific outcomes, but also the specific policy methods by which an outcome might be achieved. The policies will be implemented as scenarios via modifications of different parts of the GTAP-InVEST model (and will require switching to a “feedback version” of the model, i.e. one that allows to estimate the effect of a policy change against a baseline without such policy change, and that takes into account both the impact the policy change has on ecosystems and the knock-on impact back to the economy). The specific policy changes to be included are:

Table 1: Policy scenarios

#	Description

1	Removal of agricultural subsidies
2	Invest in agriculture intensification (including relevant infrastructures) in countries with low productivity
3	Introduce disincentives to the imports of goods and services with embedded BES loss (e.g. tariff and/or non-tariff trade barriers or consumption taxes in importing countries that target reduction of high-impact commodities such as beef or palm oi or consumption-based taxes in importing countries)
4	Adopt/ Expand use of PES schemes, whereby payments commensurate to the opportunity cost of not developing land are made to landowners in priority areas for the delivery of certain ecosystem services. Specifically, this will entail payment transfers from one region to another, which are then used to fund the subsidies in the target region.
4a	Water yield/ water regulation (Note: This would be a refinement of something already envisaged under task 3.2.2.);
4b	Carbon storage/ sequestration (i.e. expand REDD+ Schemes)
4c	Biodiversity conservation (these could be operationalized through offsets, implementing conservation activities in pixels with high endemism and allowing conversion in pixels with low endemism, keeping total area conserved constant)).

These policies will be converted into scenarios by considering each policy in isolation, in combination with all the other policies, and potentially via different combinations of policies (to be identified by the World Bank via feedback on this report). These policy-implementation scenarios will be compared against three different reference scenarios, namely:

1. Baseline economic change as modeled by GTAP with exogenous drivers (population and climate change) from the RCP/SSP inputs described above.
2. Same as 1. except with RCP 2.6
3. Same as 1. except with RCP 4.5.

These baseline scenarios are implemented in the same way as the existing GFP scenarios with the only change being different RCPs and aggregate land-use change. Specifically, we use land-use change from GTAP as the input to SEALS, along with the RCP as defined above.

Methods for specifying policies

One of the primary reasons for extending the GFP version of the GTAP-InVEST model to the feedback model is that it would enable analysis of policy changes. The basic reason why this is only partially possible with the GFP version is that most of the policies relevant to solving ecosystem challenges involve modifying a parameter within the CGE part of the model, but in the GFP version, the CGE is only run as the very last step (and thus cannot have further feedback effects). For the feedback version, running the economic component of the model twice enables analysis of these types of effects. An example of this type of policy analysis method would be changing demand for certain products with high environmental impacts (e.g. beef) in the first run of GTAP and then observing the change in land-use allocation that results. This would then be input to the SEALS-InVEST pipeline via a new downscaled landscape that reflects these endogenous land-use changes. Further, these results will then be input into the second run of GTAP to estimate additional, ecosystem-based changes in economic performance.

Implementation for policy scenario 1 is straightforward and based on many existing GTAP analyses. Subsidy and tax information is one of the key elements in the database and the standard GTAP model specifies these types of payments explicitly. Thus, we will draw from the large literature (characterized by e.g. Hertel et al. (2010) on biofuel subsidies) to parameterize this scenario.

Policy scenario 2 is somewhat more challenging to parameterize, but can be done by exogenous increases of capital input to agriculture and/or increasing country- and sector-specific total-factor productivity rates. This is similar to how we considered TFP shocks in GFP model scenarios, but now would be defined based on levels of investment that vary among countries and sectors according to strategic investment (e.g. via prioritization of developing country infrastructure). The TFP increase will be the result of increased R&D expenditure, as defined in Baldos et al. 2019.

Policy scenario 3 is similar to policy scenario 1 insofar as it is similar to existing GTAP-based experiments broadly employed in the literature. The protection rates (implemented as a tax on imports) will be defined by calculating how much loss in ecosystem services is embedded in the export of a given product. The actual dollar value of the tax will be defined based on a literature review with the exception of carbon storage, where we implement the World Banks internal value for the social cost of carbon.

The policy scenarios 4a-c are all variants of PES schemes and could be implemented by specifying a direct payment from consumers of ES to producers of ES. Each of these policies imply some degree of prevented land conversion, and so the policy is thus defined as the payment made commensurate to the opportunity cost of not developing this land.

Metrics to assess alternative policies

When assessing the merits of alternative policy options, single outputs of the model, such as global change in GDP, may not provide accurate information when there is significant shifts or unequal distributions of gains and losses. We propose to approach this question iteratively, defining a key set of outputs in the first draft of the next deliverable, and iterate on feedback received to identify the most useful set of metrics.

Challenges

Several challenges exist in this project that will be further analyzed throughout the course of the work and will result in specific improvements to the model or proposed changes for future work. At this point in the work, we have discussed as a team the challenges and have several ideas for addressing them, described in the following sections. However, note that these challenges are still being analyzed (as some of them require having the full feedback model completed), and so parts of this section may still be changed.

Elasticities and Rigidities

One challenge that this report will face is properly accounting for when CGE methodology might overestimate the adaptability of an economy (and thereby underestimate the impact of large environmental changes). In consultation with the GTAP team at Purdue University, we have established that this can be analyzed via systematic sensitivity analysis (SSA) included within the GEMPACK software suite currently in use to solve the GFP model. Focusing on cases within the SSA where the elasticity of substitution is much lower allows analysis of a world where economies are less able to adapt to changes via substitution (and thus would have proportionately larger impacts from environmental changes. Also in consultation with GTAP, we have confirmed that the elasticities typically used within the comparative-static versions of GTAP (and most other CGEs) are best described as short-run elasticities, representing the substitutability within the current economy, within a relatively narrow band of possible change. In other words, they can be used to represent marginal changes but not necessarily large systematic changes, meaning that they will overestimate the flexibility of the economy to adapt to these changes, thereby underestimating the true impact of a driver like climate change.

Using the SSA approach in GEMPACK, we will vary the elasticities used and report also where the model cannot be solved. In some traditional CGE analyses, shocks to the model are sufficiently large that they cause the model not to be solved (a solution cannot be found). Similarly, when elasticities are changed to be less flexible, non-solvable models also can be found. In this section of the report, we will highlight these situations as potential areas to explore further (rather than just exclude as outliers, as in many typical analyses) via model refinements and deeper comparative-static analysis. Ultimately, the best solution to addressing long-run rigidities is to construct the fully dynamic version of the CGE (a step saved for potential further work). However, useful analysis and results can still be generated via the comparative-statics approach in the feedback model of this project. We conclude therefore that this phase of the report can make significant advancements on assessing elasticities and rigidities, though full analysis of this will require the dynamic model in future work.

Thresholds

A concept related to but distinct from elasticity rigidity is that of thresholds, particularly those related to ecological thresholds being passed, causing non-linear, systemic change in the health of entire ecosystems. Conceptually, rigidities and thresholds are connected insofar as they present modeling challenges whereby traditional CGE methods might underestimate the impact of non-marginal events. In the current project, however, these two challenges can be assessed via modifying different aspects of the GTAP-InVEST model. In particular, ecological thresholds could be modelled via modifying the ecosystem landscape to represent one of the many observed or hypothesized “regime shifts.”

Specifically, we propose that it is possible to base our analysis on the Regime Shifts Database from the Stockholm Resilience Center (SRC), available at regimeshifts.org. Further, we could extend this set of observed regime shifts via analysis of hypothesized, potentially much larger, regime shifts identified in the literature (such as reaching a climate threshold that leads to widespread ecological transition of the Amazon forest ecosystem to shrubland and savannah.

Methodologically, these thresholds would be modeled by shocking the land-use change simulator (SEALS) rather than shocking the structure of the economy. This is a novel ability enabled by our integrated GTAP-InVEST modeling approach. To shock a land-use change simulation, we would map the observed and hypothesized regime shift dynamics into ecoregion-specific land-use change rules. For example, the Amazon regime shift could be represented here by constructing a new landscape that layers a percentage reduction land-use change allocation rule in SEALS on top of the existing change implied by different input assumptions (i.e., those from the SSPs or the first run of the GTAP projection model). The new landscape would then be used to calculate new ecosystem service impacts (linking steps 2 to 3 in figure 2), and thereby economic impacts of passing these thresholds (steps 3 to 4). Because these thresholds are defined exclusively by a biophysical/ES change, the same economic channels listed in figure 2 are used to modify inputs to GTAP-AEZ. Significant interest from outside parties has been generated on this possibility (including from the Dasgupta Review team), so we propose including as many as possible of these refinements in the current summer-2020 timeline while also considering possible extensions from outside parties to further augment this work.

Challenges for specifying policies

Some of the particular challenge that exists for this component of the work is defining how these specific policy changes can be captured in the CGE model. For example, careful analysis and explanation of what channels of impacts are endogenous in the GFP version of the model, what channels can be endogenized in the feedback version (e.g. more detailed representation of the land-use categories, crops or agricultural technologies/practices), what further elements could be made endogenous through additional model modification (e.g. dynamics, vintage capital), and what are the missing GE endogenous pathways that require exogenous intervention as part of the policy scenario design and as part of linking with the ecosystems' services model (for example linking changes in policies to productivity changes or behavioral responses by consumers/ producers (both in host countries and in their trading partners), linking changes in ecosystems' services to agricultural yields). The latter type of effect needs to be analyzed outside the CGE model by using empirically derived estimates as exogenous shocks.

The specific policies that we proposed analyzing in the Scenarios and Policies section were chosen because we could already identify specific ways to shock the feedback model that would reflect these policy changes. For example, analyzing what impact the removal of agricultural subsidies would have on environmental outcomes would be done by creating a shockfile that modifies the subsidy structure in the economy prior to solving the CGE. This type of CGE experiment has been done many times and is included as built-in analysis options in GEMPACK. However, we note that there may be other types of shocks that we are excluding when we choose our policy shocks based on what is presently able to be captured within the CGE model. Thus, we propose that the subsequent reports for this project include additional details about how the above challenges to endogenizing key aspects could be done.

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