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FOREWORD

Assessing inter-sectoral climate change risks: the role of ISIMIP

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Abstract

The aims of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) are to provide a framework for the intercomparison of global and regional-scale risk models within and across multiple sectors and to enable coordinated multi-sectoral assessments of different risks and their aggregated effects. The overarching goal is to use the knowledge gained to support adaptation and mitigation decisions that require regional or global perspectives within the context of facilitating transformations to enable sustainable development, despite inevitable climate shifts and disruptions. ISIMIP uses community-agreed sets of scenarios with standardized climate variables and socio-economic projections as inputs for projecting future risks and associated uncertainties, within and across sectors. The results are consistent multi-model assessments of sectoral risks and opportunities that enable studies that integrate across sectors, providing support for implementation of the Paris Agreement under the United Nations Framework Convention on Climate Change.

Introduction

The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) formulated an ambition, supported by 190 countries worldwide, to hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C. The need and urgency for this ambition are based on progress in climate science over the past several decades. Climate change research and assessment initially focused on whether there is a discernable change in the climate since the preindustrial era, whether humans have contributed to this change, and how to limit it. These key questions are now answered: climate change is happening and is being driven primarily by humans (Houghton *et al* 1990, Houghton *et al* 1996, IPCC 2013). There is also information showing that less than half the proven economically recoverable oil, gas, and coal reserves can be emitted up to 2050 to achieve the 2 °C goal (Meinshausen *et al* 2009, Clarke *et al* 2014).

Additional science is needed, however, to inform further international agreements on mitigation and adaptation and their implementation. Impacts[14] of recent climate change observed on all continents and across the oceans have been systematically attributed to climate change (Cramer *et al* 2014) and to its

[14] In this paper, we define 'impacts' as observed consequences of climate variability and change; and 'risks' as the results of complex interactions that could arise from a changing climate.

anthropogenic sources (Rosenzweig and Neofotis 2013, Hansen et al 2016), pointing towards major alterations and associated risks in the near future (Oppenheimer et al 2014), even if warming is limited to 2 °C.

The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) aims to contribute to understanding of the magnitude and pattern of risks and opportunities across regions and multiple sectors in a changing climate, thereby providing policymakers with foundational knowledge for science-based decisions. The project is designed to characterize risks that are likely to arise within a sector or region or at the global scale at different degrees of warming, and to determine how risks could aggregate and interact across sectors, thus informing adaptation and mitigation decisions at global and regional scales.

The project addresses such questions as:

- To what degree can impacts be ameliorated or avoided by certain adaptation measures and what are the associated economic and social costs and risks across multiple sectors and regions?
- Where and how do certain adaptation and mitigation options interact with other societal developments such as population growth, making societies more or less resilient? Are there opportunities for co-benefits, such as improved air quality, better health, and economic growth?
- When and where could the cumulative risks of extreme events such as flooding, droughts, tropical and extratropical storms, and heat waves exceed national coping capacities?
- What are the consequences of different levels of warming, e.g., between a 1.5 °C and a 2 °C world, or between a 2.5 °C, 3.0 °C, and 4.0 °C world? What adaptation pathways are needed to avoid the associated risks?

Answers to these questions will inform decisions on adaptation and mitigation, enhance approaches to facilitate resilience to the risks that cannot be avoided, and help identify opportunities for transformations to enable sustainable development despite inevitable climate shifts and disruptions. ISIMIP has a specific role to play in responding to such challenges as that posed by the Paris Agreement to differentiate risks and mitigation approaches between 2.0 °C and 1.5 °C temperature rise above pre-industrial levels.

The purpose of this paper is to review the status of multi-model and multi-sectoral risk modeling, introduce the goals and *modus operandi* of ISIMIP, and share major findings, lessons learned, limitations, and benefits of its approach.

Climate risk modeling and sectoral initiatives

Climate impact models are a key research tool to explore the possible magnitude, timing, and spatial distribution of future risks, taking into consideration the interactions of climate and development pathways. The scientists involved in risk modeling are from the physical, biophysical, and socioeconomic disciplines. They work on different scales from global (e.g., global vegetation models) to regional (e.g., hydrological models operating at river-basin scale) or very high-resolution local (e.g., energy models at the building scale).

Risk modeling suggests that the coming century is likely to be characterized by challenges to food and water security, along with growing risks to coastal zones, infrastructure, and health (Jiménez Cisneros et al 2014, Porter et al 2014, Wong et al 2014, Revi et al 2014, Smith et al 2014). Climate change acts as a threat multiplier, exacerbating current problems of, for example, mass migration and maintenance of reliable supply chains (US Dept. of Defense 2014). Growing understanding of interacting impacts means that in addition to deepening understanding within sectors, there is a need to understand the implications at national, regional, and global scales of the aggregation and interactions of risks across them (Oppenheimer et al 2014, Harrison et al 2016).

Sectoral initiatives

Climate risk modeling typically focuses on natural and managed resources or systems (e.g., water resources, coastal systems, and food systems) and economic sectors (e.g., energy, water, transportation, recreation and tourism, insurance, and financial services). Sector model intercomparisons include those for water (e.g., Goderniaux et al 2011), terrestrial ecosystems (e.g., Melillo et al 1995, Cramer et al 2001), agriculture (e.g., Rosenzweig et al 2013), coastal zones (e.g., Tebaldi et al 2012, Nicholls et al 2014), energy (e.g., Mansur et al 2008, Isaac and Van Vuuren 2009), and health (e.g., Caminade et al 2014) (box 1).

Model intercomparison is emerging in other sectors: for example, both ISIMIP and the Strategic Initiative on Climate Change Effects on Marine Ecosystems (S-CCME) are developing initiatives in fisheries (Payne et al 2016). S-CCME has identified eighteen regions as having sufficient data to model the effects of climate change on fish and fisheries (Hollowed et al 2016).

One use of multi-model sectoral intercomparisons is the development of statistical emulators that represent the results. Such emulators provide simple tools to project climate change risks for use in a wide range of scenario and policy studies, reducing the amount of computing time for extended analyses. They can also provide improved damage estimates for use in integrated assessment models (IAMs). Statistical models have been developed that emulate maize yield responses to changes in temperature and precipitation simulated by AgMIP global gridded crop models (Blanc and Sultan 2015) and for maize and wheat yields simulated by AgMIP-Maize (Bassu *et al* 2014) and AgMIP-Wheat (Asseng *et al* 2013) intercomparisons (Makowski *et al* 2015).

See the individual papers in this Special Issue for detailed multi-model studies across a broad range of sectors, including forests, global biomes, regional and global hydrology, fisheries, and agriculture, as well as papers considering cross-sectoral effects.

Box 1. Examples of sectoral model intercomparisons

Terrestrial ecosystems

The health and stability of ecosystems across the globe are threatened by changes in climate, with biomes dependent on the existing climatic system to be productive. Model comparisons for terrestrial ecosystems have typically focused on carbon and water fluxes as well as vegetation distribution and structure (e.g., Kittel *et al* 1995, Melillo *et al* 1995, Cramer *et al* 1999, 2001, Huntzinger *et al* 2013, Friend *et al* 2014). Several global vegetation models simultaneously describe risks of climate change on natural vegetation, hydrology, and crop yields (e.g., Krinner *et al* 2005, Bondeau *et al* 2007, Lindeskog *et al* 2013). Terrestrial models differ widely in complexity and purpose including satellite-based models that use data as inputs, models that simulate carbon fluxes using prescribed vegetation structure, and models that simulate both vegetation structure and carbon fluxes (Cramer *et al* 1999). Whether and how models incorporate land-use and land-cover change and other disturbances (e.g., fire) can have significant impact on a model's prediction of land-atmosphere carbon exchange (Huntzinger *et al* 2013).

Agriculture

AgMIP coordinates multi-model agricultural simulations, including global gridded crop model intercomparison (Rosenzweig *et al* 2014, Elliott *et al* 2015) and global economic model intercomparison (Nelson *et al* 2014, von Lampe *et al* 2014), and participates in ISIMIP. AgMIP, founded in 2010 (Rosenzweig *et al* 2013), is a major international effort linking the climate, crop, livestock, grassland, and agro-economic modeling communities with information technology to produce improved crop and economic models and the next generation of climate risk projections for the agricultural sector. AgMIP conducts transdisciplinary analyses of the agricultural risks of climate variability and change that link state-of-the-art climate scenarios to biophysical and economic models. Crop and livestock model outputs are aggregated as inputs to regional and global economic models to determine regional and global vulnerabilities, changes in comparative advantage, price effects, and potential adaptation strategies in the agricultural sector.

A critical area for improving crop and livestock models involves the simulation of pests and diseases under changing climate conditions. The improvement and application of pest and disease models (PDMs) for predicting yield losses due to climate change is still a challenge. Reference datasets for the development of empirical models are no longer viable since the climatic patterns to which the models are calibrated are changing. Simulation models based on quantitatively known processes represent an important method for estimating the important effects of pests and diseases on agricultural production, and groups of experts within AgMIP are tackling these challenges for a range of pests (van Bruggen *et al* 2015, Donatelli *et al* 2016).

Health

Malaria—a significant source of morbidity and mortality with its geographic range, intensity of transmission, and seasonal length sensitive to weather and climate—is one of the few health outcomes modeled by multiple research groups and was the focus of the first health model intercomparison (Caminade *et al* 2014). The results indicate an overall net increase in climate suitability for stable malaria transmission and in the size of the population at risk, with larger increases with increasing global mean surface temperature. Piontek *et al* (2014) found that malaria prevalence is expected to increase in higher latitudes, higher altitudes, and in regions on the fringes of current malaria regions because of warmer and wetter climatic conditions. However, when conditions become drier, prevalence can also decrease. The Ethiopian Highlands is one region where most models agree on projected increases in prevalence.

Human health will also be affected by climate change effects on future levels of surface ozone (O_3) (Doherty *et al* 2013). Ozone is a strong oxidant that has adverse risks for health, including exacerbation of chronic respiratory diseases, such as asthma.

Approaches and terminology for understanding risks across sectors

Natural systems—such as water bodies, forests, and icecaps—are all impacted by climate change. These systems are coupled, e.g., destruction of forests can have a strong effect on river discharge through changes in the processes of runoff and evapotranspiration. Such interactions are embedded in Earth System Models (Hill *et al* 2004, Collins *et al* 2005, Dunlap *et al* 2008) and need, in principle, to be considered before moving to the risks for economic sectors, which are

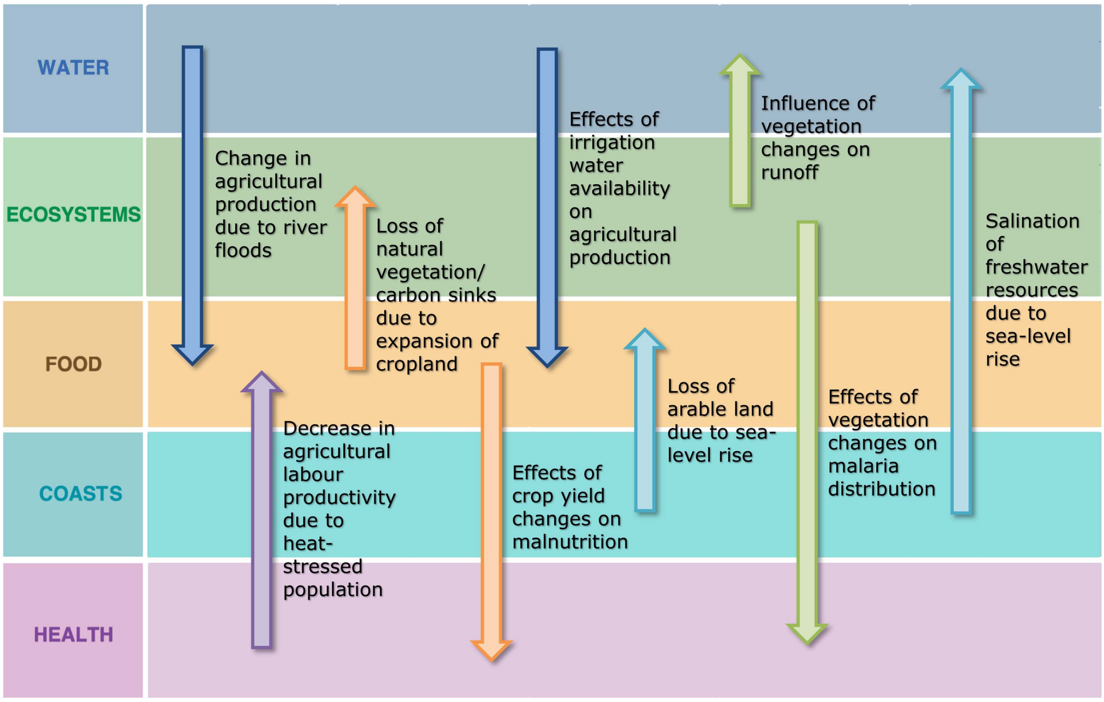

Figure 1. Climate-risk cascades across sectors (Huber *et al* 2014).

coupled to the natural systems and are themselves interactive in multiple ways.

Assessments of future risks have mainly been sectoral (e.g., Huber *et al* 2014), although most human and natural systems will experience the integrated effect of risks across multiple sectors (see figure 1). Examples of cross-sectoral interactions include shifts in food consumption patterns, such as reduced meat consumption and increasing production of plant-based food, that would reduce both water and energy usage for food production (Zimmerman *et al* 2016). Food production requires equipment, which in turn relies on the energy sector for fuel to run as well as manufacture it.

Water is a critical resource not only for growing crops but also for food processing. However, these relationships vary by crop. For example, during the California drought, farmers of high-value almonds have opted to pay higher prices for pumped groundwater, while rice farmers have opted to reduce the acreage planted (US Department of Agriculture, Economic Research Service (ERS) 2015).

Warren (2011) has explored interactions in 2 °C and 4 °C worlds, finding that in a 4 °C world, major shifts in agricultural land use and increased drought cause human population, agriculture, and remaining biodiversity to concentrate in areas remaining wet enough for economic prosperity. Ecosystem services would decline with carbon cycle feedbacks and fire causing forest losses.

Harrison *et al* (2016) found that food production and water use are highly influenced by other sectors through changes in demand, land suitability, and competition for land. The agricultural area needed for food production is affected by widespread changes in urbanization and changes in the frequency of flooding, which alter land suitability for different farming activities. Changes in irrigation water availability influence the selection of irrigated and non-irrigated crops grown in an area, which in turn affects agricultural profitability and food production. Water use has significant influences from changes in irrigation and competing demands for water from domestic and other sectors, reflected by changing population patterns in urban areas. Agricultural and forestry changes can affect habitats for particular species and thus biodiversity.

Better understanding of these integrated risks at local to national to international scales is critical for effective and efficient adaptation policies (Harrison *et al* 2016, Ruane *et al* 2016).

There are different approaches to characterizing risks that emerge across sectors. Some IAMs (e.g., Edmonds *et al* 2012) are structured to provide insights into key linkages at broad regional scales. Other modeling approaches may describe interactions by embedding more simplified risk functions into the overall system (e.g., Nordhaus and Boyer 2000, Nordhaus 2008, Hope 2006, 2008, Waldhoff *et al* 2014). In each case, it is important to ensure that linkages are addressed explicitly to avoid the 'black box' syndrome, whereby reasons for modeling results may be difficult to trace and understand.

Another approach is to use sector models that typically include more sectoral detail and rely on loose coupling to address the linkages across sectors. The

ISIMIP approach is to address the full complexity by including both natural system models, such as hydrological and ecosystem models, and socio-economic sector models such as agricultural trade models. This suite of loosely integrated models allows for explicit analysis of the coupled processes.

Types of explicit linkages include multi-sectoral, cross-sectoral, and integrated studies (box 2).

Box 2. Terminology and approaches

Multi-sectoral overlays

These occur where the spatial patterns of impacts in different sectors are overlaid to highlight 'hot-spot' regions likely to experience multiple risks, but where the analysis does not consider interactions among sectors except in terms of the cumulative risk. An example is the basic aggregation of potential direct damages, mortalities, or displaced people induced by different kinds of extreme events within a given region and time span. It can be used to identify regions subject to changing frequencies of multiple hazards from extreme events, such as heavy precipitation events and heat waves. This can be determined by overlaying independent sectoral analyses as long as these are carried out against consistent future scenarios and compatible regionalizations. The ISIMIP Fast-Track focused on this type of 'hotspot' analysis (Piontek *et al* 2014).

Cross-sectoral analyses

These are cases where two or more sectors interact directly through their supply or value chains or competition for resources; examples include the dependence of urban water supplies on energy networks, but also competition for water between, say, agriculture, mining, and the environment in one region, or for land between bioenergy and food. These studies require explicit consideration of the coupling between sectors, potentially leading to simplified 'nexus'-style analyses that integrate more detailed sectoral simulations; the sectoral analyses need a consistent basis, but additional analyses of interactions are also required.

Integrative studies

This is the term we use for emergent interactions that play out due to processes that cross scales and often depend on other subsystems. These include net effects on GDP and national tax receipts that are a result of influences from multiple sectors flowing through the economy. An increased coincidence of sub-national disasters (e.g., in space or time, within one budget cycle) can reduce tax receipts through industry disruption as well as potentially overwhelming recovery budgets and insurance. Such adaptation responses can result in competition for capital among sectors. Some extant economic models can already address these issues, but mostly these are poor at handling discontinuous change. This requires a consistent sectoral basis, but also new non-equilibrium analyses to inform national and international decision-making.

Specification of scenarios

At the heart of any integration of climate change risks across sectors (even on the purely biophysical level) are sectoral projections of impacts forced by the same *climate inputs* (van Vuuren *et al* 2011). Without this basis, even the simplest aggregations of e.g., people affected, potential deaths, and economic damages, are not possible, let alone an assessment of the potential interactions of these effects.

Consistency of *socio-economic inputs,* such as population and GDP growth rates, is equally important for the aggregation and analysis of cross-sectoral risks (Wilbanks and Kristie 2014). The Shared Socio-economic Pathways (SSPs) are now available and are being combined with the Representative Concentration Pathways (RCPs) to create scenarios that contain qualitative and quantitative elements (van Vuuren *et al* 2014). The narratives include qualitative information on factors such as governance that are known to be critical for determining the magnitude and pattern of future risks (Wilbanks and Kristie 2014, van Vuuren *et al* 2014, O'Neill *et al* 2014, 2015).

In some cases, these issues have been avoided by conducting the socio-economic evaluation in a post-processing mode, i.e., biophysical projections are done without including much information about human influences and then additional calculations are made to estimate human risks. For example, hydrological simulations are used to estimate inundation areas, and then are combined with geospatial population data to estimate the associated number of affected people.

Adaptation measures have been represented in this type of analysis as well. For example, adaptation measures may be estimated based on the original simulations by only considering flood events above a certain protection level. Then the number of affected people can be estimated again but only accounting for flood events above the specified level. Examples include the calculation of affected people based on projected flooded areas (Hirabayashi *et al* 2013) and people under risk of water scarcity (Schewe *et al* 2014). Agricultural economic models focus primarily on economically-efficient adaptation, with analyses of both costs and benefits of specific strategies (e.g., land-use conversion, intensification, and trade) (Nelson *et al* 2014).

Inclusion of socio-economic information in post-processing can allow development pathways to be considered efficiently, because no new biophysical projections from computationally-intensive impact models are required. However, there are some cases where the socio-economic information is needed by the models, such as when projecting the distribution of vectorborne diseases, which depends on population densities and socio-economic development (Jones *et al* 2008).

The scenario framework consisting of RCPs and SSPs (van Vuuren *et al* 2014) provides the consistent setting that enables multi-sectoral, cross-sectoral, and integrative research questions to be addressed across a wide range of sectors. The magnitude and pattern of future risks will depend on climate and socio-economic input variables, as well as on assumptions regarding different management options (e.g., fertilizer input, fishing quotas, regulation of water levels) or adaptation measures (e.g., installation of irrigation, dams and dikes providing protection against flooding events, availability of shelters offering protection against storms or wildfires, land-use changes affecting the distribution of wildfire occurrence) (Valdivia *et al* 2015). Thus, to make projections truly consistent, a common modeling protocol is needed covering harmonized climate and socio-economic inputs as well as story lines that include, for example, concrete descriptions of adaptation strategies.

Integrating risks within and across sectors

Most climate risk literature consists of single-sector studies utilizing single models. While often providing useful and useable insights at local scales, these are hard to aggregate within or across sectors in assessments such as the IPCC due to lack of consistency in climate inputs and scenarios across studies (see, for example, the aggregation of climate change risks on crop production in the IPCC ARS WG2 Food Systems chapter (Porter *et al* 2014).

Examples of multi-sector studies are emerging driven by common climate input data; see, e.g., Piontek *et al* (2014) for a study that analyzes climate change effects on crop yields, water resources, natural vegetation, and malaria; Arnell *et al* (2013, 2016) for studies of energy demand and supply, river and coastal flooding, changes in productivity of cropland and terrestrial ecosystems, and heating and cooling energy requirements; and van Vuuren *et al* (2011) for a study describing analysis of risks on human health, agricultural yields, potential water availability, and heating and cooling demand. This multi-sector work based on consistent assumptions, treatment of risk, and adaptation strategies is a step forward.

In addition, there is an urgent need for the integration of other risks such as the intersections of water, agriculture, energy, and health in dryland areas, and incorporation of new sectors such as health risks (besides malaria), fisheries, and tourism.

Without multi-sectorally consistent impact studies, it becomes difficult to develop methods for the analysis of cross-sectoral interactions and to aggregate risks meaningfully while accounting for potential interactions. For example, the question of the potential increase in crop production due to additional irrigation can only be addressed using water resources and crop model simulations forced by the same weather patterns. The first consistent multi-water model and multi-crop model analyses addressing this issue were recently published (Elliott *et al* 2014, Frieler *et al* 2015). Other critical interactions include:

- Competition for land from biofuels, afforestation, and agriculture;
- Multiple demands for water from agriculture, human needs, ecosystems, energy production, industry, and recreation;
- Connections between hydropower production and changing river flow, sediment transport, irrigation water withdrawal, and energy demand;
- Fertilizer inputs for enhanced crop productivity and the ensuing risks to water quality and fisheries.

The emerging generation of more comprehensive and integrative assessments of climate change considers the interaction of sectoral risks and their feedbacks through local, national, and global economies. This requires modeling frameworks that account for the interplay of social, economic, and biophysical as well as spatial dynamics. Examples of integrative approaches building on spatially explicit risk projections forced by consistent climate inputs are contained in the PESETA study (Ciscar *et al* 2012) and Climate Change Integrated assessment Methodology for cross-Sectoral Adaptation and Vulnerability in Europe (CLIMSAVE) (Harrison *et al* 2015, 2016). CLIMSAVE is a web-based interactive simulation and display environment that provides a holistic (cross-sectoral, climatic, and socio-economic change) modeling framework. The platform guides the user through simulation of potential risks under climate and socio-economic scenarios, identification of sectoral and multi-sectoral vulnerability hotspots, adaptation potential, and cost-effectiveness of adaptation measures.

Challenges of integrated modeling

While integrated sectoral modeling is useful in understanding the complex risks of climate change, its methods do contain weaknesses. For example, in regard to choices of development pathways, emissions scenarios, and climate models, and the assessment and communication of uncertainty, there may be complex relationships among the interests of scientists, policymakers, and members of society (Hulme and Desai 2008). Even the visualization of results may be affected by such complex choices.

The use of multiple impact models also engenders uncertainties. Drawing on lessons from the use of multiple climate model ensembles, difficulties in the multi-model approach may involve the use of only a small number of models, lack of transparency in regard to the distribution of the models across a given parameter space, and often-poorly simulated extreme

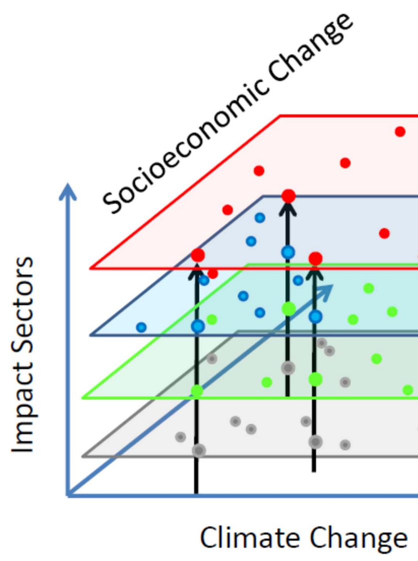

Figure 2. ISIMIP scenarios provide a consistent simulation framework across sectors based on the level of climate change (as captured by the RCPs) and socio-economic change (as described by the SSPs). The colored points in each plane represent the coverage of future climate change and socio-economic scenarios in each sector. The ISIMIP framework ensures that a subset of these points coincide in the 'sector' domain, facilitating analyses of intersecting risks.

behavior (Knutti *et al* 2010). Impact model comparison has generally not resulted in designation of 'good' and 'bad' models (potentially hampering evaluation of results), and there is concern that the same datasets are used in model development leading to lack of certainty in the independence of the individual components of the model ensembles (Knutti *et al* 2010).

Important questions pertain to the use of model ensembles to characterize uncertainty. The results produced by modeling comparison exercises are not truly independent, since frequent interactions among researchers tend to increase the consistency of the underlying model parameterizations and the results. This has the unintended consequence of reducing the range of possible outcomes. Mean reversion, herd or swarm behavior, and peer pressure may bias results.

It is also important to note that model-based outcomes of risks do not encompass the full range of possible futures due to feedbacks in the climate system that are not captured in current GCMs (Tebaldi and Knutti 2007). Lempert *et al* (2006) and Dessai and Hulme (2007) discuss strategies for robust adaptation decision-making given these underlying uncertainties.

While there is a perception that large modeling comparison exercises absorb a great deal of resources from independent research at the frontier, it is often the case that participation in such exercises is voluntary and they generally take minimal budgetary resources. Funding is needed, however, for science integration to ensure that projects have a clear focus, engender interdisciplinary insights, and are properly managed. A balance does need to be struck if such exercises become the cornerstone of integrated assessment research in regard to both time and funding, so that they do not limit innovation.

An inter-sectoral risks modeling framework: ISIMIP

An inter-sectoral modeling framework allows for a systematic assessment of the potential for cascading effects such as energy system blackouts, transportation and food system disruptions, communications breakdowns, and water supply cut-offs, as a result of direct impacts and their interactions.

ISIMIP is working to address the challenges of providing more relevant information for decision-makers by facilitating multi-sector as well as cross-sector studies (Huber *et al* 2014, Warszawski *et al* 2014). Its goal is to establish a repository of consistent climate change risk projections, thus allowing for multi-model assessments of sectoral impacts and opportunities and supporting further analyses of multi- and cross-sectoral risks and fully integrative studies (figure 2). This is achieved by reaching consensus on a number of marker climate scenarios, socio-economic projections, and management strategies, such as the RCPs and SSPs, to be used as harmonized input for risk models from as many sectors as possible to enable cross-sectoral studies, and from which more integrated studies can be developed that embed the interactions among sectors explicitly.

ISIMIP has created a partnership among the impacts simulation communities to facilitate agreement on core sets of climate and socio-economic projections leading to cross-sectorally consistent modeling protocols. ISIMIP is establishing a continuous process similar to, for instance, coordination activities for GCMs such as the Coupled Model Intercomparison Project (CMIP, now in its sixth iteration; e.g., Meehl *et al* 2005, 2014) and for IAMs such as the

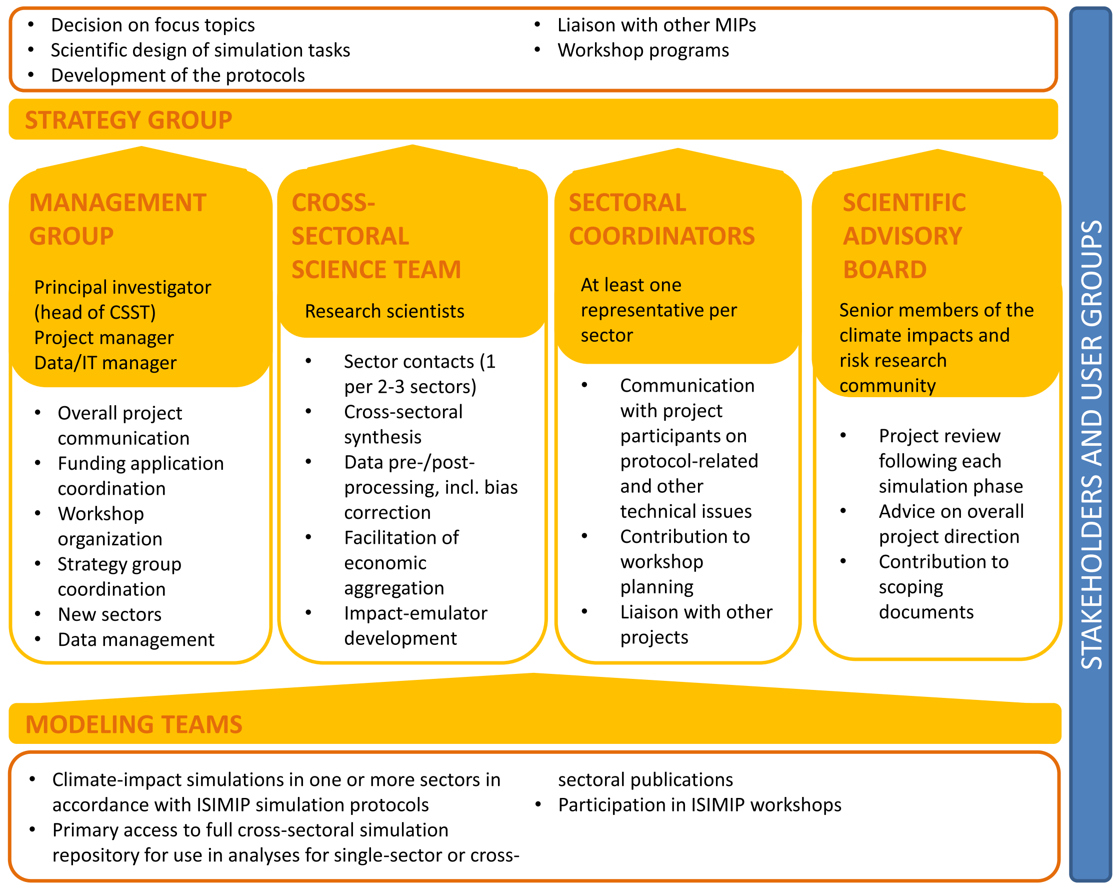

Figure 3. ISIMIP organizational structure enabling development of guiding questions by stakeholders and scientists and consistent protocols to achieve decision-relevant results.

Energy Modelling Forum (EMF; e.g., Weyant and Kriegler 2014). The activities of ISIMIP proceed in phases, each addressing specific policy-relevant research questions that determine the selection of the climate and socio-economic scenarios.

How ISIMIP works

The foundation of the ISIMIP framework is a set of simulation protocols consistent across sectors, covering a number of scenarios that can then be subsumed into and complement the protocols of sector-specific initiatives. ISIMIP is also a partnership and 'community of practice' of sectoral modeling groups who have come together to provide inputs for decision-makers on the nature and timing of inter-sectoral risks.

A Strategy Group, with representation from the leaders of the sector MIPs, a cross-sectoral science team, and the ISIMIP Scientific Advisory Board, are tasked with furthering coordination and collaboration across the sectors, both those with organized MIPs and those without (figure 3). With the involvement of a broad group of stakeholders and sector modelers, the Strategy Group has the opportunity to co-generate the guiding questions for successive rounds of simulations, experiments, analyses, and assessments. In an iterative consensus process that builds on input from the stakeholder and scientific communities, the Strategy Group decides on the guiding questions and the simulation protocols needed to answer them for each round (see figure 3 and ISIMIP Mission and Implementation document, https://isimip.org/about/#mission).

An economic integration unit has also been established within ISIMIP as a forum for mutual exchange between biophysical and economic modelers, with the goal of improving explicit linkages among the disciplinary models. For example, translation of runoff projections into flood risks, flooded areas, and direct damages will make them more usable in economic assessments. The aim is to enable better understanding of the mutual requirements within the different modeling settings and more effective data exchange.

Major findings and lessons learned

In advance of the IPCC Fifth Assessment (IPCC 2014), the Potsdam Institute for Climate Impact Research (PIK) and the International Institute for Applied Systems Analysis (IIASA), with funding from the German Federal Ministry of Education and Research (BMBF), initiated ISIMIP. The first phase of the project, the ISIMIP Fast Track, was conducted from 2012 to 2014 (figure 4). Thirty-five global risk models

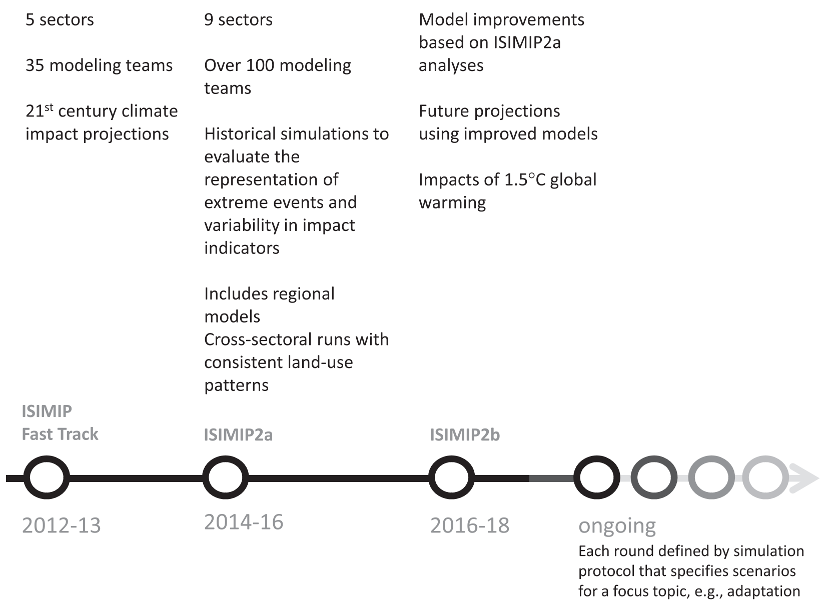

Figure 4. ISIMIP activities and timeline (see appendix A figure A1 for a more detailed timeline and information on citations).

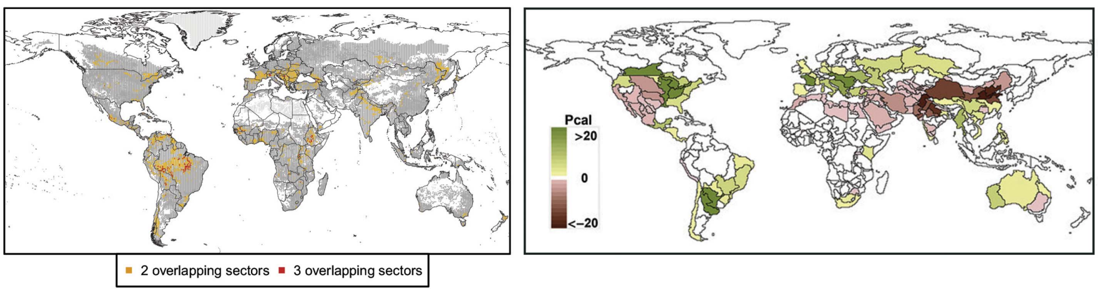

Figure 5. Major findings from ISIMIP Fast Track. (a) Multisectoral hotspots of impacts for two (orange) and three (red) overlapping sectors (Piontek *et al* 2014). (b) Potential change in total production of maize, soybean, wheat, and rice at end-of-century given maximal use of available water for increased/decreased irrigation use on what are currently rainfed/irrigated areas in total calories (Elliott *et al* 2014).

from five sectors joined: water, biomes, agriculture, coastal zones, and health (malaria). The purpose was to quantitatively assess global change impacts at different levels of climate change consistently across sectors, to estimate the uncertainty of projections across global climate models (GCMs) and global impact models, and to launch a continuous coordinated risk modeling improvement and intercomparison program (Warszawski *et al* 2014).

Climate scenario input was developed from five GCMs from CMIP5 providing climate projections for the four RCPs. Socio-economic projections of economic development and population growth were based on the SSPs. Modeling groups were asked to provide future projections of impacts assuming that their best representation of the year 2000 management conditions were fixed in the simulations over the 21st century. The associated simulations did not describe a 'likely' future, but rather enabled the quantification of future risks of climate change, thus helping to characterize future adaptation needs.

The ISIMIP Fast Track resulted in an analysis of the state of climate impacts research within individual sectors and across them, and laid the foundation for multi-sectoral and cross-sectoral climate risk analyses (figure 5). Examples of cross-sectoral analyses, where sectoral projections were combined in post-processing, include Elliott *et al* (2014) that addressed the potential increase in crop production through irrigation, based on available freshwater, and Frieler *et al* (2015) that considered competing pressures on freshwater and land availability from the perspective of agricultural production and climate protection. Results of the Fast Track were published in Special Issues of the *Proceedings of the National Academies of Science* (PNAS) (Schellnhuber *et al* 2014, Warszawski *et al* 2014), *Earth System Dynamics* (Huber *et al* 2014), and *Agricultural Economics* (Nelson and Shively 2014).

Major findings from the first round of ISIMIP studies are that multi-sectoral (water, agriculture, ecosystems, and malaria) overlap starts to be seen robustly at

Table 1. Simulation tasks in ISIMIP2.

	Fast-track models	New sectors/models
ISIMIP2a	Historical runs → validation and evaluation with focus on variability and extremes	Historical runs → validation and evaluation with focus on variability and extremes (this may, particularly for regional models, include calibration and validation for average conditions as a first step)
ISIMIP2b	Strengthening cross-sectoral integration (e.g., by application of land-use patterns generated by agro-economic models within the water and biomes sectors)	
	Simulations directed at understanding the impacts of 1.5 °C global warming and associated greenhouse gas pathways	

a mean global warming of 3 °C above the 1980–2010 mean, with 11% of the world population subject to severe risks in at least two of the four risk sectors at 4 °C (Piontek *et al* 2014). In a low probability-high risk worst-case assessment, almost the whole inhabited world is at risk for multi-sectoral pressures (Piontek *et al* 2014). Combining hydrological and agricultural model ensemble results, Elliott *et al* found that freshwater limitations in some irrigated regions could necessitate the reversion of 20–60 Mha of cropland from irrigated to rainfed management by end-of-century with associated losses in food production.

Lessons learned from the early ISIMIP work include that the uncertainty arising from the risk models is considerable (see box 3) and often larger than that from the GCMs (Piontek *et al* 2014, Prudhomme *et al* 2014, Rosenzweig *et al* 2014). In studying inland flood hazards through hydrology and land surface models, Dankers *et al* (2014) found that while large-scale patterns of change are remarkably consistent among risk models, at local scale and in individual river basins there can be disagreement even on the sign of change. This indicates that modeling uncertainty needs to be taken into account in local water resource adaptation studies. In regard to coastal flooding, a damage and adaptation costs study found that long-term coastal adaptation strategies play a central role in projecting outcomes (Hinkel *et al* 2014). The ISIMIP results indicate clearly that there is a pressing need for development of policy measures under existing but now better-characterized uncertainty (Piontek *et al* 2014, Prudhomme *et al* 2014, Rosenzweig *et al* 2014).

Box 3. Addressing uncertainty in a global economic model ensemble

A key issue that arises in ISIMIP is the presence of different types of models within the multi-model ensembles. For example, ten global economic models were used to project futures for agricultural markets and global food security (six were computable general equilibrium (CGE) models and 4 were partial equilibrium (PE) models (see appendix B table B1)). The two model families differ both in their scope—partial versus economy-wide—and in how they represent technology and the behavior of supply and demand in markets (Robinson *et al* 2014). The CGE models explicitly solve the maximization problem of consumers and producers, assuming utility maximization and profit maximization with production/cost functions that include all factor inputs. The PE models divide into groups on the supply side: 'shallow' models that specify area/yield supply functions with no explicit maximization behavior, and 'deep' models that vary in their specifications of technology. For a comparison of scenario results to be meaningful, careful analyses of the relevant model variables are essential (von Lampe *et al* 2014). Once this was done, the agricultural economic modelers found that the variability in general trends across models declined, but remained important. Finally, differences in basic economic model parameters such as income and price elasticities, sometimes hidden in the way market behavior is modeled, result in significant differences.

Current work and future activities

In its second phase, ISIMIP2a is focusing on 'Consistent evaluation of impact models with respect to the representation of extreme events across sectors' (table 1) (www.isimip.org). Extreme events are the focus of ISIMIP2a because they are a major concern of stakeholders who must manage risks for individual sectors and for regions and nations as a whole. The aggregation of the effects of extreme events is an important example of critical challenges that can only be addressed using a consistent cross-sectoral modeling framework. Research questions include 'How well do the participating models simulate the risks of extreme events such as heatwaves, droughts, and floods? What are the sectoral interactions between extreme event impacts, e.g., droughts causing water shortages leading to disruptions in food supply?'

Extremes in different sectors will not occur independently but will be spatially and temporally correlated. For example, the El Niño Southern Oscillation (ENSO) influences crop yields (Iizumi *et al* 2014), flood events (Ward *et al* 2014), tropical cyclones (Wang and Chan 2002, Kossin *et al* 2010), coral bleaching (Glynn *et al* 2001), and fisheries (McPhaden *et al* 2006), but these risks are often manifested in divergent ways in different countries (Cashin *et al* 2014).

Simulations conducted in ISIMIP2a (PIK 2015) are forced by a number of observational climate data sets to evaluate model performance and analyze interactions between sectoral impacts of historical extreme events. More than 90 modeling groups are actively participating in this phase, with sectoral coverage extended to include energy, forestry, permafrost, biodiversity, and fisheries. The papers in this Special Issue report on these results.

In addition to global-scale modeling, ISIMIP now includes multi-model regional projections allowing for comparisons between global and regional risk projections forced by the same climate and socio-economic inputs. Efforts also include the online integration of projections of the effects of land-use changes on carbon stocks and water resources.

The issue of land-use change will be addressed explicitly in the next round of modeling (ISIMIP2b). The effects of different mitigation options on crop yields and land use will be the focus. Results will contribute to understanding how a low-emission scenario (RCP2.6) can be achieved while ensuring food supply for a growing population under changing climate conditions. The associated land-use patterns will then be used as inputs for the biome and water models to assess the cross-sectoral risks.

The ISIMIP2b scenarios are designed to elicit the contribution of climate change to risks arising from low-emissions climate-change scenarios. Pre-industrial control runs are included to facilitate statistical comparison with a no-climate-change case. The simulation protocol contains all information necessary to conduct simulations for ISIMIP2b for models covering risks to global biomes, regional forests, global and regional hydrology, agriculture, permafrost, energy supply and demand, coastal infrastructure, heat-related mortality, fisheries and marine ecosystems, and tropical cyclones.

In the next phase, ISIMIP will focus more on such cross-sectoral simulations, where results from one sector are used as inputs for another sector (e.g., effects of changing runoff and river sediment transport on marine fisheries). Moreover, the assessment of adaptation strategies will become a focus topic for future simulations by prescribing protection levels. Consistent cross-sectoral simulations will enable assessment of the associated benefits but also potential trade-offs of the strategies. For example, increased water use for irrigation reduces water availability for energy generation, but to what extent? (Hanjra and Qureshi 2010). Future phases of ISIMIP will also address such topics as limits to adaptation by considering high-end global warming, early-warning by focusing on short-term future projections, and geoengineering by simulating specific proposed techniques.

ISIMIP stakeholder engagement and provision of policy-relevant information

Through a stakeholder engagement process, ISIMIP has the potential to elicit important guiding questions from policy-makers and create the protocols necessary to generating outputs that address the questions raised, such as how risks could evolve over time under different assumptions about the effectiveness of adaptation and mitigation options. In recent years there has been a growing recognition of the benefits of research processes that incorporate co-design and co-production of knowledge in order to improve the degree to which research is actionable (e.g., Lemos and Morehouse 2005, Mauser *et al* 2013). For ISIMIP, an iterative stakeholder engagement process with major public and private sector groups, such as the World Economic Forum; the Global Environmental Facility; and the Green Climate Fund of the UNFCCC can help to establish the guiding questions for the scenario protocols and to provide feedback through regular interactions. At country scales, ISIMIP results can inform National Adaptation Plans and other benchmarked reports for the UNFCCC Subsidiary Body for Scientific and Technological Advice.

However, it must be made clear to all stakeholders as part of the co-generation process that ISIMIP maintains its scientific independence and avoids policy prescription. The challenges posed by the Paris Agreement goals of 2.0 °C and 1.5 °C temperature rise are an important case in point (Rogelj *et al* 2016). ISIMIP analyses may generate findings that these goals are very hard to achieve given current technologies, and thus there may be potential conflicts between the outcomes of ISIMIP exercises and the political agenda on climate change.

The key output of ISIMIP is an open-access repository of multi-sectorally consistent, multi-model simulations that facilitate self-organizing research and analysis that in turn provide a scientific basis for the IPCC and other risk assessment processes, such as the emerging IIASA The World in 2050 and the US NSF Innovations at the Nexus of Food, Energy, and Water Systems projects. This multi-model research also has great potential to improve the basis for the damage functions embedded in the IAMs that are used to set the marker scenarios for the RCP/SSP process and to conduct experiments to provide insights on possible risks under different mitigation policies (Moss *et al* 2010, van Vuuren *et al* 2014, Wilbanks and Kristie 2014).

An important consideration in the design of simulation tasks within ISIMIP will be the tracking of a set of multi-dimensional indicators such as 'number of people affected by extreme events,' 'direct economic damages,' 'people at risk of hunger,' and 'number of people displaced' over time. This consistent and regularly-updated set of products would assist in providing knowledge for resilience and transformative decision-making as the climate system evolves.

Another potential use of ISIMIP results is linkage to the Sustainable Development Goals (SDGs), passed by the United Nations General Assembly in 2015. ISIMIP can contribute to the SDG process by providing the scientific basis for characterizing the portending climate risks under which the SDGs will need to be achieved, thus helping to explore linkages among the goals (Griggs *et al* 2014). For instance, the integrated modeling results in the water and agricultural sectors can help to develop improved understanding of the expected risks of climate change on future water and food availability. This can aid in establishing the context in which nations are undertaking SDG 2 to end world hunger and SDG 3 to achieve health and wellbeing.

Conclusions

ISIMIP is contributing to the knowledge needed by international and national stakeholders responsible for designing, monitoring, and evaluating adaptation and mitigation policies and measures. The core task is to provide a consistent framework for simulations, based on common climate and socio-economic input and scenario design, needed to address targeted sets of cross-sectoral and inter-sectoral questions. Trajectories of risk profiles through the 21st century using the ISIMIP framework will thus be responsive to the interests of decision-makers and key constituencies such as the disaster risk reduction community.

Regular summaries of ISIMIP results could provide updated risk measures that can be used by decision-makers through time and that will inform national and international assessments. These will enable the development of an 'adaptive pathway' approach for decision-makers, as irreducible uncertainties become clear.

On the technical side, ISIMIP results from the individual sectors are enabling the development of simplified risk-model emulators describing risks in terms of global mean temperature change with the goal of providing new, improved damage estimates for use in IAMs. In addition, incorporation of socio-economic development pathways will make them usable for economic assessments by e.g., translation of runoff projections into flood risks, flooded areas, and direct damages.

By conducting multi-, cross-, and integrated sectoral risk modeling over time, ISIMIP will contribute to robust and flexible decision-making in the short and longer term. ISIMIP can facilitate the assessment of the potential for crossing thresholds within individual sectors, and, importantly, the risks of inter-sectoral disruptions. The information that ISIMIP provides is critical for adaptive and transformational decision-making in the coming decades.

Appendix A

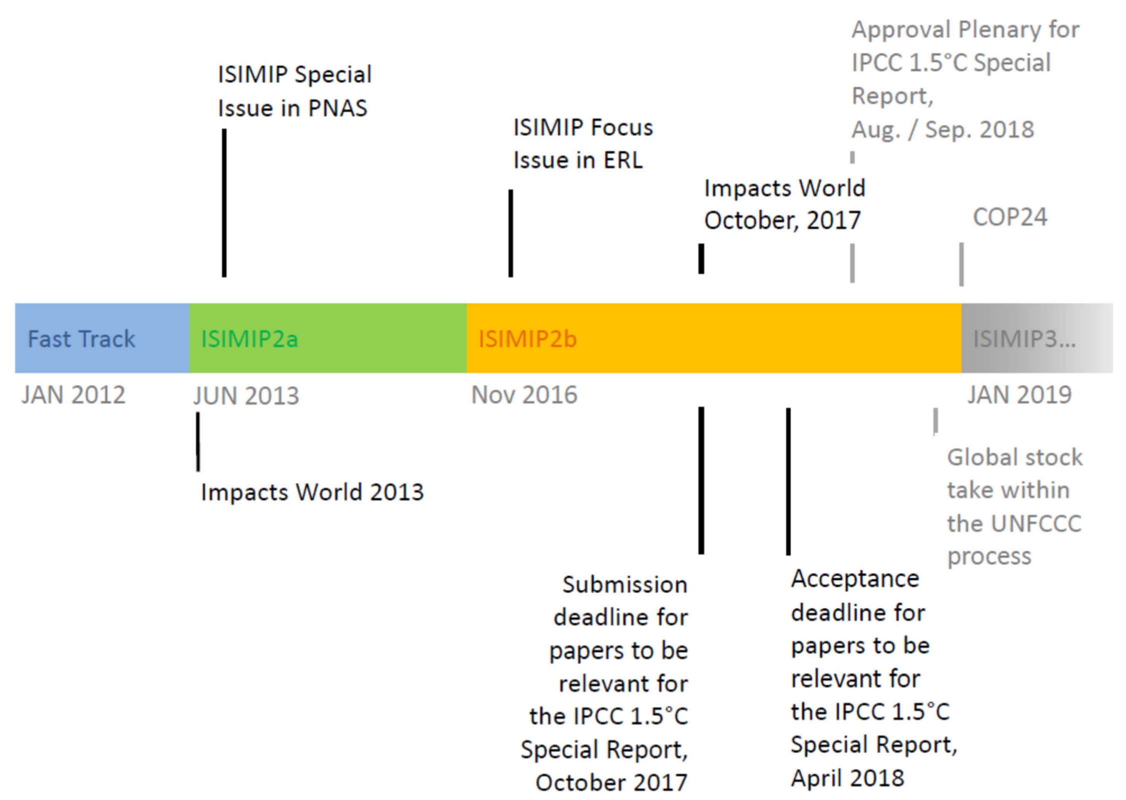

Figure A1. Detailed ISIMIP timeline. As of 29 December 2016, there are nine peer-reviewed articles with ISIMIP in the title (nineteen when including abstracts) and the lead paper in the ISIMIP PNAS Special Issue (Warszawski *et al* 2014) has been cited as a reference 168 times, according to Google Scholar, www.googlescholar.com.

Appendix B

Table B1. AgMIP global economic model characteristics as presented in von Lampe *et al* (2014).

Model (Reference)	Institution	Type	Economy coverage	Agric. sectors[a]	Regions[b]	Base year	Agric. policies	Bioenergy	Global numeraire	Agric. supply	Final demand	Trade
AIM (Fujimori *et al* 2012)	NIES, Japan	CGE	Full economy	8/1	89/17	2005	Implicitly assumed unchanged	Endogenous first and second generation	US CPI	Nested CES	LES utility	Nonspatial; Armington gross-trade
ENVISAGE (van der Mensbrugghe 2013)	FAO/ World Bank	CGE	Full conomye	10/5	11/9[c]	2007	Price wedges (based on GTAP)	None explicitly represented	High-inc. manuf'ed exports	Nested CES	LES utility (w/ dynamic shifters)	Armington spatial equilibrium
EPPA (Paltsev *et al* 2005)	MIT, USA	CGE	Full economy	2/0	7/9	2004	Subsidies, taxes, tariff equivalents	Endogenous first and second generation	US CPI	Nested CES	Nested CES utility	Armington spatial equilibrium
FARM (Sands *et al* 2013)	USDA, USA	CGE	Full economy	12/8	5/8[c]	2004 (& 2009)	Price wedges (based on GTAP)	Little for electricity and heating	European service sector	Nested CES	LES utility	Armington spatial equilibrium
GTEM (Plant 2007)	ABARES, Australia	CGE	Full economy	7/7	5/8[c]	2004	Implicitly assumed unchanged	Endogenous first generation	Capital goods	Nested Leontief and CES	CDE utility	Armington spatial equilibrium
MAGNET (Woltjer *et al* 2011)	LEI-WUR, The Netherlands	CGE	Full economy	10/9	29/16	2001 (& 2004, 2007)	Price wedges (adjusted from GTAP); milk quotas	Endogenous first generation (incl. biofuel targets)	World GDP deflator	Nested CES	CDE private demand[d] and Cobb-Douglas utility	Armington spatial equilibrium
GCAM (Wise and Calvin 2011)	PNNL, USA	PE	Agriculture, Energy	18/0	7/9[c]	2005	Implicitly assumed unchanged	Endogenous first and second generation	n.a.	Leontief	Iso-elastic[d]	Heckscher-Ohlin nonspatial, net-trade
GLOBIOM (Havlik *et al* 2013)	IIASA, Austria	PE	Agriculture, forestry, Bioenergy	31/6	10/20	2000	Implicitly assumed unchanged	Exogenous demand	n.a.	Leontief	Iso-elastic[d]	Enke-Samuelson-Takayama-Judge spatial equilibrium
IMPACT (Rosegrant *et al* 2012)	IFPRI, USA	PE	Agriculture	32/14	101/14	2000	Price wedges (based on PSE/CSE)	Exogenous demand for feedstock crops	n.a.	Iso-elastic[d]	Iso-elastic[d]	Heckscher-Ohlin nonspatial, net-trade
MAgPIE (Lotze-Campen *et al* 2008)	PIK, Germany	PE	Agriculture	21/0	0/10	2005	Implicitly assumed unchanged	Exogenous demand	n.a.	Leontief	exogenous	Based on historical self-sufficiency rates

[a] Figures indicate the number of raw and processed agricultural products represented, respectively.
[b] Figures indicate the number of individual countries and multi-country aggregates represented, respectively.
[c] Regional breakout specific for this application.
[d] Elasticities adjusted over time.

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