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The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies

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ABSTRACT

The Agricultural Model Intercomparison and Improvement Project (AgMIP) is a major international effort linking the climate, crop, and economic modeling communities with cutting-edge information technology to produce improved crop and economic models and the next generation of climate impact projections for the agricultural sector. The goals of AgMIP are to improve substantially the characterization of world food security due to climate change and to enhance adaptation capacity in both developing and developed countries. Analyses of the agricultural impacts of climate variability and change require a transdisciplinary effort to consistently link state-of-the-art climate scenarios to crop and economic models. Crop model outputs are aggregated as inputs to regional and global economic models to determine regional vulnerabilities, changes in comparative advantage, price effects, and potential adaptation strategies in the agricultural sector. Climate, Crop Modeling, Economics, and Information Technology Team Protocols are presented to guide coordinated climate, crop modeling, economics, and information technology research activities around the world, along with AgMIP Cross-Cutting Themes that address uncertainty, aggregation and scaling, and the development of Representative Agricultural Pathways (RAPs) to enable testing of climate change adaptations in the context of other regional and global trends. The organization of research activities by geographic region and specific crops is described, along with project milestones.

Pilot results demonstrate AgMIP's role in assessing climate impacts with explicit representation of uncertainties in climate scenarios and simulations using crop and economic models. An intercomparison of wheat model simulations near Obregón, Mexico reveals inter-model differences in yield sensitivity to [CO_2] with model uncertainty holding approximately steady as concentrations rise, while uncertainty related to choice of crop model increases with rising temperatures. Wheat model simulations with mid-century climate scenarios project a slight decline in absolute yields that is more sensitive to selection of crop model than to global climate model, emissions scenario, or climate scenario downscaling method. A comparison of regional and national-scale economic simulations finds a large sensitivity of projected yield changes to the simulations' resolved scales. Finally, a global economic model intercomparison example demonstrates that improvements in the understanding of agriculture futures arise from integration of the range of uncertainty in crop, climate, and economic modeling results in multi-model assessments.

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1. Introduction

The worldwide agricultural sector faces the significant challenge of increasing production to provide food security for a population projected to rise to 9 billion by mid-century while protecting the environment and the functioning of ecosystems. This challenge is compounded by the need to adapt to climate change by taking advantage of potential benefits and by minimizing the potentially negative impacts on agricultural production. The Agricultural Model Intercomparison and Improvement Project (AgMIP; www.agmip.org) aims to improve substantially the characterization of world food security under climate change and to enhance adaptation capacity in both developing and developed countries.

To examine the full range of climate change impacts on agriculture, both biophysical and economic aspects need to be considered and combined (Hillel and Rosenzweig, 2010). Methodologies for assessing the biophysical effects of climate on crop yield include statistical models (e.g., Schlenker et al., 2006; Lobell and Burke, 2010) and process-based dynamic crop growth models (e.g., Keating et al., 2003; Brisson et al., 2003; Jones et al., 2003; van Ittersum and Donatelli, 2003; Challinor et al., 2004). For simulating the combined biophysical and economic effects of climate change on agriculture, reduced form statistical models have been used (e.g., Mendelsohn et al., 1994) as well as internally or externally coupled biophysical and economic simulation models designed for integrated assessment of economic, technological, policy, and environmental changes at regional or global scales (e.g., Rosenzweig and Parry, 1994; Fischer et al., 2002; Hermans et al., 2010; Nelson et al., 2010).

AgMIP utilizes intercomparisons of these various types of methods to improve crop and economic models and ensemble projections to produce enhanced assessments by the crop and economic modeling communities researching climate change agricultural impacts and adaptation (Table 1). This paper describes the scientific approach and structure of AgMIP; Climate, Crop Modeling, Economics, and Information Technology Team Protocols; Cross-Cutting Themes; and pilot study examples.

Table 1
AgMIP objectives.

Scientific
• Intercompare crop and agricultural trade models as well as methodological options relating to scenario generation and the aggregation and scaling of model projections.
• Incorporate crop and agricultural trade model improvements in coordinated regional and global assessments of future climate conditions.
• Produce state-of-the-art, multi-model climate impacts assessments of agricultural regions.
• Include multiple models, scenarios, locations, crops, and participants to explore uncertainty and the impact of methodological choices.
Organizational
• Build the transdisciplinary community of climate, crop, economics, and information technology experts required to address crucial regional and global questions related to climate impacts on the agricultural sector.
Outreach
• Develop a framework to identify and prioritize regional adaptation strategies.
• Increase scientific and adaptive capacity of agricultural regions in developing and developed countries.
• Link to key on-going efforts (e.g., the Consultative Group on International Agricultural Research's Climate Change and Food Security program, CGIAR CCAFS; Global Future; the United Nations Food and Agriculture Organization's Modeling System for Agricultural Impacts of Climate Change, UN FAO MOSAICC; GEOSHARE; National Adaptation Plans; and the Coordinated Regional Climate Downscaling Experiment, CORDEX)

1.1. Model Improvement

Recent reviews have described how models may be improved to enhance their ability to project climate change impacts on crops (Boote et al., 2010; White et al., 2011; Rötter et al., 2011). AgMIP is targeting several key issues with the goal of making significant progress in model improvement. The first issue is resolving the debate in the literature concerning the simulation in dynamic crop growth models of elevated CO_2 effects (Kimball, 1984; Tubiello and Ewert, 2002; Long et al., 2006; Ainsworth et al., 2008). More broadly, this issue relates to improving the simulation of CO_2, temperature, and water interactions. AgMIP is addressing this need by bringing together free-air carbon dioxide enrichment (FACE) researchers and crop model developers to create a coordinated set of data and model tests for use in model improvement.

Another key issue for improving the use of crop models is accounting for yield gaps. Yield gap refers to the difference between actual yield and potential yield with no biological constraints due to water, nitrogen, pests and diseases, and other factors. Because most crop models do not consider pests and diseases, variations in management among farmers in the region, high-resolution rainfall distributions, or nutrients other than nitrogen, simulated yields are often closer to potential than actual yield. These limitations are very difficult to predict, due largely to a lack of observed data that quantify those variations. Researchers have shown that these yield gaps can be accounted for empirically by using crop model simulations, historical regional yields, and statistical methods (Jagtap and Jones, 2001, 2002; Irmak et al., 2005). Since economic models need actual production for regions to predict economic consequences accurately, AgMIP is examining different methods for developing regionally aggregated yields adjusted for yield gaps using multi-year samples of observed historical regional yields and evaluated using independent years for the same region.

Statistical approaches (e.g., Schlenker and Roberts, 2009; Lobell et al., 2011) are gaining in prominence for assessing climate change impacts on crop production due to their ability to rapidly assess large and diverse datasets. However, statistical models have difficulty offering process-level understanding and testing of adaptation strategies, so extrapolation beyond observed samples is risky even with extreme caution. AgMIP has ongoing activities that assess the strengths and weaknesses of using crop model simulations and statistical regression results to predict yields at aggregated scales using field and regional crop data at multiple locations under current and future climates.

The recent global food price volatility has revealed a stronger sensitivity to climatic variability than previously anticipated (Easterling et al., 2007). A key aspect of AgMIP is to create capacity-building partnerships between and among agricultural crop and economic modelers around the world, enhancing the evaluation of current and future climate impacts and adaptations. Through economic model testing, intercomparison, and improvement, AgMIP aims to significantly enhance information (including uncertainty estimates) to guide policymakers regarding both current and future food prices.

1.2. Climate variability and change assessments

AgMIP builds on early efforts in crop model intercomparison by the Global Change and Terrestrial Ecosystems (GCTE) project of the International Geosphere-Biosphere Program (IGBP; Walker and Steffen, 1996) and on the activities of the International Consortium for Agricultural Systems Applications (ICASA; Hunt et al., 2006). Multi-model comparisons have also been carried out previously to assess crop model water and nutrient dynamics (Diekkrüger et al., 1995; Kersebaum et al., 2007). AgMIP also utilizes an ensemble approach similar to other groups of modelers,

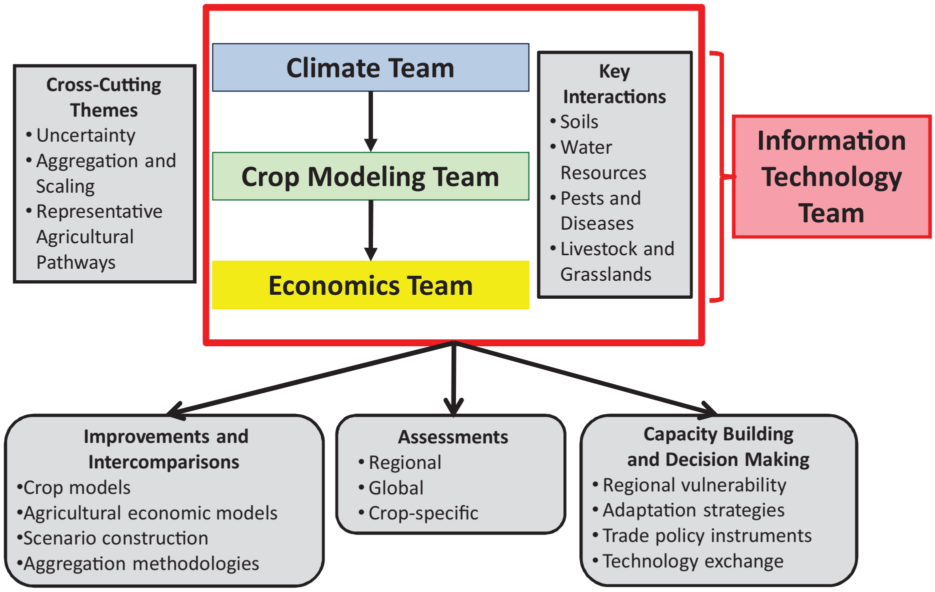

Fig. 1. AgMIP Teams, Cross-Cutting Themes, key interactions and expected outcomes.

such as the Coupled Model Intercomparison Project (CMIP; now on CMIP5; Meehl et al., 2000; Taylor et al., 2009), multi-model assessments of the carbon cycle (Hanson et al., 2004) and the land surface (Henderson-Sellers et al., 1995), and the Energy Modeling Forum (EMF; Clarke and Weyant, 2009; now in its twenty-fifth year).

Coordination among the agricultural modeling community has been hampered by a lack of standardization of data and scenarios as a basis for intercomparison (Rötter et al., 2011). As a result, for more than two decades, the majority of studies on climate change and agriculture have utilized only one crop model and only one economic model. Furthermore, studies use different sets of climate scenarios and assumptions, thus limiting the scope for large-scale comparisons and rigorous estimations of uncertainty.

Multi-model climate, agronomic, and economic projections are essential inputs of the Vulnerability, Impacts, and Adaptation (VIA) research community to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5; now underway) and the UN Framework Convention on Climate Change (UNFCCC). AgMIP's projections of future agricultural production and its economic consequences will set the context for local-scale vulnerability and adaptation studies, supply test scenarios for national-scale development of a range of policy instruments (including trade, agriculture, and natural resource management), and contribute to projections of land use change.

2. AgMIP structure and scientific approach

The Agricultural Model Intercomparison and Improvement Project (AgMIP) is a set of distributed activities for agricultural model intercomparison and future climate change assessments with participation from multiple crop and economic modeling groups around the world (Fig. 1). AgMIP research activities are organized under four project teams (Climate, Crop Modeling, Economics, and Information Technology), with guidance provided by a Leadership Team as well as a Steering Group and Donor Forum. In addition, there are three AgMIP Cross-Cutting Themes – Uncertainty, Aggregation and Scaling, and Representative Agricultural Pathways (RAPs) – which span the activities of all teams).

AgMIP activities are designed to facilitate extended applications and research on crucial agricultural issues including soil management, water resources, pests and diseases, and livestock. For example, initial efforts to assess future water resources will target key irrigated agricultural areas, such as California's Central Valley and regions of India, using a range of methods from

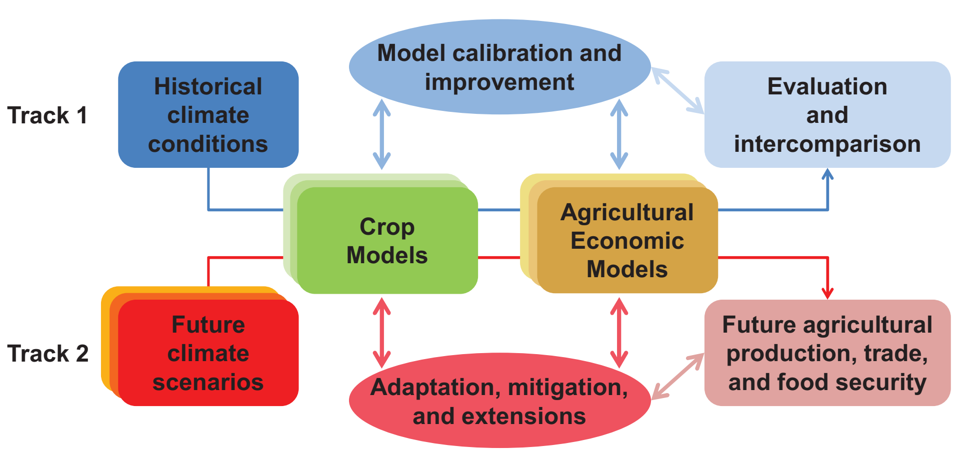

Fig. 2. Two-track approach to AgMIP research activities. Track 1: Model Intercomparison and Improvement; Track 2: Climate Change Multi-Model Assessment.

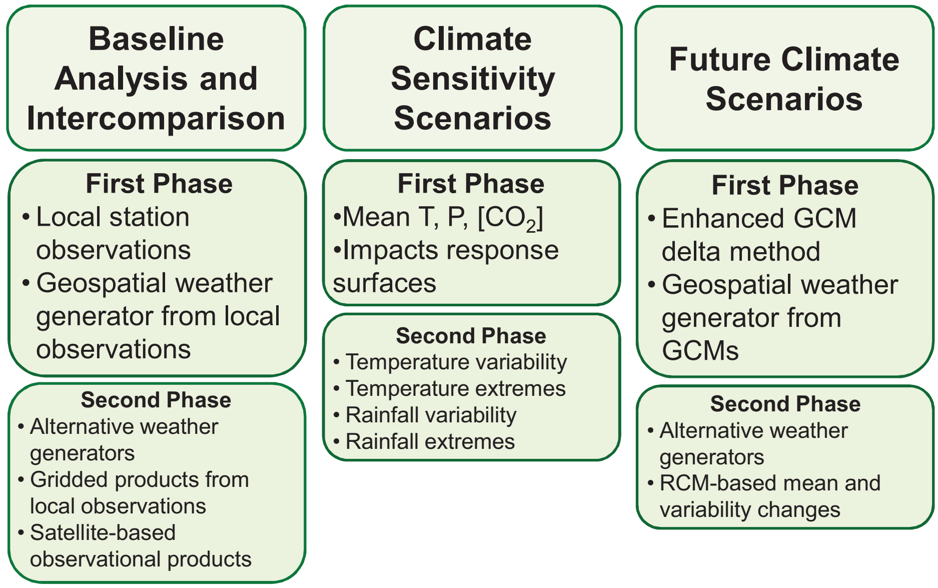

Fig. 3. Overview of Climate Team agro-climatic analyses and prioritized scenarios.

large-scale hydrologic analysis to integrated water resources management models. While pest and disease effects on production will be included via yield-gap factors in the initial phase of AgMIP, AgMIP encourages broader efforts in this area since direct simulation and prediction of these effects are extremely difficult.

There are two primary scientific tracks by which AgMIP achieves its goals (Fig. 2). Track 1, *Model Intercomparison and Improvement*, conducts crop and economic model intercomparisons during a historical period when results can be validated with observed conditions and field trials in order to identify strengths, weaknesses, and uncertainties. Track 2, *Climate Change Multi-Model Assessment*, examines climate change effects on food production and food security at field to global scales, including analyses of adaptation[1] measures over a range of futures designated by climate scenarios and RAPs. Scenarios and AgMIP Protocols are distributed on the web, and multi-model results are collated and analyzed to ensure the widest possible coverage of agricultural crops and regions.

Initial AgMIP efforts focus on mechanistic (i.e., process-based) crop models, regional economic impact assessment models, partial equilibrium agricultural market models, computable general equilibrium (CGE; including dynamic CGE) models, and integrated assessment models. In future activities, AgMIP will engage the broader community of scientists exploring the impacts of climate change on agriculture to conduct comparisons across mechanistic, statistical, and empirical approaches

3. AgMIP protocols

The AgMIP Protocols describe the processes and tasks necessary to conduct internally consistent model intercomparisons and multi-model assessments efficiently and comprehensively. The purpose of developing the Protocols is to provide guidance on the operating procedures, progress evaluations, and anticipated deliverables from each AgMIP team and for the integration of the project as a whole. Further detail and updated versions of the AgMIP Protocols are made available at www.agmip.org in order to facilitate participants' efforts to contribute to, reproduce, and analyze AgMIP results.

[1] Development and testing of mitigation strategies will be addressed in a subsequent phases of AgMIP.

3.1. Climate Team protocols

The objectives of the Climate Team are to:

1. Improve documentation, standardization, and transparency of climate data collection and scenario generation sources and methods.
2. Provide historical climate information to enable coordinated agricultural model intercomparison and baseline period analysis in major agricultural regions.
3. Create scenarios to test crop model sensitivity to key climate phenomena.
4. Develop an ensemble of future climate scenarios for major agricultural regions that may be used by field-based or gridded modeling systems with horizontal resolution on the order of 0.5°.
5. Perform agro-climatic analyses to understand agricultural regions' vulnerabilities to historical climate and projected future conditions.

Two types of climate scenarios are produced (Fig. 3). First-phase experiments are scenarios that are generated for simulations at all locations for consistent aggregation and intercomparison. Second-phase experiments are scenarios that allow exploration of additional important research questions, but are not required of all researchers/locations.

Local station observations serve as the foundation for AgMIP model intercomparisons and baseline period analyses. At least 30 years of data are needed to enable climatological analysis (WMO, 1989; Guttman, 1989), thus baseline analyses will focus on the 1980–2009 period. Crop model simulations and intercomparisons require daily rainfall, solar radiation, and minimum and maximum temperatures representing farm-level conditions. Surface moisture (dewpoint temperature, vapor pressure, or relative humidity) and winds can allow calculation of more complex evapotranspiration methods.

Station data are subject to quality assessment and quality control, with radiation gaps filled using NASA Prediction of Worldwide Energy Resource (POWER; Zhang et al., 2007), and solar radiation, winds, and surface moisture variables provided by the NASA Modern-Era Retrospective-analysis for Research and Applications (MERRA; Bosilovich, 2008). Data are also compared to and filled with gridded observational products from satellites (e.g., ISCCP,

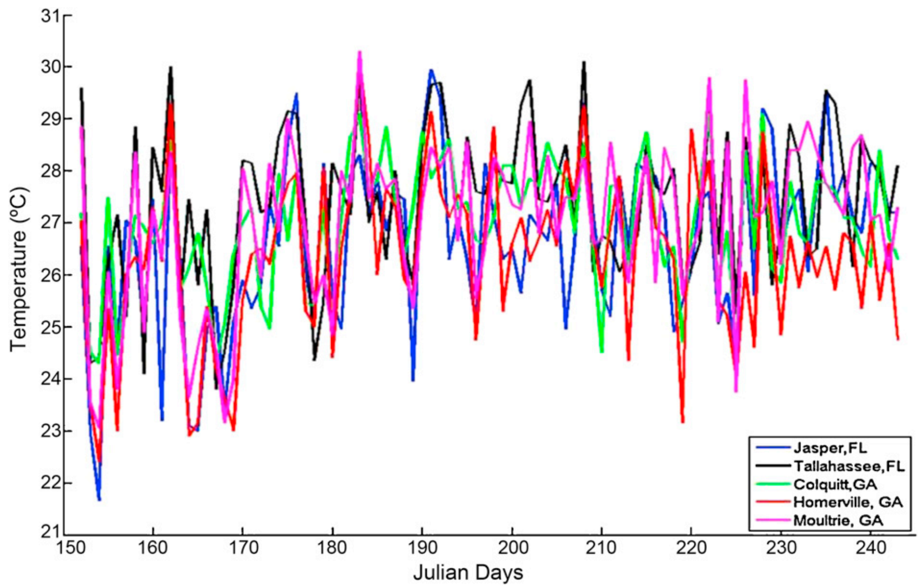

Fig. 4. Growing season temperature (°C) time series produced by Geo Spatial-Temporal weather generator (GiST, Baigorria and Jones, 2010) for five weather stations in Georgia and Florida showing patterns of fluctuations that reflect seasonally-varying correlations of temperatures and weather events among nearby stations.

Zhang et al., 2004; CMORPH, Joyce et al., 2004; POWER, Zhang et al., 2007), station networks (e.g., WORLDCLIM, Hijmans et al., 2005; Willmott and Matsuura, 2009; New et al., 2002), and recent retrospective (Re-) analyses (e.g., GLDAS, Rodell et al., 2004; MERRA, Rienecker et al., 2011; ERA-INTERIM, Berrisford et al., 2009; CFSR, Saha et al., 2010).

Weather generators (e.g., GiST, Baigorria and Jones, 2010; MarkSIM, Jones et al., 2002; WM2, Hansen and Mavromatis, 2001; NHMM, Robertson et al., 2007; LARS-WG, Semenov et al., 1998) allow for an increased number of iterations to better understand baseline climate variability. AgMIP prioritizes weather generators that can maintain geospatial correlations (e.g., GiST and NHMM; see Fig. 4) and those that can explicitly represent interannual variability (e.g., WM2 and MarkSIM) in order to enable realistic representation of climate extremes spanning across several AgMIP Sentinel Sites in regions where crop model simulations are conducted.

The Climate Team also creates climate sensitivity scenarios that test the simulated response of regional crops to changes in [CO_2], temperature, and precipitation. Scenarios with plausible mean changes in these variables are simulated to facilitate the creation of impact response surfaces that highlight key crop model sensitivities, thresholds, and inflection points (Räisänen and Ruokolainen, 2006; Ruane et al., in press-a). Weather generators also enable the creation of scenarios to investigate the impacts of shifts in climate variability, including changes to the standard deviation of daily temperature, the number of rainy days, and the distribution of extreme events. Climate scenarios that draw from observational products with varying resolution enable an investigation of the sensitivity of agricultural simulations to the scale of climate inputs.

The set of AgMIP future climate scenarios enables projections of crop production under plausible future climates, with analysis of uncertainties owing to data quality, climate models, societal emissions pathways, and methodological techniques. Future climate scenarios are based on climate change simulations from an ensemble of general circulation models (GCMs) from the Third Coupled Model Intercomparison Project (CMIP3; Meehl et al., 2007) and CMIP5 (Taylor et al., 2009).

Projections are made for three periods under high and low emissions scenarios (A2 and B1, respectively; SRES, 2000) for CMIP3 and representative concentrations pathways (RCPs; Moss et al., 2010) for CMIP5. As preliminary investigations of the decadal experiments in CMIP5 (2005–2034) have raised concerns about their utility for impacts assessment (Goddard et al., 2012), we use the 2010–2039 near-term period to understand climate variability in relation to climate change and to develop effective adaptation strategies to near-current conditions early in the century. Mid-century (2040–2069) and end-of-century (2070–2099) periods address the agricultural impacts of the emerging climate change signal and its interaction with ongoing climate variability.

First-priority future scenarios are generated using the delta method in which simulated mean monthly changes are imposed on baseline observations (Wilby et al., 2004). This method, while simple, allows comparison with many published results. The AgMIP Climate Team also employs weather generators and quantile-based distributional shifts to create scenarios that alter interannual and intraseasonal climate variability based on regional climate model (RCM) projections (e.g., Baigorria and Jones, 2010; Jones et al., 2002; Hansen and Mavromatis, 2001; Robertson et al., 2007).

Although RCM simulations only cover a subset of GCMs, emissions scenarios, and future years, outputs from ongoing RCM intercomparisons (e.g., CORDEX, Giorgi et al., 2009; NARCCAP, Mearns et al., 2009; and ENSEMBLES, van der Linden and Mitchell, 2009) are included in the AgMIP Protocols to capture changes in mesoscale dynamics (e.g., changes in temperature extremes, frequency and intensity of precipitation, interactions with complex topography) and the uncertainty introduced by dynamical downscaling. Statistically downscaled data may also provide a more realistic spatial representation of climate changes (e.g., Wood et al., 2004; Maurer et al., 2007; Maurer et al., 2009; Maurer and Hidalgo, 2008).

The AgMIP Climate Team participates in the agro-climatic analysis of climate, crop, and economic model results in order to improve understanding of the crucial climate phenomena that affect agricultural vulnerability and changes in production and trade.

3.2. Crop Modeling Team Protocols

The objectives of the Crop Modeling Team are to:

1. Evaluate models for a range of crops and regions by comparing outputs with observed growth and yield data, including responses to [CO_2], temperature, water shortage, water excess, and interactions with management factors.

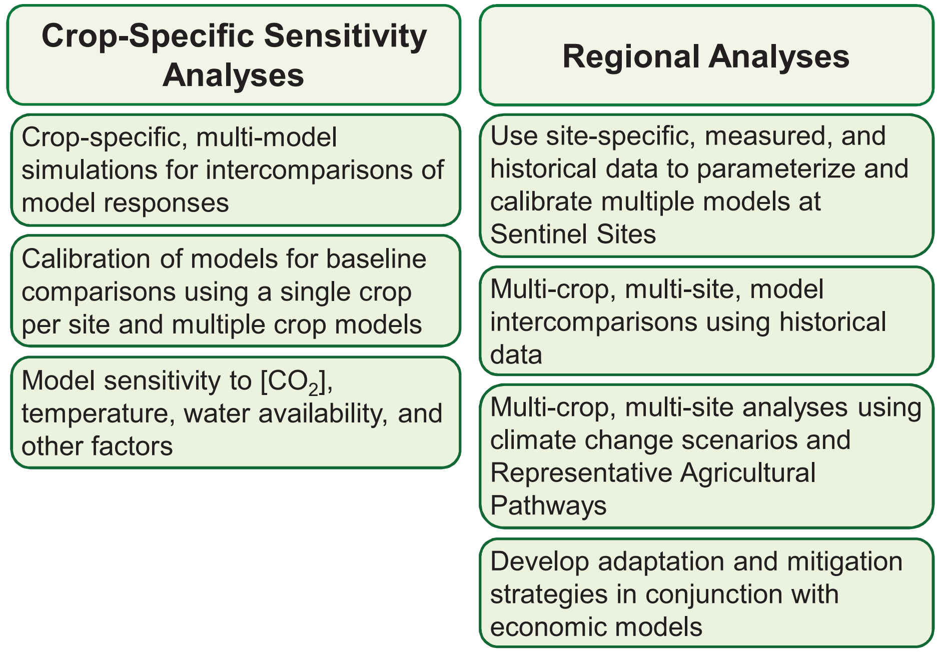

Fig. 5. Crop Modeling Team activities. Both crop-specific and regional model intercomparisons result in model improvements. Regional analyses supply data to regional and global economic analyses.

2. Refine model algorithms and/or parameters to improve predictability.
3. Solve for genetic coefficients to account for cultivar variation.
4. Represent crop management systems, e.g., sowing dates, rotations, irrigation, and nitrogen (N) fertilization practices, for crops over single and multiple seasons and in different regions.
5. Calibrate models for soil carbon, nitrogen fertility, and water-holding capacity in agricultural regions around the world.
6. Define and account for yield gap factors not related to water and N supply.
7. Simulate the set of AgMIP climate change scenarios with a suite of improved and calibrated crop models to create a coordinated set of yield inputs for the AgMIP economic assessments.
8. Characterize uncertainties in modeled outcomes relative to uncertainties in soil and weather inputs, model parameters, and model formulation.
9. Develop and evaluate adaptation strategies such as changes in management and genotypic improvement for future climate.

The Crop Modeling Team is conducting several activities (Fig. 5). In the first activity, crop model sensitivity and uncertainty are evaluated: multiple models for the same crop are initially calibrated using Sentinel Site-specific datasets, followed by analyses of the models' responses to [CO_2], temperature, water availability (rainfall), nitrogen supply, sowing date, and other factors, both in isolation and selected combinations. AgMIP Sentinel Sites provide the data needed to test and improve crop models (Fig. 6). The primary goal of this activity is to obtain an estimate of crop model uncertainty calculated from the responses of an ensemble of crop models for a given crop and region. A second goal is to evaluate the accuracy of predicted responses to climate change factors by comparing to published responses to [CO_2] and temperature.

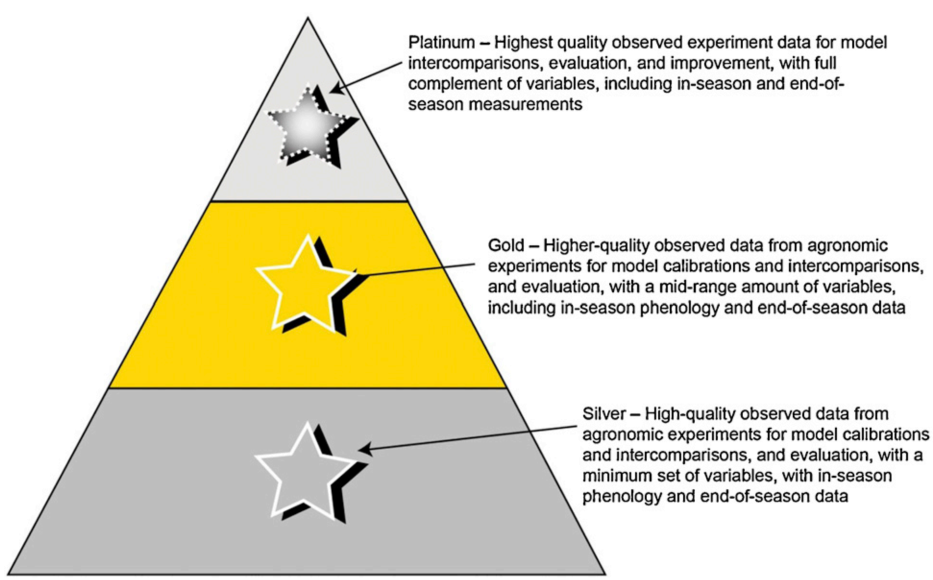

Fig. 6. The AgMIP Sentinel Site classification system for field experimental data that meet progressively more requirements to calibrate mechanistic crop models for a given site.

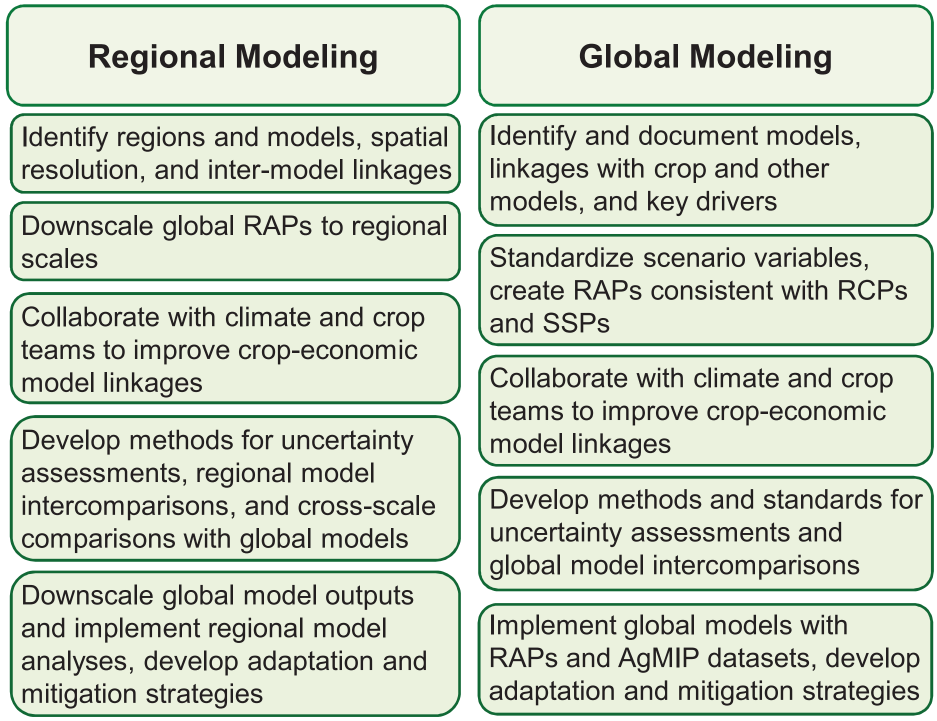

Fig. 7. Economic Team activities. Regional and global modeling activities are done interactively.

The second activity calibrates crop models to intensive and extensive site-specific data, initially starting with available site-specific data on crop responses to various treatments (water, nitrogen, sowing date, other factors) for as many AgMIP Sentinel Sites as possible. Data consist of intensive in-season time-series information (such as soil water content, leaf area index, crop biomass, grain mass) as well as end-of-season yield components. Some site-specific data only have long records of end-of-season information (as in crop variety trials), but these sites are included as they have the advantage of capturing effects of multi-site and multi-year weather variation. Calibration of model parameters and code improvement by the crop modelers are documented. The objective of this step is to improve simulated responses to climatic, soil, and management factors.

The third crop modeling activity is regional crop yield estimation over many soils, fields, sowing dates, and farmers for the past few decades. Regional yield data are often available from various agencies, but tend to suffer from three problems: (1) aggregation over many sites; (2) missing site-specific information on soils, cultivars, sowing dates, crop management, pest control, etc.; and (3) undefined yield gaps compared to well-managed crops on known farm or research fields. In this case, the crop modelers determine distributions of representative crop management and soils, run the models with that information, and compare simulated results to district-wide yields, possibly making bias-adjustments that account for yield gaps. This is essential to provide economic models with inputs that simulate actual production.

Crop modelers interact with climate scientists and economists to project future agricultural production, with uncertainty estimates, in agricultural regions and use crop models to develop strategies for adaptation to future climate risks, such as varied sowing dates, alternative crops, and improved cultivars. The basis of uncertainty estimates is the variability among members of the ensemble used for prediction. The realism of such uncertainty estimates can be quantified to some extent with comparison of simulated hindcasts to data; however, simulated projections involve new unknowns, which can only be roughly evaluated (Spiegelhalter and Riesch, 2011).

3.3. *Economics Team protocols*

The Economics Team is establishing a methodological and procedural foundation for the systematic comparison and improvement of regional and global agricultural economics models used for analysis of climate change impacts and adaptations in the agricultural sector (Fig. 7). The objectives of the Economics Team are to:

1. Improve documentation, standardization, and transparency of economic data and models.
2. Develop Representative Agricultural Pathways (RAPs) coordinated with the Representative Concentration Pathways and Shared Socio-economic Pathways being developed by the global integrated assessment community.
3. Advance the methods and procedures used to link crop and economic models for analysis of climate change impacts and adaptations in the agricultural sector.
4. Design and implement regional analysis of climate change impacts and adaptations using new methods for crop and economic model linkages, and carry out intercomparisons for a set of designated test regions where high-resolution biophysical and economic data are available.
5. Facilitate intercomparison of global agricultural system models using AgMIP crop model simulations.

Achieving these objectives involves participating in AgMIP Cross-Cutting Themes (described in Section 4) to build collaborations among climate scientists, crop modelers, and economists to improve methods and procedures that allow crop model simulations to be used as inputs into economic models. First, an important part of AgMIP's work is to facilitate the transdisciplinary development of agricultural scenarios referred to as Representative Agricultural Pathways (see Section 4.3). Second, methods are needed to allow site/point analyses to be scaled up to agro-ecological zones (AEZs) or larger regions (see Section 4.2), and to statistically characterize uncertain yield distributions and the effects of temperature thresholds and crop failure in economic

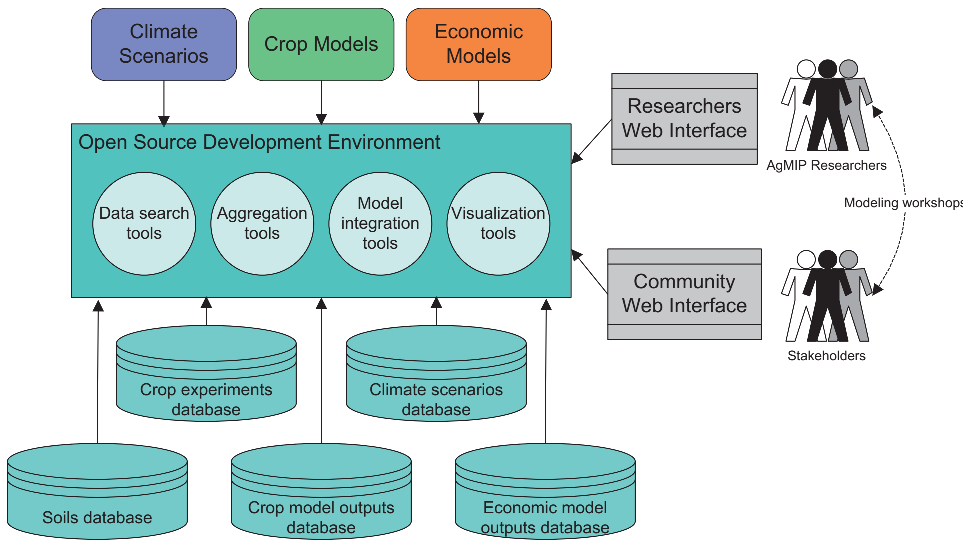

Fig. 8. AgMIP database management and exchange system. Project data and models are accessed via a model and data interface to a common database. A separate community interface allows project results to be shared openly.

models (see Section 4.1). A third important issue that arises in using crop model simulations is how to interpret crop model yields (e.g., as absolute or relative productivities). Initially, AgMIP crop modelers are aggregating from site to regional yields and bias-correcting the simulated regional yields to account for 'yield gap' relationships; these methods will be further addressed as AgMIP proceeds. A fourth important set of issues concerns the characterization of management data, including spatial and temporal aggregation of inputs, representation of human labor, pest management, measurement of capital stocks or capital service flows, and dynamic feedbacks from economic decision models to crop models, within and across seasons.

Another major AgMIP initiative involves coordinating and facilitating intercomparisons of regional and global agricultural economic models being used for climate change impact and adaptation research. Regional economic impact assessment models provide greater capability to evaluate impacts of climate change on poverty, risk of hunger, and other social and environmental outcomes (Antle, 2011) taking prices as given, whereas market equilibrium models provide the capability to quantify changes in market prices and real incomes of consumers and producers. The AgMIP Leadership Team works with regional agricultural economic modeling teams to implement a suite of model runs utilizing the AgMIP crop model simulations and RAPs so that impacts can be assessed under consistent socio-economic scenarios. Regional models are intercompared for a selected set of regions where high-resolution biophysical and economic data are available. For these regions, it will be possible to compare alternative methods for coupling biophysical and economic models (e.g., Antle et al., 2001), as well as cross-validate global models with regional models for socioeconomic indicators that include poverty and risk of hunger.

For global economic model intercomparison, an initial activity is underway using a set of models with global coverage and a range of other key features, including:

1. Significant disaggregation, to the country level at a minimum.
2. Explicit integration of biophysical modeling at a relatively high spatial resolution of crop response to management, choice of variety, and weather.
3. Water supply and demand responses to weather and irrigation infrastructure investment.
4. Some mechanisms to model biotic stresses and yield gaps.
5. Multiple policy levers for agricultural trade and investments of many kinds.

3.4. Information Technology Team protocols

The AgMIP Information Technology (IT) Team facilitates model integration, intercomparisons, and assessments done by the other AgMIP teams by supplying useful and innovative solutions from the IT domain. The overall aim of the Information Technology Team is to develop an IT infrastructure that allows easy and secure access to shared data, scenarios, models, and results of AgMIP researchers, with both a short-term perspective for the completion of AgMIP goals and a long-term perspective for open public access to facilitate continuing research and applications of AgMIP data (Fig. 8).

The objectives of the IT Team are to:

1. Develop the AgMIP Harmonized Database, a data-sharing mechanism with metadata, semantic inter-operability through the shared definition of variables, parameters, inputs, and outputs across models.
2. Link data conversion tools to the AgMIP Harmonized Database.
3. Design and implement an online geo-enabled results viewer, for presentation of results in graphs, charts, maps, and tables.
4. Develop or apply a modeling framework that simplifies running multiple models jointly, either from different domains or from a single domain.

Providing these IT solutions is challenging because AgMIP teams and participants are widely distributed across the globe with differing access to the internet and advanced hardware. There is a large diversity of data and models covering a span of domains and each have their proprietary developments, specific implementations, and purposes. The two AgMIP scientific tracks and the complex subject matter lead to a wide set of user demands on IT infrastructure. Other domains, most notably bio-informatics (Stein, 2002) and plant biology (http://iplantcollaborative.org/), have faced and overcome similar challenges by setting up an advanced IT infrastructure.

An important determinant in integrating across domains, scales, and geographical locations is the adoption of shared formats through standards and shared language through semantic interoperability (Janssen et al., 2011). Semantic interoperability has been achieved through the use of ontologies (Gruber, 1993). Relevant examples for agriculture and climate are FAO's Agrovoc ontologies (www.fao.org/agrovoc) and the SEAMLESS ontologies (Athanasiadis et al., 2009), and the climate and forecast metadata conventions (Eaton et al., 2010), respectively. Available standards are being critically reviewed, so that they can be adopted and extended to suit AgMIP goals.

4. AgMIP Cross-Cutting Themes

In addition to AgMIP's four disciplinary teams, AgMIP has identified three Cross-Cutting Themes that require transdisciplinary collaboration to achieve AgMIP goals.

4.1. Uncertainty

End-users, stakeholders, and the broader scientific community have made it clear that projected climate impacts are not useful unless related uncertainties are characterized and assessed. For its evaluation of future food security, AgMIP's transdisciplinary framework produces cascading uncertainty passed from an ensemble of climate simulations under several scenarios to an ensemble of crop model simulations, which are then aggregated to force an ensemble of economic models.

AgMIP is developing methods to identify and track uncertainties throughout its framework, beginning with pilot investigations that quantify the contribution of uncertainty in yield changes owing to climate scenario and crop model distributions. Uncertainty owing to observational dataset errors are also tracked through the framework. In this way AgMIP can provide estimates of uncertainty at various phases of the impacts assessment process and pinpoint crucial bottlenecks, which will help prioritize future data collection and model improvement efforts.

Uncertainty estimates of the full ensemble of AgMIP results are presented as cumulative distributions describing the probability of each outcome. In some cases this will be an empirical distribution, based on the finite number of models in an ensemble. In others this will be a continuous distribution, if, for example, parameter uncertainty is described by a normal distribution. These distributions are summarized by standard deviation or confidence intervals. It is important to emphasize that the level of uncertainty depends on the formulation of the prediction problem. For example, Wallach et al. (2012) found that uncertainty in predicting yield averaged over many climate scenarios was much smaller than the uncertainty in prediction for a given scenario. The realism of the AgMIP uncertainty estimates will be verified to the extent possible by comparing the probability distributions of hindcasts with historic data using confidence intervals and the Brier score.

Climate uncertainties have been widely explored by the IPCC (Solomon et al., 2007); however, fewer studies have explored uncertainties introduced by crop and economics models (e.g., Aggarwal, 1995; Monod et al., 2006; Challinor et al., 2009). AgMIP allows the quantification of uncertainties relating to weather, soil, and management inputs; model parameters; and model formulation. AgMIP will evaluate the likelihood of extreme agroclimatic events (e.g., droughts, heavy downpours, extreme heat, cold, and frost) and their impacts. In economic models, uncertainties include population and income growth rates, elasticity estimates, rate of technological development, and price shocks.

4.2. Aggregation and scaling

AgMIP research initiatives must overcome significant obstacles in scale dependence to link field-level crop models to regional and global economic models. AgMIP is developing and evaluating procedures to scale field-level outputs up to regional and country scales. Aggregation is facilitated by the availability of quality geographic data regarding the spatial distribution of climate (daily weather), topography, soils, land-use, farm-level management, socioeconomic conditions, and reported yields. While excellent data exist in some regions, data-sparse regions are often those with large spatial heterogeneity in farming conditions and practices. For these regions, AgMIP will investigate the potential of satellite, remote sensing, and other observational products to fill gaps in data. Techniques used in agricultural models that operate on scales closer to global climate model resolutions and have regional and global foci (such as GLAM, Challinor et al., 2004; LPJmL, Bondeau et al., 2007; PEGASUS, Deryng et al., 2011; IMPACT, Nelson et al., 2009; GLOBIOM, Havlík et al., 2011) will also be compared.

Aggregation of field-scale crop model outputs to a regional or larger-scale economic model generally follows one of several approaches (e.g., Hansen and Jones, 2000; Ewert et al., 2011). One approach involves disaggregating the region into approximately homogeneous sub-regions in a type of biophysical typology (Hazeu et al., 2010) with associated AgMIP Sentinel Sites for calibrated crop model simulations, and then converting yields to regional production using planted areas in each sub-region (Burke et al., 1991; de Jager et al., 1998; Yu et al., 2010; Ruane et al., in press-b). Another approach uses multivariate sensitivity tests to cast probabilistic distributions of farm-level conditions into an estimate of regional production (Haskett et al., 1995). In a third approach, farm behavior is explicitly taken into account, and crop models are linked to farm economic models to provide farm production estimates, which can subsequently be upscaled through response functions (Pérez Domínguez et al., 2009; Ewert et al., 2009). A fourth approach is to make crop model simulations at high spatial resolution but with relatively coarse management differences, potentially utilizing reported regional yields to assist in bias-correction. Relative responses to different climate futures are then aggregated up to economic units of analysis and used to adjust exogenously-determined changes in productivity (Nelson et al., 2010).

4.3. Representative Agricultural Pathways

To enable a simulation framework with consistent climate, economics, and field-level assumptions across a range of scales, a Cross-Cutting Theme is building on previous and current agricultural scenario development to create a set of Representative Agricultural Pathways (RAPs). These provide a linked set of necessary variables for field-level crop models and regional and global economic models in AgMIP assessments (Fig. 9). These scenarios help constrain uncertainty in each region, allowing stakeholders and policymakers to assess risk, and also contribute to monitoring, evaluation, and decision-making.

To ensure that climate and agricultural scenarios are not contradictory, the basis for the RAPs is the set of SRES emissions scenarios and RCPs used in the IPCC AR4 and AR5, respectively (SRES, 2000; Taylor et al., 2009). The RAPs description of national, regional, and global policy also links to the socio-economic scenarios developed for IPCC AR4 and AR5 (Moss et al., 2010). Potential RAPs variables for economic models include population growth, income growth, and technology changes, as well as trade, investment, energy, and agricultural policy.

AgMIP RAPs also act to capture plausible farm-level improvements, as climate change impacts assessments that assume static farm management are generally pessimistic in their lack of development and adaptation (Burton et al., 2001). To better model crops at the farm scale, the economic, technological, and scientific development of each agricultural region will be used to specify plausible regional land use, irrigation, fertilizer and chemical applications, regional shifts in crop species, and improved genetic characteristics of cultivars that may be developed or more widely distributed in the coming decades. These more detailed analyses of adaptation will also improve the capacity to understand the potential spatial relocation of crops in response to climate change, using both regional and global economic models.

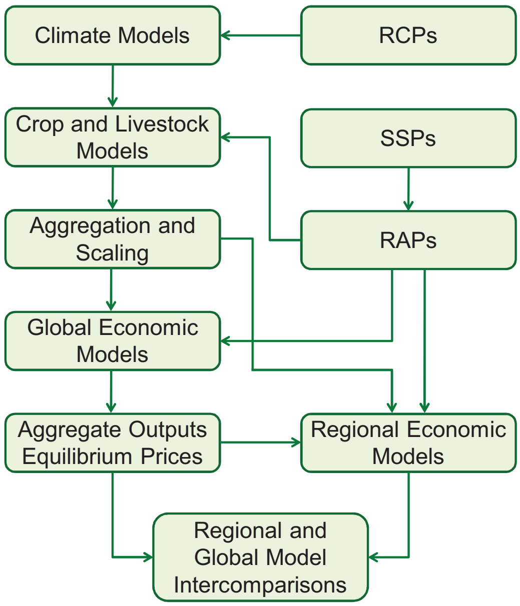

Fig. 9. Flowchart of modeling efforts in the AgMIP framework, demonstrating that AgMIP results are determined by specified Representative Concentration and Shared Socio-economic Pathways (RCPs and SSPs), and Representative Agricultural Pathways (RAPs).

Several RAPs will be created to specify evolving conditions for farm-level management options and country/regional-level economic policies over the 21st century. AgMIP RAPs will facilitate an important assessment of the scale-dependent and intertwining roles of climate change, economic development, and adaptation on the agricultural sector. AgMIP RAPs will also contribute to standardizing agricultural model simulations of future conditions, allowing independent researchers to directly compare their results.

5. AgMIP protocol examples

As illustrations of the need for and use of AgMIP Protocols, crop model sensitivity and future climate impacts were tested for a wheat site in Mexico and projections of climate change economic effects on agriculture were compared at regional, national, and global scales.

Table 2
AgMIP Sentinel Site data for Obregón, Mexico.

Environment
• Daily weather including rainfall, maximum and minimum temperatures, and solar radiation
• Soil parameters for soil layers including lower limit, drained upper limit, bulk density, organic carbon, maximum potential rooting depth, and initial soil water and soil mineral N contents
• Initial surface residues
Genetics
• Qualitative information for genetic coefficients for cultivar Yecora70
Management
• Irrigation and water management (non-water limited, non-N-limited)
• Sowing date
• Plant density
Calibration and Validation
• Multi-year grain yields
• Total biomass
• Anthesis and maturity dates

5.1. Wheat Yield near Obregón, Mexico

Crop model simulations were conducted for wheat in Mexico with emphasis on the differential responses of multiple crop models and the resulting uncertainties. A subset of AgMIP climate scenarios was generated for Obregón, Mexico (27.33°N, 109. 9°W). Fig. 10 demonstrates the range of mean temperature changes for AgMIP future periods projected by an ensemble of 16 CMIP3 GCMs, the first priority scenarios in the AgMIP Protocols (Note that the pilot's baseline period went from 1974–2003 as opposed to the standard 1980–2009 AgMIP baseline period).

Five crop models, APSIM-Nwheat (Asseng, 2004), CERES-Wheat (Ritchie et al., 1985), two SALUS wheat models (Basso et al., 2010), and APES-Wheat (Donatelli et al., 2010; Ewert et al., 2009) were used for baseline analysis, sensitivity tests, and future climate simulations. Crop modeling groups were first supplied with observed field experimental data from Obregón, Mexico (Sayre et al., 1997) for model calibration (Table 2). Since this process can be hampered by the lack of suitable experimental data in some regions of the world, the implications of partially calibrated crop models on climate impact simulations are explored in the AgMIP Crop Model Pilots and Uncertainty Cross-Cutting Theme.

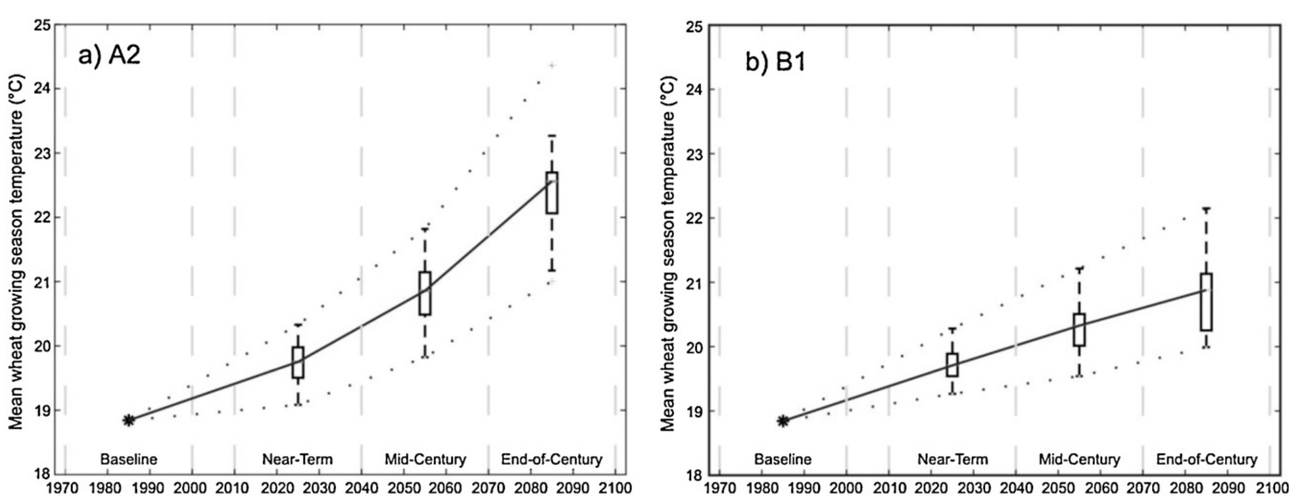

Fig. 10. 16-GCM ensemble of projected wheat-growing season temperatures for Obregón, Mexico, for the (a) A2 and (b) B1 scenarios. Boxes represent the inter-quartile range (IQR) and whiskers represent the furthest value within 1.5× IQR (values beyond this are considered outliers). The solid line connects median scenarios for each period, while dotted lines track the maximum and minimum. Vertical dashed lines denote each 30-year time period. Note that the baseline period in this experiment differs from the standard AgMIP baseline period of 1980-2009.

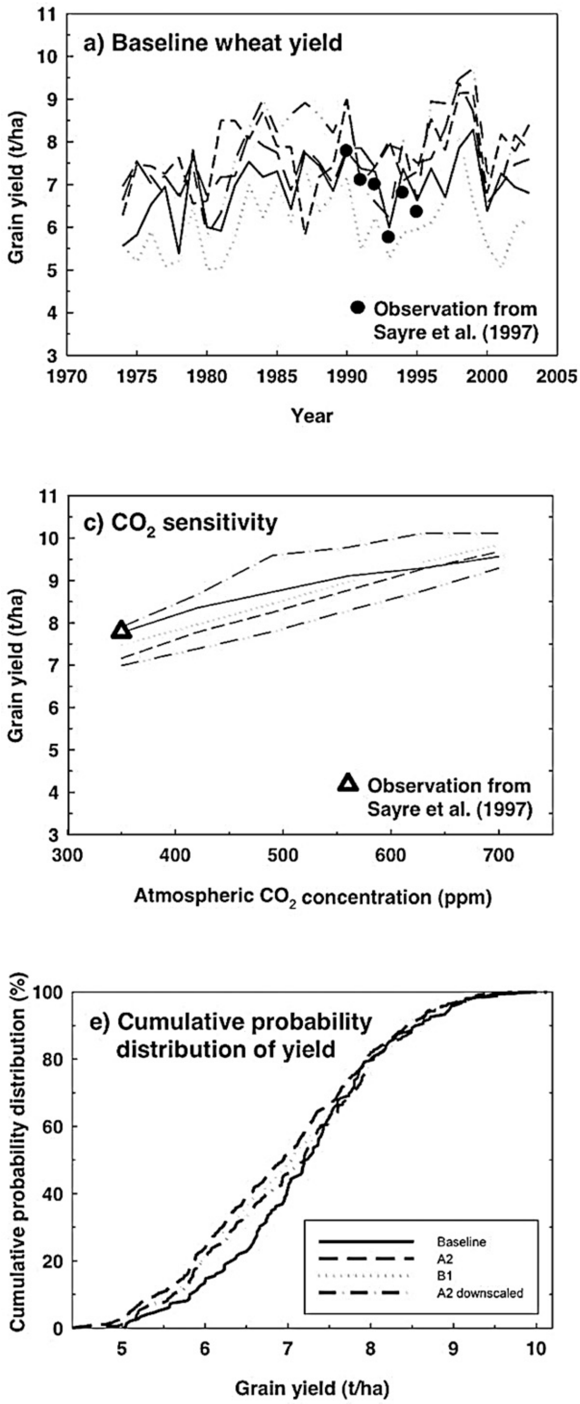

Fig. 11. Obregón, Mexico wheat model ensemble results with five crop models for (a) baseline period 1974-2003, (b–d) cropping season 1989–1990, and (e and f) future climate change scenarios for 2040–2069 compared to the baseline using five different GCMs. The atmospheric CO_2 concentrations were 351 ppm for the baseline, 498 ppm for the B1, and 556 ppm for the A2 climate change scenario for 2040–2069. (a) baseline yields; (b) temperature sensitivity (+/− standard deviation as error bars); (c) CO_2 sensitivity; (d) relative CO_2 sensitivity; (e) cumulative probability distribution of yields among scenarios; and (f) cumulative probability distribution of yield changes among scenarios.

The variability in grain yields between the years was influenced by season-to-season temperature and radiation variability, as crops were well-watered and well-fertilized each year (Fig. 11a). Thirty-year coefficients of variation of simulated yields averaged 12.1% across all crop models, which is smaller than the typical variability in observations from experiments in typical rain-fed environments (Taylor et al., 1999). All crop models were remarkably consistent in their yield variability. Simulated grain yields were within the range of observed grain yields for the period 1990–1995 (Sayre et al., 1997).

Simulated wheat yield responses to increasing air temperature are shown in Fig. 11b. The standard deviation among the wheat models was not constant with changes in air temperature and was largest at the highest temperature increase. In general, the simulated yield response to increased temperature was similar to the reported observed yield response to increased temperature under well-watered and well-fertilized growing conditions (Lobell and Ortiz-Monasterio, 2007; Wheeler et al., 1996).

All crop models indicated an increase in yield with an increasing atmospheric [CO_2] (Fig. 11c). However, the individual quantitative response of each model differed, with the difference between the models varying at each [CO_2]. The simulated mean relative response of 19.6% (±2.8%STD) of grain yield to an elevated [CO_2] of 550 ppm (Fig. 11d) was consistent with non-water limited and non-N-limited Free-Air CO_2 Enrichment (FACE) reported by Amthor (2001). However, this response is higher than that found by Ainsworth et al. (2008), and could be less under N-limited conditions or more under water-limited conditions (Kimball, 2010).

The five crop models at Obregón were driven by ten mid-century scenarios (2040–2069) created using the delta approach based on changes from five different CMIP3 GCMs (CSIRO MK3.0, Gordon et al., 2002; GFDL CM2.1, Delworth et al., 2006; MPI Echam5, Jungclaus et al., 2006; NCAR CCSM3.0, Collins et al., 2006; and HadCM3, Johns et al., 2006) and two emissions scenarios (A2 and B1; SRES, 2000) and then compared to the historical baseline period. Two additional scenarios were created using the delta approach based on changes projected using ¼ and ½ degree statistical downscaling (Bias-Corrected Spatial Disaggregation, BCSD, downscaling method; Wood et al., 2004; Maurer et al., 2007; Maurer et al., 2009) of the MPI Echam5 A2 climate simulations to explore the sensitivity of climate scenarios to the presence and extent of downscaling. Each of these scenarios assumed no change in climate variability. Atmospheric [CO_2] was set at 351 ppm for the baseline, 498 ppm for the B1, and 556 ppm for the A2 climate change scenarios, each representing the central year's concentration for the 31-year period. Simulated yields were analyzed following methods used by Gouache et al. (in press) to quantify causes and effects of variation, and the probability and uncertainty of projected outcomes.

On average, wheat yields were reduced in all five crop models under the future scenarios, mainly at the lower yield range (Fig. 11e). Yields in the A2 scenario were more reduced than in the B1 scenario. While higher projected temperatures in the future climate scenarios reduced grain yields (Fig. 11b), the increased atmospheric [CO_2] compensated for some of these losses (Fig. 11c and d). The simulated yields using the two different downscaling approaches were only slightly different from the simulated yields using the A2 GCM scenarios. There was at least a 60% probability of 30-year mean yields declining by 2040–2069 across scenarios and downscaling approaches (assuming an equal likelihood of all model/scenario combinations), and a corresponding <40% chance of increases in yield (Fig. 11f). There was 30% probability of >10% yield loss with A2, a 10% probability of >10% yield reduction with B1, and an ~15% chance of >10% yield reduction with the downscaling scenarios (Fig. 11f).

On average, grain yields were reduced by only a few percent with little difference between the scenarios and downscaling approaches (Fig. 12). For a given emissions scenario, differences in the projections of temperature changes from the five GCMs are shown by the horizontal scatter and error bars in Fig. 12, but note that each scenario does not have the same atmospheric [CO_2]. Most of the variability in absolute yield response to a given emission scenario was caused by the five crop models rather than by differences in the five GCMs. For example, 88% of the simulated variance in A2 yields was a first-order effect due to variability between crop models (which may be influenced by biases in the baseline calibration), 10% was the first-order effect due to variability between GCMs, and we attribute the residual 2% to crop model/GCM interactions. This is apparent in the mean yields' wide vertical scatter for any given temperature value in Fig. 12. This scatter remained much larger than the sensitivity of any given model's simulated yield to the climate changes.

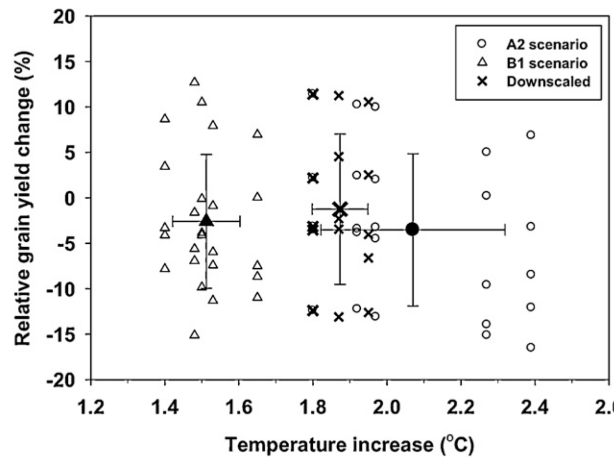

Fig. 12. Changes in growing season temperatures and wheat yields (mid-century, 2040–2069, vs. baseline, 1974–2003) at Obregon, Mexico. Uncertainty is due to emissions scenario, global climate model, crop model, and downscaling approaches. Larger filled symbols represent the average across experiments, with bars showing the standard deviation (horizontal bars for GCMs' growing season temperature; vertical bars for crop models' yield change). Atmospheric CO_2 concentrations are 351 ppm for baseline, 498 ppm for B1, and 556 ppm for A2.

5.2. Sensitivity of projections to economic model resolution

To illustrate the value of AgMIP to economic model intercomparison and improvement, we consider the role of scenario definition and model resolution by examining predictions of the national economic model used in the 2001 U.S. National Climate Assessment (Reilly et al., 2003), and the predictions of a sub-national integrated assessment model (Antle et al., 2004) for wheat production in the Northern Plains of the United States. The national model is based on data aggregated to U.S. regions, whereas the regional model is based on farm-level simulations aggregated to the regional level.

The U.S. Assessment's estimates for changes in wheat production due to climate change ranged from approximately −13 to +17%, depending on climate model and adaptation assumptions, whereas the Montana study showed yields ranging from −47 to +57% (Table 3). Economic returns in the Montana study also varied widely, depending on the CO_2 fertilization effect and the degree of adaptation, from −60 to +69%. In contrast, the impacts on producer surplus obtained in the U.S. Assessment with aggregate data were small and negative for the Great Plains region. Thus, the disaggregated results imply a much higher degree of uncertainty about possible outcomes, with much more adverse outcomes possible if the effects of adaptation and CO_2 fertilization are not fully realized.

These two economic studies used the same global climate model but different crop models, as well as different types of economic models and data aggregation. Thus, it is not possible to disentangle differences in predictions due to climate and crop models from differences due to economic models and aggregation. AgMIP facilitates economic model intercomparison using common climate scenarios and crop models, so economists will be able to identify differences in predictions caused by differences in economic model structure and data aggregation. Similar intercomparisons will be possible between global and regional economic models.

5.3. Sensitivity of global economic projections to model linkages and inter-model uncertainty

Global economic model intercomparisons contribute to future projections of food security and adaptation in three ways: (1) improvements in individual models such as those describing crop and economic performance, (2) improvements in linkages across

Table 3
Montana agro-ecological zone wheat yield and net returns changes for 2050, and US wheat yield changes for 2030 and 2090 using the Canadian Centre for Climate Modelling GCM (%), revealing uncertainties owing to scenario definition and economic model resolution.

	Climate change only	CO_2 fertilization only	Climate + CO_2
MT winter wheat	−27 to −19	+19 to +56	+6 to +25
MT spring wheat	−47 to −44	+48 to +57	−17 to +8
MT net returns without adaption	−60 to −49	+37 to +46	−28 to 0
MT net returns with adaptation	−45 to −25	+56 to +69	−8 to +18
US winter wheat	NA	NA	−13, −9
US spring wheat	NA	NA	+17, +12

Notes: Montana data are for 2050 from Antle et al. (2004). US data are from McCarl (2008); first number is for 2030, second number is for 2090, both with adaptation.

these models, and (3) an assessment of inter-model differences and uncertainty. The economic models may also serve to more realistically capture the transdisciplinary effects of climate on agriculture by closely linking biophysical models and socioeconomic behavior.

A recent example of the benefits of linking models for plausible scenarios, reported in Nelson et al. (2010), demonstrates the challenges addressed in the AgMIP Protocols for model intercomparison. In this example, the linked modeling environments include climate, hydrology, water resources, crop, and socioeconomic conditions. Five quantitative perspectives on 2050 climate were used to drive agronomic performance of the important food and feed crops using the Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al., 2003) suite of crop models. A hydrology model also used the climate data to determine water supply as an input into a water supply-demand model. The water model then determined water availability for irrigation, generating yield stress factors for irrigated crop production. The water model and DSSAT productivity effects were combined to drive aggregated crop productivity effects in the International Food Policy Research Institute (IFPRI) IMPACT model. Three overall scenarios (optimistic, baseline, pessimistic) of GDP and population futures (similar to the proposed AgMIP RAPs) are each paired with the five climate scenarios for a total of 15 plausible futures.

Nelson et al. (2010) used prices as a useful single indicator of the range of possible outcomes. The first three columns of Table 4 report mean price changes from 2010 to 2050 for maize, rice, and wheat across the three overall scenarios as well as standard deviations and coefficients of variation. The price increases reflect a dramatic change in the long-term outlook for crop prices relative to the 20th century when prices declined throughout the period. The second three columns report the mean effect of climate change isolated from simultaneous future economic development, comparing price increases in a future with a perfect mitigation climate scenario to the mean of those under the other four climate scenarios.

This analysis suggests both the value of the AgMIP activities and the challenges in doing model intercomparisons with so many linked processes. It is not sufficient to only compare results from the various wheat models, for example. Improvements in understanding of agricultural futures require integration of the range of projected yields of multiple crops across various emissions scenarios, climate models, crop models, and economic models, all with associated uncertainties. An important contribution of AgMIP is to facilitate examination of additional dimensions of uncertainty in global economic analyses, allowing economic model differences and inter-model uncertainty to be quantified through multi-model assessment.

6. Crop-specific, regional, and global AgMIP activities

AgMIP activities that are underway include pilot studies on specific crops, integrated regional assessments, and global crop and economic model intercomparisons.

6.1. AgMIP crop-specific studies

The Crop Modeling Team has defined a series of studies that include crop model intercomparisons on a crop-by-crop basis. These characterize uncertainties in predicted responses to climate change variables using high-quality AgMIP Sentinel Sites around the world. Fig. 13 shows the locations of crop model intercomparisons for the AgMIP Wheat, Maize, and Rice Pilots (pilots for sugarcane, sorghum, millet, soybean, peanut, potato, and others are also in development). Groups that have developed models for the specific crops lead these analyses, and the AgMIP Protocol-based activities are open to all crop models and modeling groups for each target crop.

6.2. Regional AgMIP activities

AgMIP Regions are geographical areas in which collaborations are developed to implement the Protocols and provide outputs for use in regional and global assessments. AgMIP regional activities are underway in Sub-Saharan Africa, South Asia, North America, South America, Europe, and in development in Australia and East Asia (see Fig. 13). In Sub-Saharan Africa and South Asia, ten multi-disciplinary and international teams are undertaking integrated analyses of food production systems with a special focus on adaptation to climate change to improve food security in their regions (Rosenzweig et al., 2012). In other regions, AgMIP is holding workshops to bring together climate scientists, agronomists,

Table 4
Price outcomes of the IMPACT scenarios. For each crop and economic scenario, results are shown for economic development and climate change under an ensemble of GCM scenarios (left three columns) and for economic development assuming perfect mitigation to climate change (right three columns).

Scenarios	Maize	Rice	Wheat	Maize	Rice	Wheat
	% price change, 2010 mean to 2050 mean *(2050 std. dev. and CoV)*			% price change, 2050 perfect mitigation to 2050 mean CC		
Baseline	100.7 *(24.6; 0.104)*	54.8 *(4.2; 0.011)*	54.2 *(14.0; 0.060)*	32.2	19.8	23.1
Optimistic	87.3 *(25.4; 0.114)*	31.2 *(2.0; 0.006)*	43.5 *(13.8; 0.063)*	33.1	18.4	23.4
Pessimistic	106.3 *(25.5; 0.109)*	78.1 *(4.3; 0.010)*	58.8 *(15.3; 0.065)*	34.1	19.5	24.4

Source: Table 7 in Nelson et al. (2010).

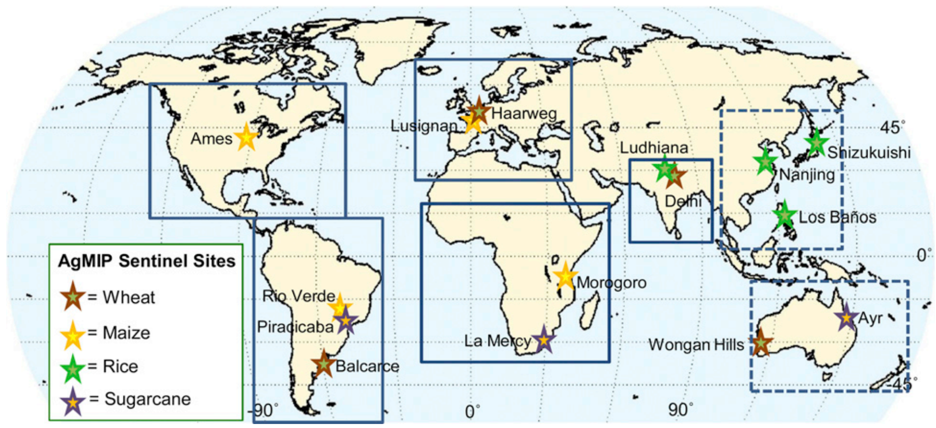

Fig. 13. Sentinal Sites for AgMIP Wheat, Maize, Rice, and Sugarcane Pilots and approximate coverage of AgMIP regional activities (blue boxes; dashed lines indicate regions in development).

and economists from leading national, regional, and international institutions to build capacity and conduct simulations and analyses at field-to-regional scales according to the AgMIP Protocols. Participation from scientists in all agricultural regions is crucial to AgMIP goals, as local expertise is vital to establishing grounded simulations for regional agriculture and improving prediction of global agricultural futures.

6.3. Global AgMIP activities

The AgMIP Coordinated Climate-Crop Modeling Pilot (C3MP) is organizing crop modelers from around the world to run consistent experiments (at sites where they are currently modeling) using AgMIP climate scenarios and to submit results to the AgMIP Harmonized Database (see http://www.agmip.org/). The robustness and detail of regional projections of the agricultural impacts of climate change will improve incrementally with each result for an additional crop, site, and/or model. These pilot results will also form a starting point against which the improvement of crop models and regional and global assessments through AgMIP activities may be gauged.

AgMIP is also coordinating global biophysical and economic model intercomparisons, bringing together key international modeling groups to test reference and future climate scenarios as part of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP, 2012).

Table 5
Overview of AgMIP timeline, plans, and milestones.

AgMIP Domain	2012	2013	2014	Outcomes
Climate	Regional and global data quality assessment and quality control. Weather generation and sensitivity scenarios	Generation of future scenarios based on CMIP 3/5 changes in means and variability	Full regional and global data, scenarios, and analyses	Improved understanding of regional and global climate hazards for agricultural sector
Crop Modeling	Multi-model intercomparison and improvement Crop-specific pilots Responses to [CO_2], temperature, and water	Multi-model improvement and simulations with RAPs	Multi-model production changes with adaptation Regional and global assessments of crop production	Improved regional and global models for yield and productivity changes Global and regional assessments of crop production
Economics	Regional model improvement RAPs development and pilot Global multi-model reference intercomparison	Improvements in regional simulations Global multi-model climate change intercomparison	Regional and global assessments with Representative Agricultural Pathways	Improved regional and global multi-model agriculture and food security assessments
Information Technologies	Development of AgMIP Harmonized Database and Toolshed Incorporation and translation of inputs and outputs	Expansion, quality assessment, and quality control of Harmonized Database and Toolshed	Applications for visualization of data in Harmonized Database and Toolshed	User-friendly database and tool for multi-model, transdisciplinary assessment of climate impacts on agriculture
Cross-Cutting Themes	Pilot studies for Uncertainty, Aggregation and Scaling, and Development of RAPs	Regional and global Cross-Cutting Theme applications	Regional and global Cross-Cutting Theme applications	Improved methodologies for regional and global assessments with adaptation and uncertainty
Regional/Global	Build assessment teams and initiate programs for transdisciplinary assessment	Mid-assessment Additional crops, models, and regions represented	Full assessment with adaptation	Improved food security assessments for regional and global decision-makers with adaptation Improved regional and global capacity

7. Conclusions, project milestones, and future plans

AgMIP aims to enable a major advance by rigorously characterizing climate change impacts on agriculture in both biophysical and socioeconomic systems (see Table 5 for milestones). The Protocols and preliminary results presented here show that there is now enhanced capacity for the agricultural climate change research community to conduct such model intercomparisons and improvements, as well as to coordinate multi-model assessments of future climate impacts and adaptation on the agricultural sector and food security. AgMIP has begun the process of identifying Sentinel Sites with high-quality climate, soils, crop cultivar, crop management, and socioeconomic data for rigorous model intercomparisons and assessments. AgMIP research activities are underway in many regions.

In subsequent phases, AgMIP will address other key areas of the agricultural system including livestock and grasslands, water resources, pests and diseases, spatial shifts and land use change, and mitigation.

AgMIP is developing through a process of strong international collaborations. A major goal of AgMIP is to create capacity-building partnerships around the world, enhancing the ability of researchers in each agricultural region, as well as globally, to evaluate current and future climate impacts and adaptations, and thus contribute to future food security.

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