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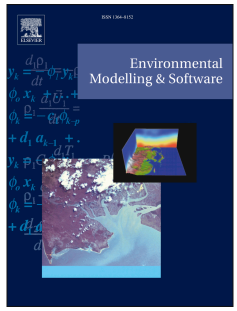

Producing Policy-relevant Science by Enhancing Robustness and Model Integration for the Assessment of Global Environmental Change

R.F. Warren, N.R. Edwards, F. Babonneau, P.M. Bacon, J.P. Dietrich, R.W. Ford, P. Garthwaite, D. Gerten, S. Goswami, A. Haurie, K. Hiscock, P.B. Holden, M.R. Hyde, S.R. Joshi, A. Kanudia, M. Labriet, M. Leimbach, O.K. Oyebamiji, T. Osborn, B. Pizzileo, A. Popp, J. Price, G. Riley, S. Schaphoff, P. Slavin, M. Vielle, C. Wallace

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Title: Producing Policy-relevant Science by Enhancing Robustness and Model Integration for the Assessment of Global Environmental Change

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Abstract: We use the flexible model coupling technology known as the bespoke framework generator to link established existing modules representing dynamics in the global economy (GEMINI_E3), the energy system (TIAM-WORLD), the global and regional climate system (MAGICC6, PLASIM-ENTS and ClimGEN), the agricultural system, the hydrological system and ecosystems (LPJmL), together in a single integrated assessment modelling (IAM) framework, building on the pre-existing framework of the Community Integrated Assessment System. Next, we demonstrate the application of the framework to produce policy-relevant scientific information. We use it to show that when using carbon price mechanisms to induce a transition from a high-carbon to a low-carbon economy, prices can be minimised if policy action is taken early, if burden sharing regimes are used, and if agriculture is intensified. Some of the coupled models have been made available for use at a secure and user-friendly web portal.

Keywords: integrated assessment, integrated assessment modelling, climate change mitigation, carbon price

Highlights

- A flexible bespoke framework generator was used to couple software modules together
- As in the Community Integrated Assessment System, alternative couplings were produced
- Modules represent the energy system, climate, ecosystems, agriculture and hydrology
- They were applied to simulate a transition from a high-carbon to a low-carbon economy
- Associated carbon prices can be minimised by early action and burden sharing regimes

Introduction: Integrated assessment models are increasingly used as tools for projecting scenarios of global change by drawing together information from a variety of disciplines. However, such models often do not assemble detailed treatments of both the earth system and the global economy within a single framework, and often consist of single pieces of software. Here we describe the assembly and use of a modular integrated assessment framework that is based on the principle of coupling together alternative combinations of modules, each implemented at a different institution, to produce an enhanced integrated modelling framework (Warren *et al.* 2013; http://ermitage.cs.man.ac.uk). We couple together state-of-the-art, intermediately complex models representing the global economy and social actors within it, the physical climate system, the energy system, the agricultural system, the hydrological system, and ecosystems. This type of integrated assessment modelling is needed in order to study the complex interactions between climate change, climate change impacts, climate change mitigation, and decisions about land use management. The work was performed as part of the EU project 'Enhancing robustness and model integration for the assessment of global environmental change' (ERMITAGE). These integrated assessments are now of particular topical interest in view of the recent adoption of the United Nations Framework on Climate Change's Paris Agreement (UNFCCC, 2015) by 195 countries.

Most of this framework is incorporated within the Community Integrated Assessment System (CIAS) (Warren et al. 2008), whilst some of the coupled models exist independently of CIAS (specifically, the coupling between the energy technology model REMIND and the land use allocation model MagPIE, see Table 2 for details). The approach is based on the advanced flexible bespoke framework generator which is language-independent (Armstrong *et al.* 2009). The flexible approach allows new modules to be added to the system with minimum disruption, for example when climate models are upgraded with new information, or when updated modules become available simulating climate impacts in new sectors. The approach has created long-lasting coupled models available for use in research for the future, by drawing together a range of models created at different institutions. The co-location of many of the models in the same system (CIAS) allows for increased, easy use of the models in the future at a secure and user-friendly web portal.

Methodology The first step in the modelling processes is to determine conceptually the required linkages between models. This was achieved through bilateral discussions at workshops which allowed model developers from different disciplines to work together. Initially the team created a prioritised list of model couplings needed to answer the research questions we have. Once the list of model couplings had been agreed, the team then worked together to determine the scientific requirements of the couplings. These requirements included detailing (a) which are the variables output from one model that are to become the input to another model? (b) are any unit conversions required? (c) is any spatial or temporal aggregation required to allow for differences in the spatial or temporal resolution used in different models? (d) when during the operation of the code should the variables be passed? Once these requirements had been determined we used the Bespoke Framework Generator version 2 (BFG2) to couple models together according to the requirements in a language-independent fashion (Ford et al. 2006, Warren et al. 2008). BFG2 has a simple interface which allows users to automatically create metadata describing model linkages; and it continues by using this meta-data to automatically generate the coupling code. The metadata follows a 'DCD' approach: it contains Description (D) information about the variables to be exchanged between the models that are to be coupled, specifically the variable names, units, and temporal and spatial scales; Composition (C) information detailing which quantities should be exchanged between the model codes at which times during the running of the code; and Deployment (D) information detailing which machines will run the code. We initially coupled pairs of models together before moving on to more complex coupled models involving three or more components. Finally, couplings were incorporated into framework of the Community Integrated Assessment System (CIAS, Figure 1), which allows users to execute the couplings at a user-friendly web portal.

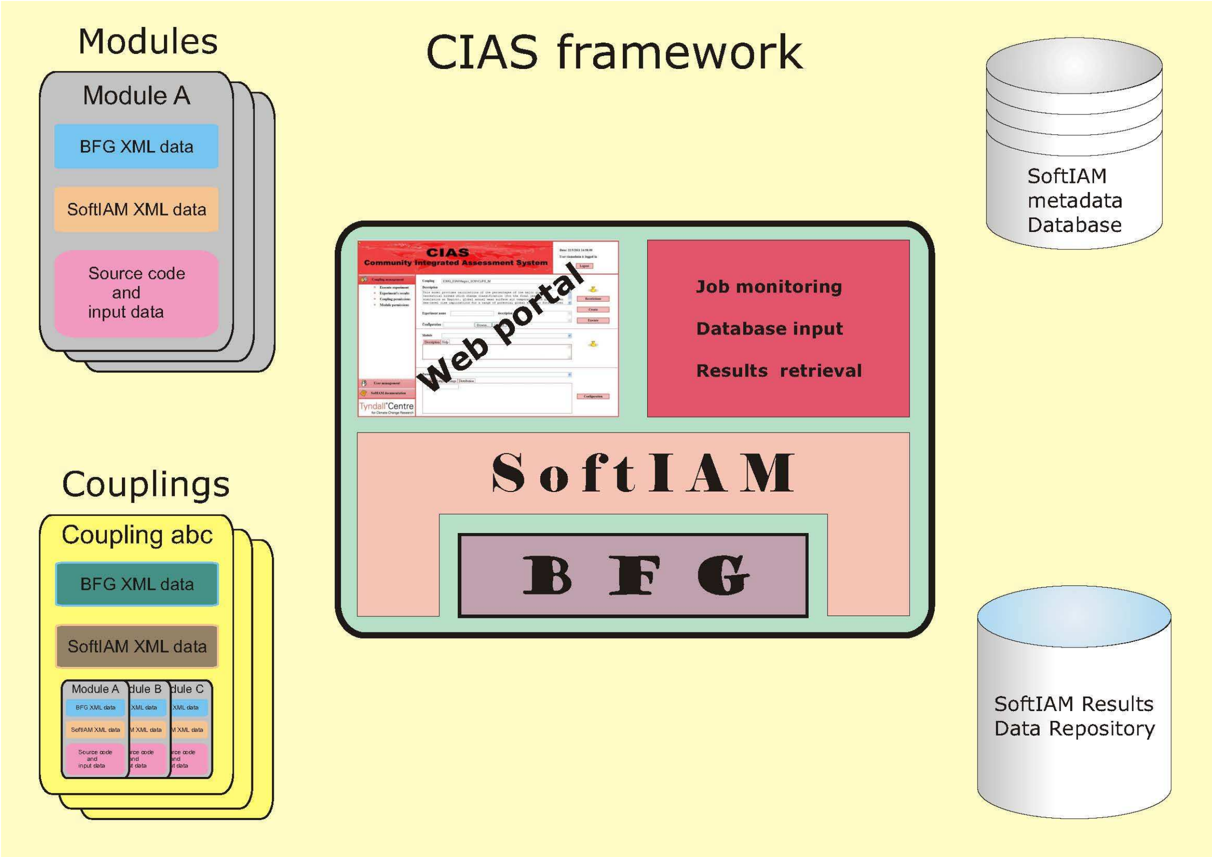

Figure 1 Principal components of the CIAS framework. The CIAS web-portal is the visual top layer of the SoftIAM technology which couples models together using BFG. Module and coupling properties are described in XML files. SoftIAM is used to compile, build, deploy and execute the models on different platforms and the results are stored in a file server. The metadata for each model run is stored in a searchable database. The web portal allows users to set up, run and access experiments without needing to understand the complex underlying framework (Goswami and Warren, 2011).

CIAS (Warren et al. 2008) is a framework that supports and enables the creation and running of integrated assessment models. It connects together alternative sets of component models: thus one of these sets is broadly equivalent to 'an integrated assessment model' and may be referred to as 'a coupled model'. It is flexible and multi-modular, and enables models to communicate with each other even if they are written in different programming languages or operate on different platforms. The CIAS web portal supports users in running the integrated models: it is facilitated by the softIAM technology (Goswami & Warren, 2011). For each coupling, the softIAM technology supports a variety of coupling-specific features related to the selection of modes of operation, changing model parameters, selecting variables for output, and user management. Model coupling outputs are stored in a database, and can be accessed from the web portal. Table 1 provides the list of models used, and Table 2 shows the list of linkages between the modules which we created.

Table 1. Modules used in the coupling process

Type of model	MODEL	BRIEF DESRIPTION AND KEY REFERENCE
Overall Integrator	CIAS (UEA)	Community Integrated Assessment System: links combinations of models together in a flexible fashion to address policy questions (Warren et al. 2008)
Global welfare,energy and technology	REMIND-R	An inter-temporal optimization model maximizing global welfare subject to equilibrium conditions on different markets (Leimbach et al, 2010a, 2010b; Luderer *et al.* 2015).
Global macro-economic	GEMINI-E3	A large-scale, global CGE model, covers around 20 regions at World level (with explicitly EU, USA, India, China). It has a disaggregation of industries and types of inputs that is specifically designed to allow for substitution in energy production and use. *GEMINI-E3* has been used extensively to simulate national and international climate policies (http://gemini-e3.epfl.ch/). (Bernard and Vielle 2003, 2008)
Land use allocation	MAgPIE	Demand in 10 categories of food and feed energy is simulated in 10 economic world regions, and is met by 20 cropping activities and 3 livestock actvities. Trade in food products between regions is simulated endogenously. Coupled to the grid-based dynamic model LPJmL to simulate spatially explicit land-use and water-use patterns whilst considering technological and agro-economic change, including trade. (Lotze-Campen *et al.* 2008, Popp *et al.* 2014)
Energy and technology (World)	TIAM-WORLD	A technology-rich model of the entire energy/emission system of the World split into 16 regions, providing a detailed representation of the procurement, transformation, trade, and consumption of a large number of energy forms. (Loulou and Labriet, 2008; Loulou *et al.* 2009; Labriet *et al.*, 2012, 2013a, 2013b).
Global Climate	Magicc-6 (UEA)	Simple, widely used climate model tuned to emulate

		alternative complex global circulation models. Can simulate global climate change outcomes for the RCP scenarios. See wiki.magicc.org/index.php?title=The_MAGICC_Wiki. (Meinshausen et al., 2011).
Global climate	PLASIM_ENTSem	An emulator of an intermediate complexity Global Climate Model (Holden et al. 2014)
Regional Climate	ClimGEN	ClimGEN generates regional climate change projections using the method of pattern scaling. (Warren et al 2012)
Ecosystems, crops, pastures, freshwater	LPJmL	Dynamically represents the global terrestrial biosphere (9 natural vegetation types), major crops (12 types), pastures, and optionally bioenergy (two grasses and one tree). Uses ClimGEN projections to simulate coupled carbon, water and vegetation dynamics in response to climate change and human land use (Rost et al., 2009, Beringer et al., 2011).

Table 2. List of coupling sequences created in our integrated modelling framework. Couplings with a tick mark are included already in the CIAS integrated modelling framework, whilst those with a cross could not be incorporated within the timescale of the ERMITAGE project's funding, and instead were run 'off-line' by exchanging files.

Coupling Sequence (feedbacks not shown)	**BFG2 status**	**CIAS status**
PLASIM-ENTSem_GEMINI-E3	✓	✓
PLASIM-ENTSem_ClimGEN_LPJmLem(crop)_GEMINI-E3	✓	✓
PLASIM-ENTSem_ClimGEN_LPJmLem(crop)	✓	✓

MAGICC_ClimGEN_LPJmLem(crop)	✓	✓
PLASIM-ENTSem_ClimGEN_LPJmLem(NPP)	✓	✓
MAGICC_ClimGEN_LPJmLem(NPP)	✓	✓
TIAM_PLASIM-ENTSem	✓	x
LPJmL_MagPIE	×	×
MAGICC_ClimGEN_LPJmL_MagPIE_REMIND	×	×
MAGICC_ClimGEN_LPJmL_MagPIE_TIAM	×	×
MAgPIE_TIAM	×	×

We used a third key software technology, statistical emulation, to speed up the run time of some of our model couplings. In this approach, a model is replaced by a computationally much faster and functionally smoother model 'emulator', derived from a large ensemble of simulations. We created emulators for PLASIM-ENTS (Holden *et al.* 2014) and also for the simulation of net primary production and crop yields by LPJmL (Oyebamiji *et al.* 2015). The methodologies are described in detail in these references. In summary, the PLASIM-ENTS emulator uses singular vector decompositions of the spatiotemporal outputs of a large ensemble of transient 21st century climate simulations, considering a wide range of future emissions scenarios. The dominant components of the decompositions are fitted as polynomial functions of future forcing and model parameters. The approach represents an advance on pattern scaling as it allows us to address non-linear spatiotemporal feedbacks and model parametric uncertainty by representing multiple modes of variability. The LPJmL emulator is constructed in a two-stage approach. The first stage uses step-wise regression to fit crop yields as smooth functions of local climate variables, under the assumption that each LPJmL grid cell is an independent sample. The second stage combines principal component analysis and weighted least squares to allow for bias in predicted spatial patterns, correcting for the anticipated residual of the first stage. In table 2, coupling sequences in which the models have suffix ‘em’ refers to emulators of the full codes.

Figure 2 illustrates the emulation of precipitation from PLASIM-ENTS. Deriving the emulated precipitation fields required ~1 minute of CPU time, compared to ~1 year of computer time required for the full simulation. This can result in the loss of representation of more complex processes such as feedbacks and non-linearities, which might be important.

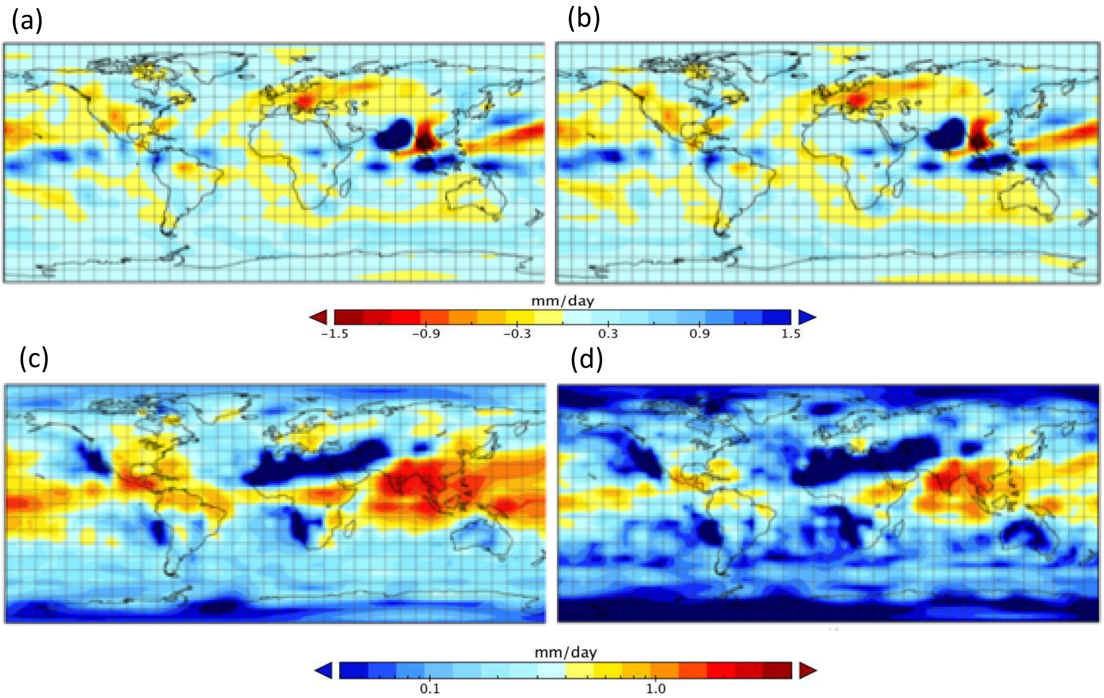

Figure 2: The change in decadally-averaged June-July-August precipitation between 2000 and 2100 AD in response to RCP4.5 forcing: a) PLASIM-ENTS (simulated) ensemble mean, b) PLASIM-ENTS_em (emulated) ensemble mean, c) simulated ensemble standard deviation and d) emulated ensemble standard deviation. Note the logarithmic scale.

Thus, use of emulators of more complex models allows the statistical (as opposed to mechanistic) representation of more complex processes than would otherwise be possible within integrated models. The statistical emulation needs to be robust: in this example the emulated ensemble reproduces the simulated mean field extremely closely in relation to the ensemble variance. It is also able to reproduce the pattern of the simulated uncertainty field, though somewhat understating its magnitude.

Example couplings

EXAMPLE 1: PLASIM-ENTSem_ClimGEN_LPJmLem

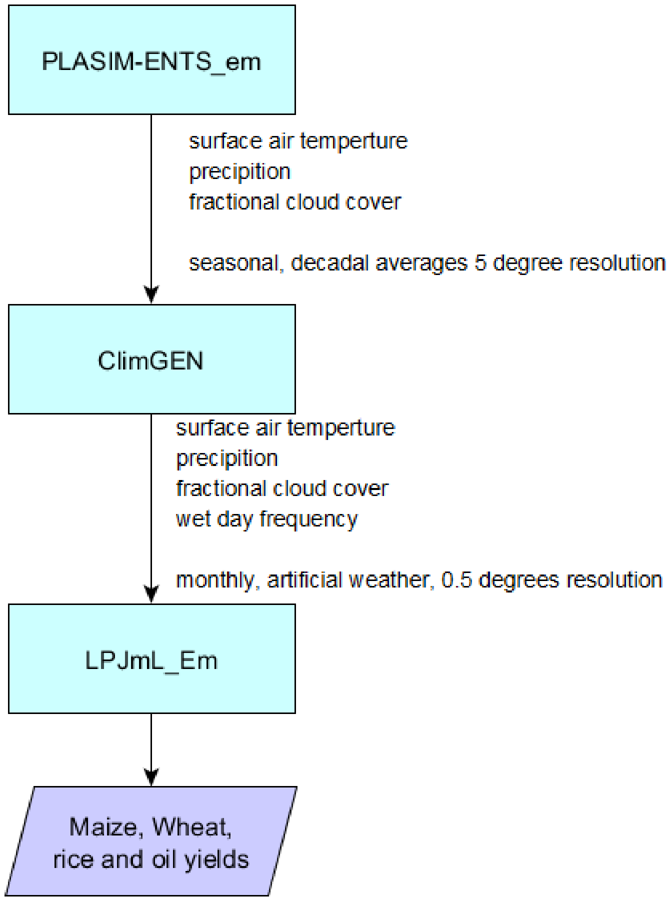

Figure 3a. The exchange of variables between models in the bespoke framework generator (BFG2) for the PLASIM-ENTSem_ClimGEN_LPJmLem coupling. This diagram is generated automatically from the BFG2. The rectangles denote models and the parallelogram denotes outputs from the model. Arrows indicate the direction of data flow within the coupling. Model names within these figures may differ slightly from the text as they are program names.

In this relatively simple coupling (Figure 3a), measures of global climate change such as temperature are used to drive a pattern scaling module CLimGEN which in turn drives an emulator of a climate change impact model, LPJmLem The process begins with the provision of historical and projected global time series of greenhouse gas concentrations to the climate model emulator PLASIM-ENTSem (Holden *et al.* 2014) which simulates global climate changes for near-surface temperature, precipitation and cloud cover on a 5° grid scale. The seasonally-resolved climate projections are passed to ClimGen which downscales the data to a 0.5° grid. In pattern scaling, linear relationships between projected local climate change and projected global mean temperature change are diagnosed directly from outputs of global circulation models; these are combined with observed climatological data to create projected fields of climate change (here precipitation and temperature) at a resolution of 0.5 ° x 0. 5 ° (Warren *et al.* 2011 for further detail). Finally, the downscaled climate change projections are used by LPJmLem to project impacts resulting from the studied global climate change scenarios. Outputs from this coupling are, for example, gridded projections of crop yields.

EXAMPLE2 GEMINI-E3_PLASIM-ENTSem

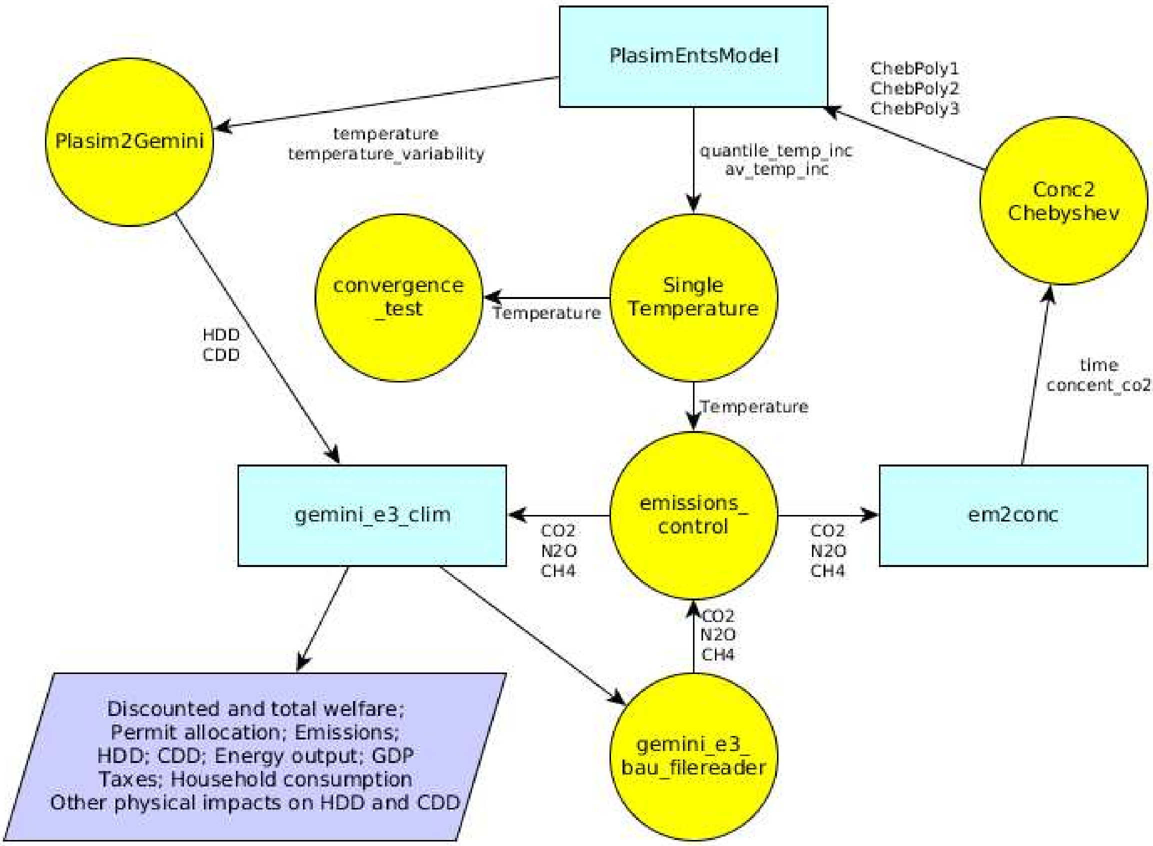

Figure 3b The exchange of variables between models in the bespoke framework generator (BFG2) for the PLASIM-ENTSem_GEMINI-E3 coupling. This diagram is generated automatically from the BFG2. The circles denote transformations, the rectangles denote models and the parallelogram denotes outputs from the model. Arrows indicate the direction of data flow within the coupling.

Model names within these figures are slightly different from the text as they are program names for example: gemini_e3 is GEMINI-E3.

This particular coupling (Figure 3b) has been designed to use the emulator of the climate model PLASIM-ENTSem to create greenhouse gas emissions constraints for the macro-economic model GEMINI-E3 in order to derive climate policy (such as a carbon tax scheme) that constrains the global annual mean temperature rise occurring between pre-industrial times and 2050 to a particular level. It is also designed to investigate the impacts of climate changes on heating and cooling demands, and the economic consequences thereof.

Since GEMINI-E3 is a time-step optimization model, it is not feasible to compute endogenously an optimal emissions path with respect to the economy. For this reason, we have implemented a soft coupling approach, in which no optimisation occurs, which gives realistic emissions profiles given the anticipated temperature expectations. These emissions profiles are used in GEMINI-E3 as an upper bound on the emissions for the assessment of potential climate policies. As the number of "satisfactory" emissions trajectories is potentially unlimited, the coupling constrains its search to a subset of trajectories with two functional forms - a class of simple linear functions, and a class of more complex smooth polynomials. For each proposed trajectory, PLASIM-ENTSem can compute a temperature increase and the coupling algorithm selects the one that meets the given warming target. For the resulting selected trajectory, PLASIM-ENTSem also provides Heating Degree Days (HDD) and Cooling Degree Days (CDD) to GEMINI-E3. This allows GEMINI-E3 to evaluate the impact of climate change on heating and cooling demands and the resultant economic consequences.

Outputs of this coupling are economic measures for each economic region in each time period (e.g. discounted and total welfare); permit allocation; GDP; carbon taxes; and the heating and cooling demand.

EXAMPLE 3. PLASIM-ENTSem_ClimGEN_LPJmLem_GEMINI-E3

This coupling (Figure 3c) is an extension of the PLASIM-ENTSem_GEMINI-E3 one presented in the previous section where the emulator of the agriculture model LPJmLem has been integrated between PLASIM-ENTSem and GEMINI-E3 in order to evaluate physical and economic consequences of climate change on the agricultural sector. For a specified climate policy (see previous section for more details) PLASIM-ENTSem sends climate information at the grid cell level (temperature, precipitation, etc) to LPJmLem that then predicts agricultural variables such as crop yields changes for irrigated or non-irrigated paddy rice, maize and temperate cereal and oil-crop at a spatial resolution of 0.5 x 0.5 degrees. This information is converted into GEMINI-E3 regions using a conversion key to aggregate the data regionally, and then used to analyse the economic impacts of the selected policy or RCP.

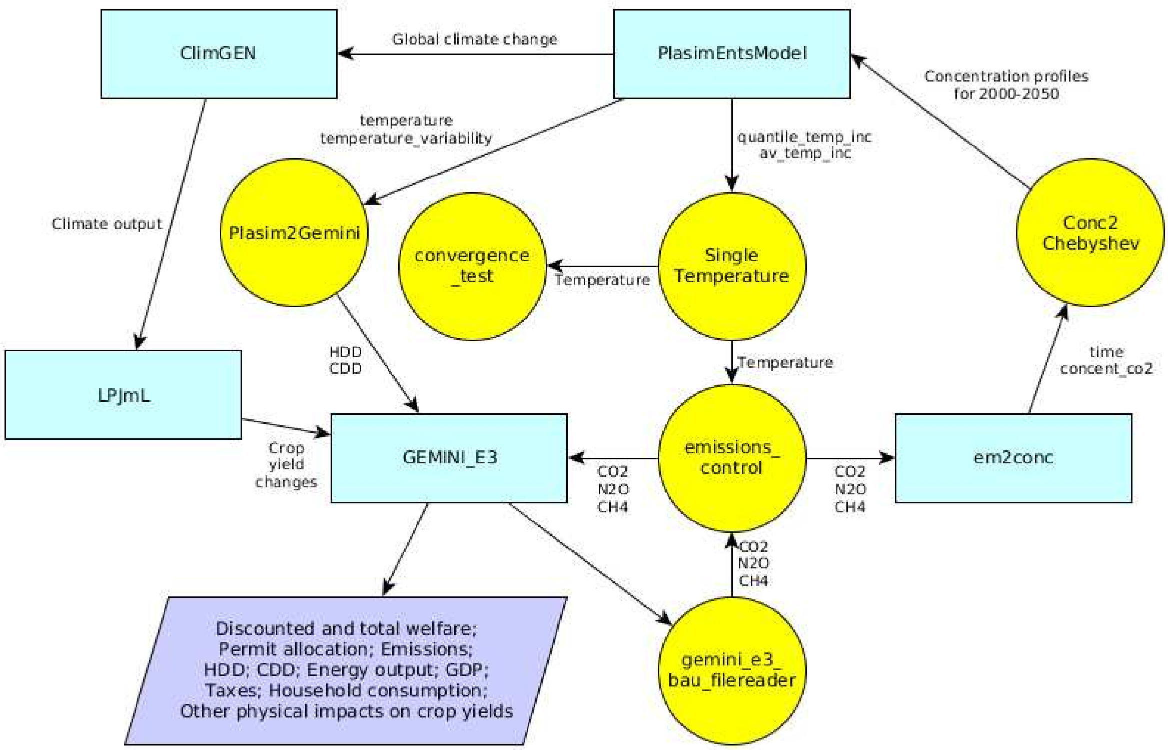

Figure 3c. The exchange of variables between models in the bespoke framework generator (BFG2) for the PLASIM-ENTSem_ClimGEN_LPJmLem_GEMINI-E3 coupling. This diagram is generated automatically from the BFG2. The circles denote transformations, the rectangles denote models and the parallelogram denotes outputs from the model. Arrows indicate the direction of data flow within the coupling

EXAMPLE 4: MAGICC_ClimGEN_LPJmL_MagPIE_REMIND

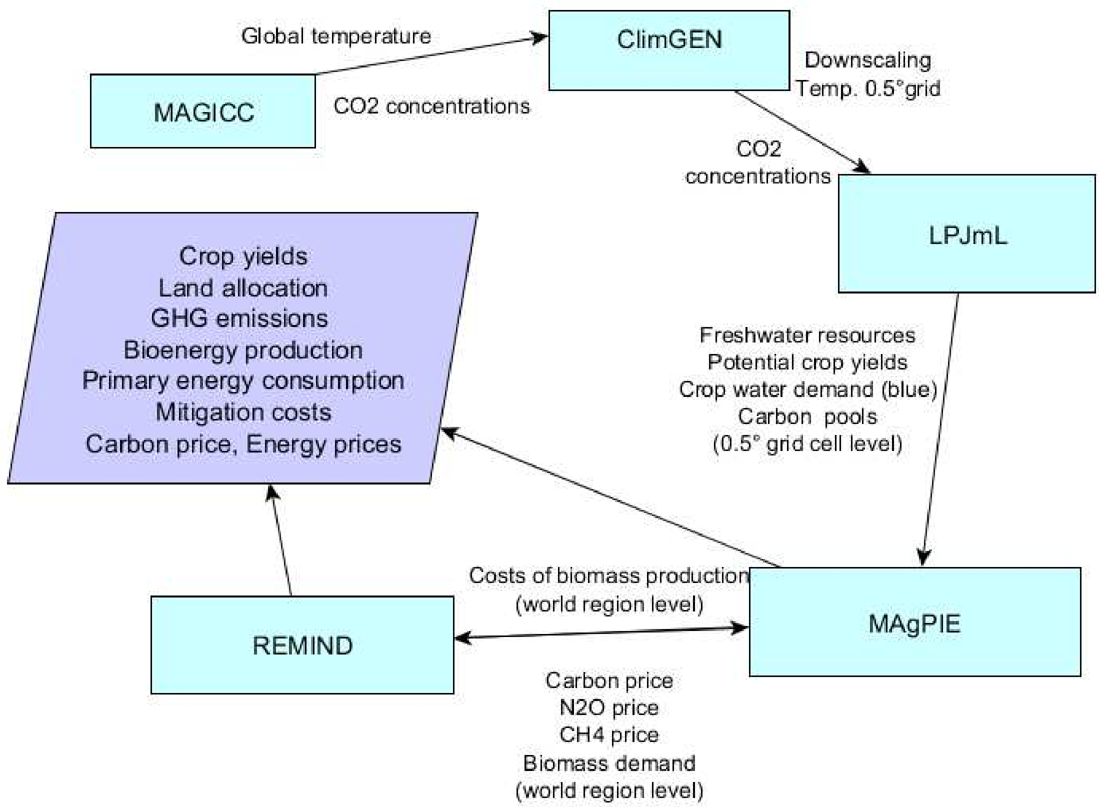

Figure 4. The exchange of variables between models in the bespoke framework generator (BFG2) for the MAGICC_ClimGEN_LPJmL_MagPIE_REMIND coupling. This diagram is generated automatically from the BFG2. The rectangles denote models and the parallelogram denotes outputs from the model. Arrows indicate the direction of data flow within the coupling.

This coupling (Figure 4), which is implemented off-line, uses MAGICC to simulate radiative forcing pathways, global mean temperature and CO_2 time series for the 21st century. ClimGEN generates the corresponding 0.5° regular climate change pattern grid for a selected GCM (eg GFDL-CM2.0). These data are then used to perform climate change impact simulations with the LPJmL bio- and agrosphere model (or alternatively its emulated version LPJmLem, see example 1), focused on variables relevant for use as boundary conditions in the subsequent model chain. LPJmL is set up to provide biophysical inputs to the MAgPIE agro-economy and land use allocation model.

MAgPIE considers the following biophysical constraints on land use patterns, per 0.5° grid cell globally (from LPJmL): (i) Changes in freshwater resources, defined as changes in runoff from the surface and from below-ground and water availability in rivers, lakes and reservoirs; (ii) Changes in soil and vegetation carbon pools; (iii) Changes in potential crop yields of 12 rainfed and irrigated crop types with pasture parameterized in LPJmL, each determined under condition of 7 different management options; (iv) Changes in net irrigation water demand; (v) Sowing and harvest date for all irrigated and rainfed crops.

The first and second of these constraints are examined for potential natural vegetation and the others for both natural and agricultural vegetation. All simulations for the relevant constraints iii-v above were performed for all 7 management options that can be interpreted as different cropping intensities. All runs were made for the two RCPs and the GFDL-CM2.0 GCM and – to separate fertilization and increased water use efficiencies due to enhanced atmospheric CO_2 concentrations – variants were computed in which ambient CO_2 concentration was held constant after year 2002. All results are only used to estimate *potentials* (irrespective of current land use patterns and management practices) as needed for biophysical constraints in the MAgPIE model. Crop distribution is then calculated by MAgPIE based on the simulated local biophysical potentials.

To determine crop production and land allocation, MAgPIE relies on additional information on bioenergy demand from REMIND (Popp *et al.* 2011). REMIND computes the bioenergy demand based on a biomass supply curve that uses MAgPIE results from a large number of previous model runs (Klein *et al.* 2014). In return, MAgPIE gets from REMIND data on greenhouse gas prices. In the RCP3PD scenarios which imply the presence of climate policies, GHG prices represent information on external costs of GHG emitting activities and the urgency of emissions reduction, respectively. Bioenergy is part of a broader technology portfolio that REMIND uses in order to meet the economies' demand on final energy such as transport energy, electricity, and non-electric energy for stationary end uses. Techno-economic parameters (investment costs, operation & maintenance costs, fuel costs, conversion efficiency etc.) characterize each conversion technology. They essentially determine future technology choice and energy mix. Major outputs from REMIND include primary energy consumption, CO_2 emissions, fossil fuel prices, carbon prices and mitigation costs (i.e. GDP and consumption losses).

EXAMPLE 5: PLASIM-ENTSem_TIAMWorld

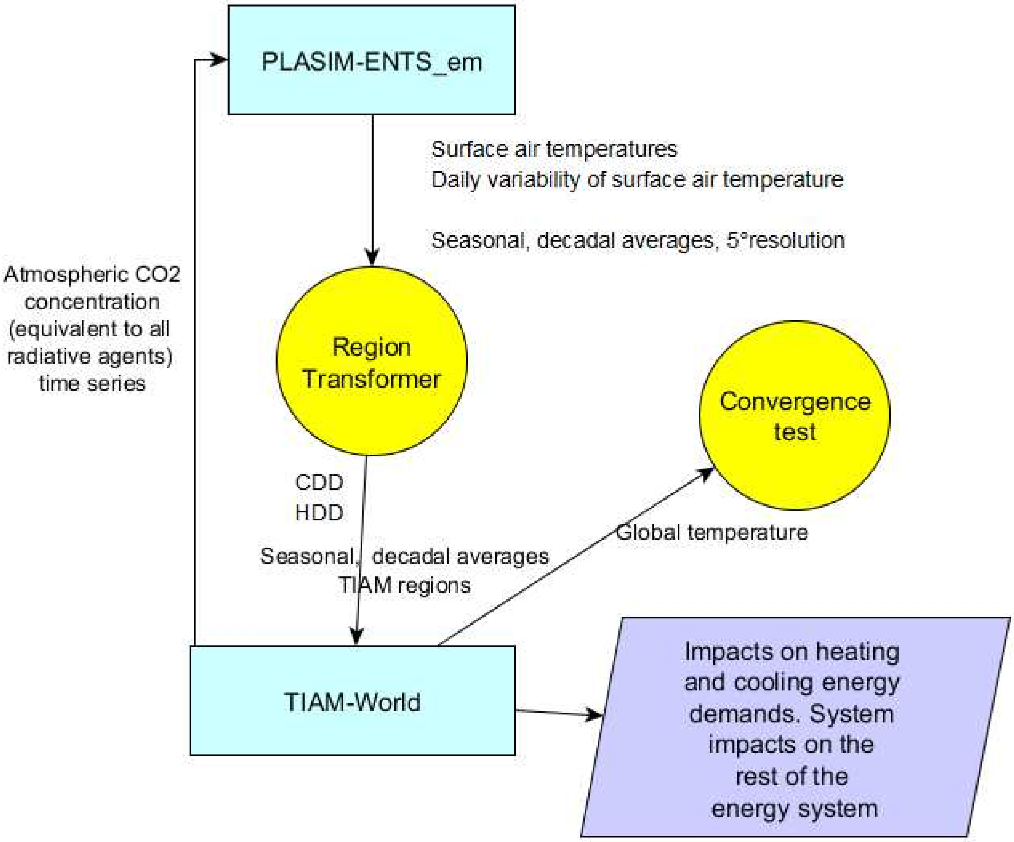

Figure 5. The exchange of variables between models in the bespoke framework generator (BFG2) for the PLASIM-ENTSem_TIAM-WORLD coupling. This diagram is generated automatically from the BFG2. The circles denote transformations, the rectangles denote models and the parallelogram denotes outputs from the model. Arrows indicate the direction of data flow within the coupling.

The objective of the coupling (Figure 5) of TIAM-WORLD and the emulator of PLASIM-ENTSem is to use regional and seasonal temperature changes obtained from PLASIM-ENTSem in order to represent the possible heating and cooling adjustments due to climate change. Indeed, the climate module included in TIAM-WORLD provides only the global average surface temperature increase. In essence, there is an iterative exchange of data between the two models, whereby TIAM-WORLD sends to the climate emulator a set of total greenhouse gas concentrations for the entire 21st century, computed in TIAM-WORLD, and the climate emulator sends to TIAM-WORLD the seasonal and regional temperatures, converted into seasonal heating and cooling degree-days (HDD/CDD) for each of the regions of the model. PLASIM-ENTS emulated outputs (seasonal mean and variance of temperature at 5-degree resolution) were converted to heating and cooling Degree days under the assumption that daily temperatures are scattered about the seasonal mean with a normal distribution. These data were integrated onto the 16 TIAM-WORLD regions as a population-weighted average. The transformation and its validation are described in detail in Holden et al 2014. These seasonal and regional degree-days are then used to compute new seasonal and regional heating and cooling demands in TIAM-WORLD. The new heating and cooling services result in the endogenous computation of a new supply-demand equilibrium. The same approach has been used to model 1) the impacts of regional temperature changes on the efficiency and availability of thermal power plants; 2) the impacts of regional precipitation changes on hydropower; 3) and all the impacts together (Labriet *et al.*, 2015).

The coupling can be applied both as a *single iteration* linkage and as an iterative loop. The single iteration linkage feeds into TIAM-WORLD with HDD and CDD from PLASIM-ENTSem run once with greenhouse gas concentration provided by TIAM-WORLD. This linkage allows the assessment of the impacts of climate change on energy dynamics related to heating and cooling as well as the possible adjustments on the entire energy system. The loop refers to the iterative exchanges of greenhouse gas concentrations and HDD/CDD. It is needed to assess the possible feedback between the energy and climate systems: climate change results in HDD/CDD changes, which may themselves result in more or less greenhouse emissions.

Illustrative results and discussion

We used both the simpler and more advanced couplings to create 21st century scenarios in a harmonized fashion, using common or similar datasets for population, GDP and land use. In particular, we used the couplings to explore economic instruments and technical solutions necessary to achieve a transition from a higher to a lower carbon world, specifically from the representative concentration pathway RCP6 (Fujino et al. 2006) to that of RCP2.6 (van Vuuren et al 2011b) under the common socioeconomic pathway SSP2 (Moss et al. 2010). This is a question of topical interest in view of the recent adoption of the United Nations Framework on Climate Change's Paris Agreement in which 195 countries emphasized the 'urgent need to address the significant gap between the aggregate effect of Parties' mitigation pledges in terms of global annual emissions of greenhouse gases by 2020 and aggregate emission pathways consistent with holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C', (UNFCCC, 2015) since RCP2.6 is broadly consistent with constraining global average temperature rise to 2 °C above pre-industrial levels, although we do not in this study explore scenarios which reduce temperatures more than this.

Early international assessments, such as the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart, 2000) used self-consistent socio-economic scenarios (characterised by population, GDP, land use and energy use) and greenhouse gas emission pathways over time. SRES scenarios were based upon an analysis of how demographic, social, economic, environmental and technological aspects of our society might evolve globally. In these scenarios, two main 'axes' of change were considered: (a) environmental versus economic and (b) globalisation versus regionalisation of markets and cultures. Hence, the four scenarios may be briefly summarised as A1 (Global, economic); A2 (Regional, economic); B1 (Global, environmental); B2 (Regional, environmental). A new process, independent of the original SRES scenarios, has since been established (Moss *et al.* 2010). This recognises that different socioeconomic pathways might have the same climatic change outcome. Hence, SRES scenarios have now been 'replaced' by the Representative Concentration Pathways (RCPs), which were used in the IPCC Fifth Assessment Report (AR5) and new Shared Socio-economic Pathways (SSPs) (van Vuuren *et al.,* 2011a, Kriegler *et al.,* 2012, Ebi *et al.* 2014).In SSPs, the 'axes' of change are (a) challenge to mitigation and (b) challenge to adaptation. For example, increased population is a challenge to mitigation because energy demand will be higher. SSPs are based on new set of socio-economic data, including some trends important in SRES such as population and GDP. However, other data may also be important, but most fundamentally, there is a change in the way in which the data are used. The RCPs and SSPs have not been designed as a new, fully integrated and self-consistent set of socio-economic and emission scenarios over time, but instead offer the potential to mix and match alternative combinations. This is undertaken in a framework (a matrix) that combines climate forcing on one axis (as represented by the Representative Forcing Pathways) and socio-economic conditions (represented by the Socio-Economic Pathways) on the other. Thus we apply this new methodology in our research.

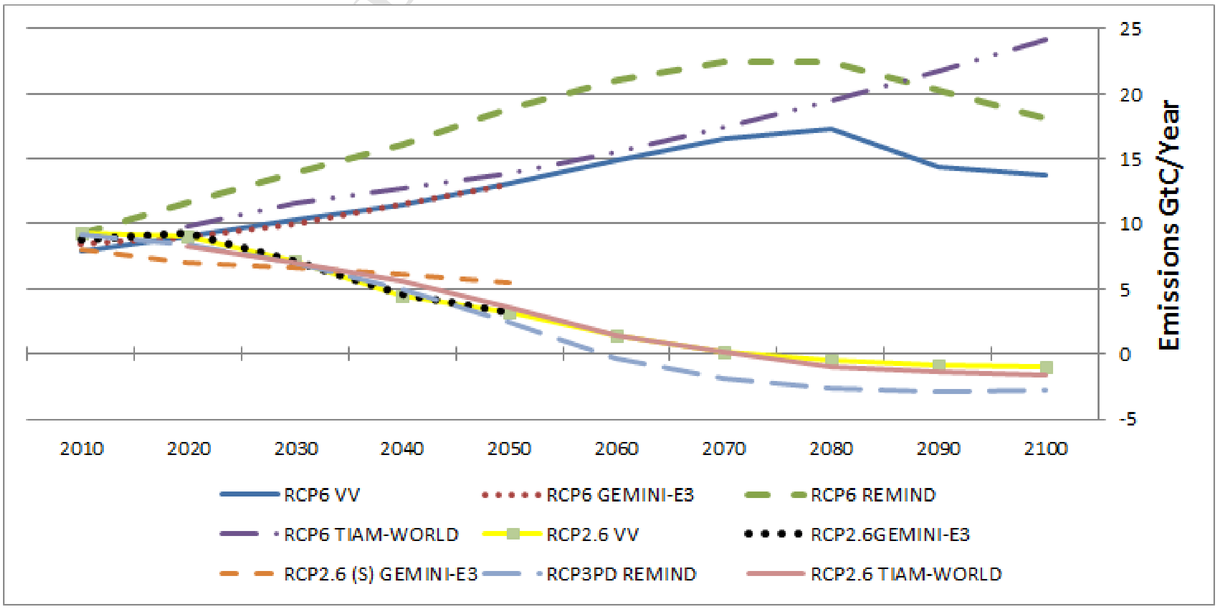

Figure 6. Future Emissions for RCP6 and RCP2.6. Source GEMINI-E3; REMIND; TIAM-WORLD; Van Vuuren *et al.* (2011a).

Firstly, we ensured that our model couplings were reasonably harmonised in projecting greenhouse gas emissions associated with the RCP6 pathway and the RCP2.6 pathway (Figure 6). We used the five couplings above (and others) to derive policy relevant information.

The paths of the emissions from the three models GEMINI-E3, REMIND and TIAM-WORLD are illustrated in Figure 6 alongside reference RCP2.6 and RCP6 trajectories from van Vuuren *et al.* (2011a) labelled RCP6VV and RCP2.6VV showing that our simulations from all three models are broadly consistent with theirs. Substantial emissions reductions are needed in order to stabilize the greenhouse gas concentrations in the atmosphere to a level of around 450ppm CO_2eq (RCP2.6). Model couplings including those listed above were used to explore this transition, and to create different strategies for, or implications of reaching these emission reductions. Carbon prices, policy design, energy technologies, and climate change impacts were all explored.

Applying the coupling in example 3, the GEMINI-E3 model explores how the carbon price required to achieve the transition depends on the time of onset of climate change mitigation and on burden sharing approaches to climate change policy. Applying the coupling in example 4, REMIND simulates the most cost-effective way to achieve the emission reductions globally, exploring how this changes when the availability of biomass is low. Other couplings are used to explore the consequences of these emission reductions. Applying the coupling in example 5, TIAM-WORLD simulates the consequences of climate change for heating and cooling demand in the two RCP scenarios, and finally the coupling in example 2 assesses sea level rise impacts in the two scenarios.

Table 3. Carbon price (US$2007) in RCP2.6 scenario (output from the GEMINI-E3 model as used in coupling example 3).

	2020	2030	2040	2050
Egalitarian, Slow	0	51	466	1685
Sovereignty, Slow	0	48	354	1049
Equalization of cost, Slow	0	50	409	1335
Equalization of cost, Fast	18	63	161	360

Referring to the coupling in example 3, here the GEMINI-E3 model can be used to explore a set of standard burden sharing approaches (Babonneau *et al.* 2015, and alternative constraints on the date at which climate policy (in the form of the use of a carbon price in international markets) is instigated. Table 3 highlights the key findings. The model indicates that large rises in carbon prices are needed to achieve the necessary emission reduction; however these are greatly reduced if policy is instigated in 2020 rather than 2030. The importance of early policy action has also been highlighted in other studies which report on the implications of short-term emission targets for the cost and feasibility of long-term climate goals such as the 2C target for limiting warming (Luderer *et al.* 2013, Riahi et al., 2015; Rogelj *et al.* 2012,).

In assessing the transition from RCP6 to RCP2.6, REMIND selects from a large set of potential energy conversion technologies. Generating negative emissions by using biomass in combination with carbon capturing and sequestration turns out to be a favourable, cost-effective option (Figure 7, left panels). The associated carbon price increases from almost 10 $/tCO2 in 2010 to around 220 $/tCO2 in 2050. The meta-analysis of recent mitigation studies of Clarke *et al.* 2014 identifies a number of studies that demonstrate feasibility of RCP2.6, whilst emphasizing that higher carbon prices and reliance on bioenergy with carbon capture and storage are necessary to achieve this (Azar *et al.* 2010). Hence, our results are in line with the findings of many other studies. However, we also explore the effects of limiting the supply of bioenergy (Leimbach et al., 2016). Within both RCP2.6 scenarios (low and high biomass potential) there is a fast phase-out of the coal technologies which are the most carbon-intensive (Figure 7, upper panels). Importantly, while bioenergy and solar are similarly important for the long-term energy mix in the RCP2.6 scenario (high biomass potential), solar energy is the dominant source of energy in the RCP2.6_biolow scenario. The high sensitivity of the energy system to the availability of biomass can also be seen in Figure 7 (lower panel), which shows the structure of biomass consumption. In the case of sufficient availability of bioenergy, it is cost effective to produce biofuels for the transport sector. However, it is most cost effective to use biomass to produce hydrogen when the biomass potential is low, as this technology has comparatively lower emissions. Furthermore, hydrogen has the potential to replace fossil resources in sectors other than transport. Coupling outputs suggested that carbon prices up to 600 $/t CO2 were needed to achieve the transition to RCP3PD if biofuel cropping was minimised in order to reduce competition for land with agricultural crops and preserve natural ecosystems and biodiversity.

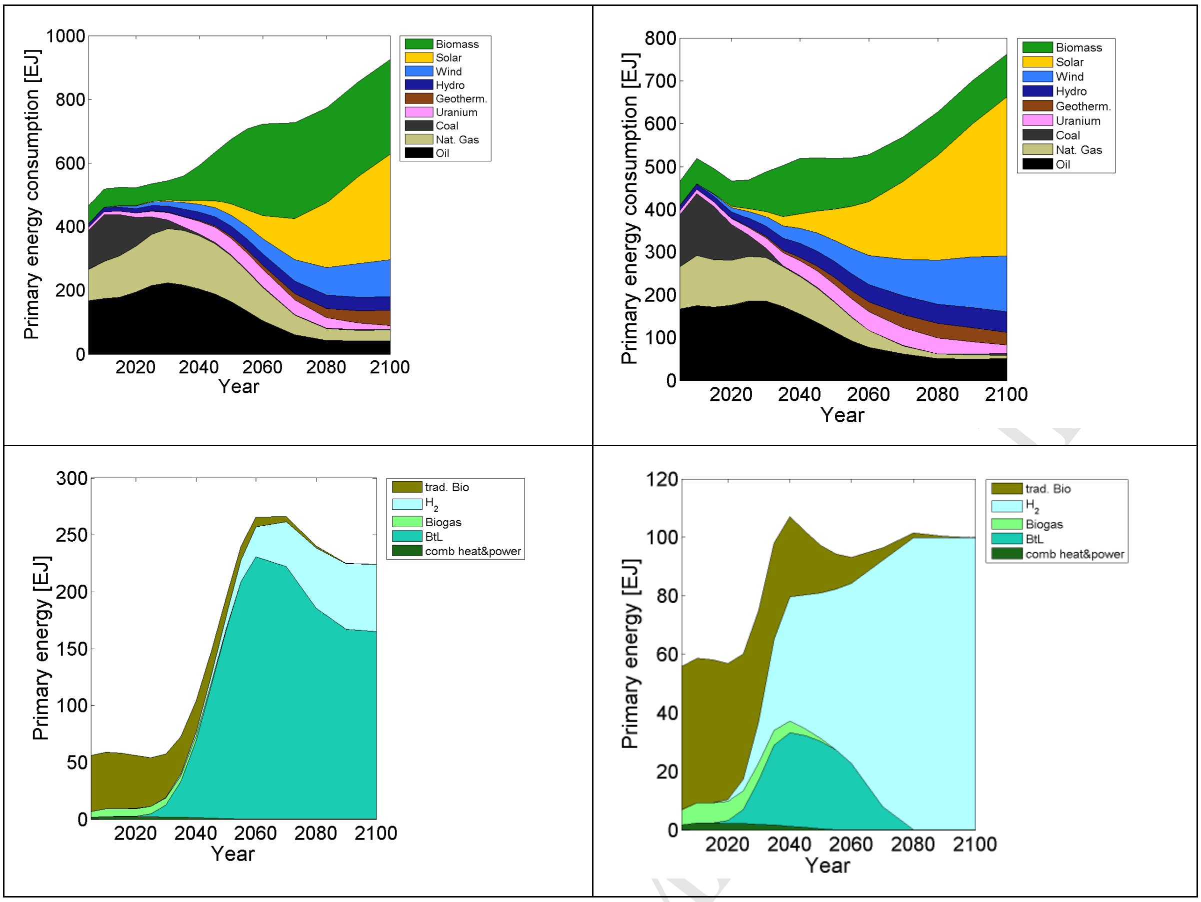

Figure 7: upper left: Primary energy consumption in RCP2.6 scenario; upper right: Primary energy consumption in RCP2.6-biolow scenario; lower left: Biomass consumption in RCP2.6 scenario; lower right: Biomass consumption in RCP2.6-biolow scenario; Source REMIND.

Our studies project that reliance on biofuels for mitigation would induce widespread deforestation and other land use change globally (consistent with the findings of many other studies, e.g. Fargione *et al.* 2008; Searchinger *et al.* 2008, Popp *et al.* 2012, Oppenheimer *et al.* 2014), unless a carbon taxation scheme is used that includes terrestrial carbon (consistent with the findings of Wise *et al.* 2009). Our results indicate that the main response option in land-use to climate change mitigation policy is agricultural intensification through investments in yield-increasing technological change. These are estimated to be 41% to 72% higher in the policy (RCP3PD) scenario compared to the BAU (business as usual, RCP6) scenario over the 1995 technology level. These are shown in Figure 8. The role of agricultural intensification has also been highlighted elsewhere (Lotze-Campen *et al.* 2010, Tilman *et al.* 2011, Smith *et al.* 2013).

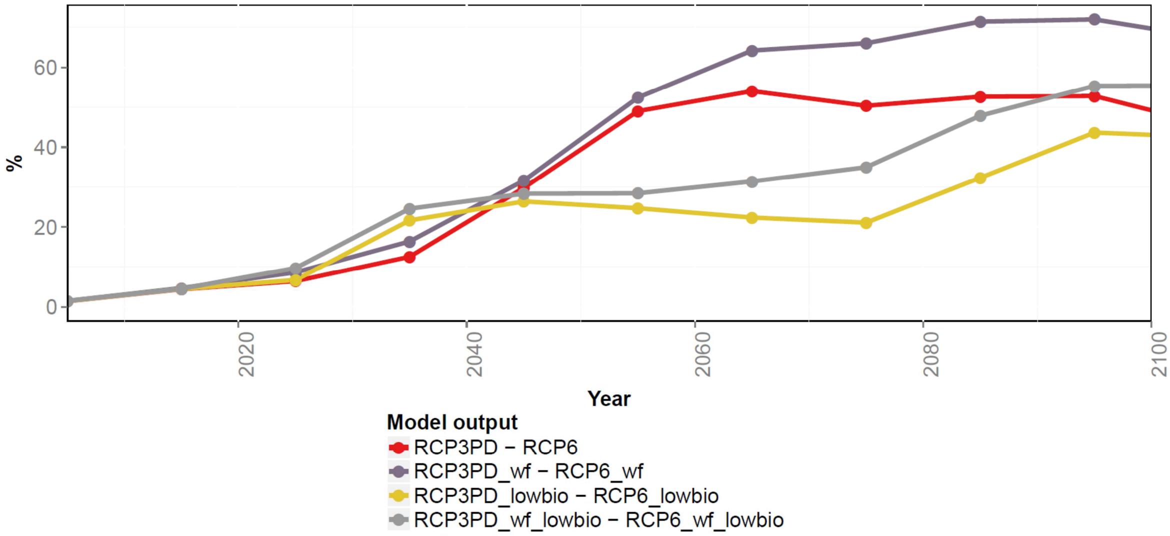

Figure 8. Yield increases with respect to 1995 due to technological change: Difference between the RCP3PD and the RCP6 scenario for the different assumptions on CO_2 fertilization and bioenergy potentials.

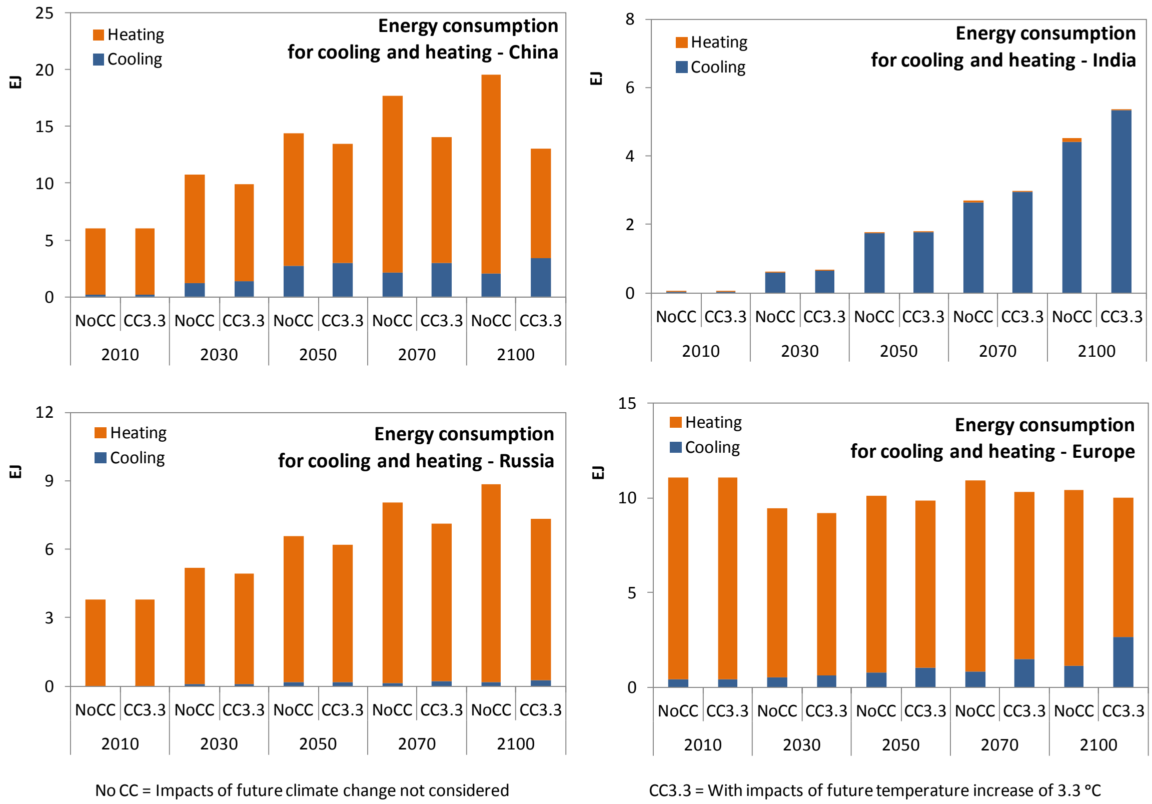

Figure 9 Energy consumption for heating and cooling corresponding to a long-term global average temperature increase of 3.3°C (Reference Case) - Focus on four countries

Results obtained with the coupling PLASIM-ENTSem_TIAM-WORLD coupling (example 5) explore the feedback between the climate system and the energy system (Figure 9). They show that the climate feedback induced by adaptation of the energy system to heating and cooling is found to be insignificant, partly because heating and cooling-induced changes compensate and partly because they represent a limited share of total final energy consumption. However, significant changes are observed at regional levels in the reference case RCP6 (Labriet et al., 2013). In contrast, they are negligible in RCP2.6, with smaller temperature changes. While the increase in cooling demand is met with electricity, the decrease of heating demand results mostly in a decrease in gas consumption, this reflects the relatively higher costs of natural gas compared to other energy sources for heating in the longer term. The need for power capacity to satisfy additional cooling services and the pressure on electriciy demand result in increases in electricity prices (for example, up to 30% in Europe in the mid-term, and 50% in the long term). Thus climate change was projected to have minimal effects on heating and cooling demand globally, but effects were important regionally, especially in Europe.

A coupled PLASIM-ENTS_GEMINI-E3 sequence is also used to analyse the impacts of sea-Level rise (SLR) in the twenty first century. To estimate SLR, we first use the emulator of the climate model PLASIM-ENTS to compute the warming profile related to the GEMINI-E3 baseline scenario. The temperature increase is used to derive SLR using a semi-empirical relationship. Then the physical consequences of SLR are computed using GIS analysis which are incorporated in GEMINI-E3 (see Joshi *et al.* (2015)). The simulation results suggest that the potential development of future coastal areas is a greater source of uncertainty than the parameters of SLR itself in terms of the economic consequences of SLR. At global level, the economic impact of SLR could be significant when loss of productive land along with loss of capital and forced displacement of populations are considered. Furthermore, highly urbanised and densely populated coastal areas of South East Asia, Australia and New Zealand are likely to suffer significantly if no protective measures are taken. Hence, it is suggested that coastal areas needs to be protected to ameliorate the overall welfare cost across various regions.

Coupled economic and climate models were also exploited in a game theoretical framework to analyse fairness and robustness of the international environmental agreements. First, we identify a total emission budget over the 2010-2050 period that is compatible with the warming at the end of the century being less than 2°C, according to our climate models. First results show that an acceptable voluntary burden sharing agreement could be obtained among all groups of countries with a balanced welfare loss below 1% of total discounted household consumption. In such an agreement (see Figure 10), 15.3% of the total emission budget of 424GtC is allocated to USA, 8% to EU, 22.5% to China, 7.5% to India, 4.8% to Russia. In a "robust" solution that prevents potential emissions overshooting in such commitments and takes potential errors arising in the various approximations made in our methodology into consideration, the welfare loss rises to 1.8% for each group of countries. This analysis has recently been extended (see Haurie *et al.* 2015 and Babonneau et *al*. 2015).

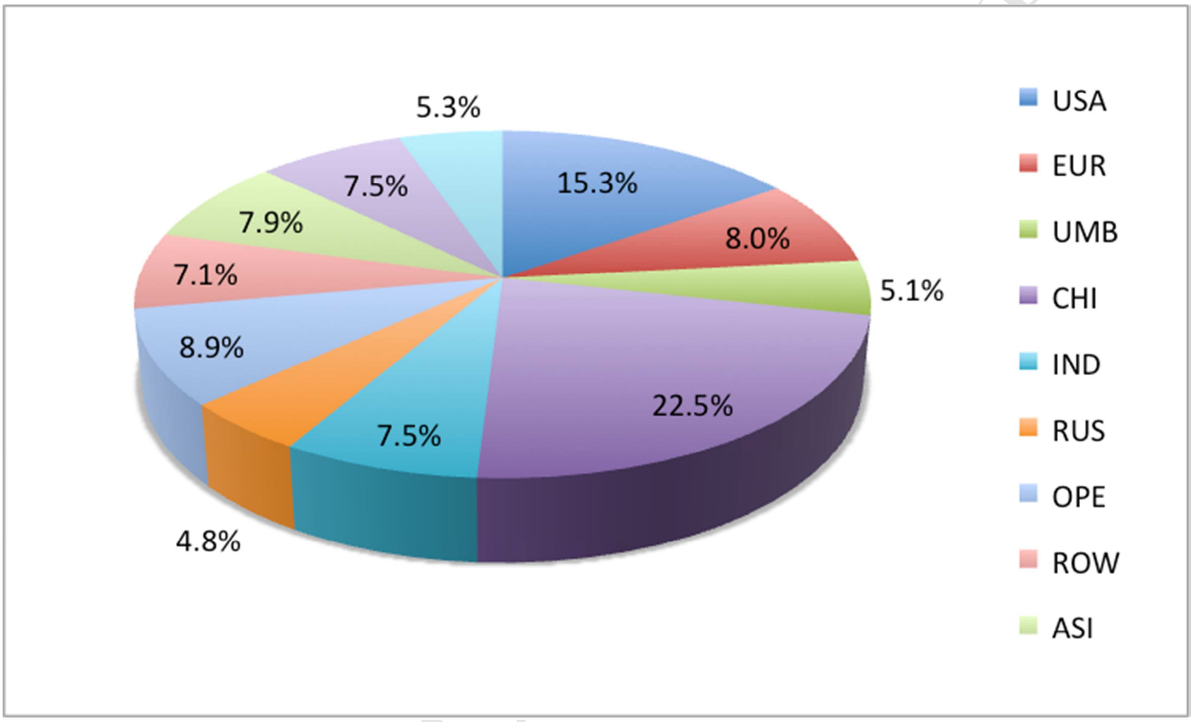

Figure 10. Fair burden sharing (taken from Babonneau et al. 2013)

Conclusions: A set of coupled models has been developed within an integrated framework that can be used in future research projects involving policy makers and other stakeholders, based on the Community Integrated Assessment System, the Bespoke Framework Generator, and the use of statistical emulators for model coupling. We use it to show that when using carbon price mechanisms to induce a transition from a high carbon to a low carbon economy, prices can be minimised if policy action is taken early, if burden sharing regimes are used, and if agriculture is intensified. This is of particular relevance owing to the recent adoption of the Paris Agreement (UNFCCC, 2015). The approach has created long-lasting coupled models available for future policy relevant research. Exploration of the robustness of coupled model outputs to uncertainties should form a key part of this future work.

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Software Availability Table

Software name: BFG2
Developer: Rupert Ford
Contact address and postcode: STFC Daresbury Laboratory, Warrington
WA4 4AD, U.K Tel.: +44 1925 60 3217 E-mail: rupert.ford@stfc.ac.uk<mailto:aa@manchester.ac.uk>
Year first available: 2005
Hardware required: None specific
Software required: Python2, libxml2, libxslt, Python lxml2
Program language: Python, xslt
Program size: Approx. 500 KB (compressed tar file)
Availability: Downloadable
from: http://cnc.cs.manchester.ac.uk/projects/bfg.php<http://www.cs.man.ac.uk/>
Cost: Free for non-commercial use

Software name: SoftIAM
Developers: Sudipta Goswami, Santiago de la Nava Santos, Rachel Warren
Contact address: Tyndall Centre (contact: Rachel Warren), Tel.: +44 1603 593912; fax: +44 1603 593901. Email: r.warren@uea.ac.uk
Year first available: 2004
Hardware required:
Software required: BFG2
Program language:
Program size:
Availability:
Cost: Not for sale

Software name: CIAS
Developer: Sudipta Goswami, Santiago de la Nava Santos, Matt Hyde, Rachel Warren
Contact address: Tyndall Centre (contact: Rachel Warren) Tel.: +44 1603 593912; fax: +44 1603 593901. E-mail: r.warren@uk.ac.uk
Year first available: 2005
Hardware required: PC
Availability: Some applications are accessible via web portal upon request for password
Cost: Not for sale

Software name: PLASIM-ENTSem
Developer: Philip Holden, Neil Edwards
Address: Environment, Earth and Ecosystems, The Open University, Milton Keynes, UK
Email: philip.holden@open.ac.uk, neil.edwards@open.ac.uk
Year first available: 2012
Hardware required: None specific
Software required: R
Program language: R
Program size: 152MB (NB mostly input files, the code itself is very small)
Availability: philip.holden@open.ac.uk, neil.edwards@open.ac.uk
Cost: Free for non-commercial use

Software name: GEMINI-E3
Developer: Alain Bernard and Marc Vielle
Contact address and postcode: Marc Vielle, EPFL ENAC LEURE, BP2140, Station 16 CH-1015 Lausanne, Switzerland Tel.: +41 21 6932031 fax: +41 21 6933840 E-mail: marc.vielle@epfl.ch
Year first available: 1995
Hardware required: None specific
Software required: GAMS (The General Algebraic Modeling System)
Program size: Approx. 10 Mo
Availability: contact email to enquire for availability
Cost: not for sale

Software name: TIAM-WORLD
Developer: KanORS-KANLO-ENERIS
Contact address and postcode: Amit Kanudia SDF L7B NSEZ Phase II NOIDA 201305 UP INDIA Tel.: +91 9871 488 591; E-mail: amit@KanORS.com
Year first available: 2005
Hardware required: PC
Software required: GAMS + Solver (CPLEX, Xpress) under windows environment
Program language: GAMS
Program size: About 1 million row LP
Availability: contact via email
Cost: contact via email

Software name: REMIND
Developers: Nico Bauer, Lavinia Baumstark, Christoph Bertram, Anastasis Giannousakis, Markus Haller, Jerome Hilaire, David Klein, Marian Leimbach, Antoine Levesque, Gunnar Luderer, Michael Lueken, Ioanna Mouratiadou, Michaja Pehl, Robert Pietzcker, Franziska Piontek, Anselm Schultes, Jessica Strefler, Tino Aboumahboub,Tabare Curras, Alexander Körner, Sylvie Ludig, Jana SchwanitzContact address and postcode: Potsdam Institute for Climate Impact Research, P.O.Box 601203, 14412 Potsdam; Germany; Tel.: +49 331 288 2556; E-mail: leimbach@pik-potsdam.de
Year first available: 2010
Hardware required: PC/unix machine
Software required: GAMS (CONOPT Solver)
Program language: GAMS
Program size: Approx. 370 MB
Availability: Model description downloadable from http://www.pik-potsdam.de/research/sustainable-solutions/models/remind
Cost: No commercial use

Software name: LPJmL vs. 3.2
Developer: PIK (LPJmL team) and collaborators
Contact address and postcode: Dieter Gerten (responsible scientist), see above; Tel.: +49 331 288 2577; fax: +49 331 288 2695; E-mail: gerten@pik-potsdam.de
Year first available: 2007
Hardware required: None specific (Unix preferably)
Software required: None specific
Program language: C
Program size: Approx. 1.5 MB (tar file, source code only)
Availability: Via http://www.pik-potsdam.de/research/projects/cooperations/lpjml or via contact email to enquire for availability
Cost: Free for non-commercial use in case of cooperation agreement

Software name: MAgPIE
Developer: Potsdam Institute for Climate Impact Research (contact: Alexander Popp)
Contact address: Potsdam Institute for Climate Impact Research, P.O.Box 601203, 14412 Potsdam; Germany; Tel.: +49 331 288 2463; E-mail: popp@pik-potsdam.de
Year first available: 2008
Hardware required: None specific
Software required: GAMS (CONOPT & CPLEX Solver)
Program language: GAMS, R Program size: Approx. 30 MB Availability: upon request Cost: upon request

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