Report from the Joint GEOGLAM/AgMIP Workshop:

"Integrating Earth Observations with Models to Forecast Within-Season Crop Production at Multiple Scales"

10-11 March 2015; Beltsville, MD, USA

Executive Summary

A joint workshop was held by the GEOGLAM and AgMIP international programs with the aim of improving the interactive use of Earth observations and models for within-season agricultural production forecasting. The international workshop was attended by circa 70 scientists, analysts and program managers from 10 countries and was hosted by the US Department of Agriculture - Agricultural Research Service, Beltsville, Maryland, USA. The Group on Earth Observations (GEO) Global Agricultural Monitoring (GEOGLAM) program is focused on Earth Observation (EO) data from ground and space to monitor seasonal, regional-to-global agricultural production. The Agricultural Model Intercomparison and Improvement Project (AgMIP) uses biophysical and socioeconomic modeling techniques to conduct regional and global assessments of climate impacts on crop production.

Representatives from the two programs explored the potential synergies between observation and model-based methods for within-season crop production estimation. Both programs use well-instrumented sites around the world to test and compare methods, and are complementary in several ways. The strength of Earth observation-based methods is that they utilize spatially-explicit measurements of previous and current surface and crop conditions, and they provide the means to identify crop type and distribution. The strength of the model-based approaches is that they simulate the biophysical processes of crop production driven by agro-meteorology, and through the use of weather or climate predictions, can be used to estimate future crop production. Operational crop monitoring systems use a variety of methods, including satellite and ground-based observations and crop models, which are usually employed in a convergence-of-evidence approach. A number of research and development efforts are currently exploring how these approaches might be better integrated.

The goal of the workshop was to outline a broad international research agenda for the combined use of Earth observation data and models to improve within season production forecasts at multiple scales.

The meeting involved programmatic and state-of-the-science review presentations, individual research method presentations, and breakout group discussions and report back (available online at www.usgeoglam.org). Breakout sessions converged around four major themes for the research agenda: global-scale analyses, local-scale (test site) experiments, crop production in smallholder agricultural systems, and method and technique development. The discussions held initially in groups and subsequently in plenary are summarized below with associated recommendations and next steps to advance the research. Eight collaborative research activities were suggested with near-term and longer-term components (numbered below). We also agreed to continue to look for additional opportunities for the two programs to interact and collaborate in the future.

Global Data and Analyses

The generally poor state of current global data on agriculture was recognized by both groups as an obstacle to progress. Initial discussion centered on the data sets being used in the AgMIP Global

Modeling Activity and how they might be updated or improved by the use of currently or soon to be available EO-derived products, which included crop-type distribution maps, cropping intensity layers, the distribution of irrigated lands, evapotranspiration (ET), and leaf area index (LAI). Efforts by both communities to develop 'best available' maps from multiple sources could benefit from improved coordination in regard to e.g., yield reference data, crop calendars, soil type, fertilizer use, and irrigation timing.

Recommendation 1: Compare the global fields/data sets currently being used by both programs, and exchange information on potential improvements and new emerging EO products, e.g., ET, LAI and soil moisture. This initiative would include a combined effort to generate a dataset of 'best available' sub-national production estimates and harvest indices for different crops and regions.

Although the AgMIP global modeling activities to-date have been primarily focused on simulations based on long-term climate projections, global models can also be applied to within-season forecasting. These can be compared with satellite-derived production estimates to understand where the estimates agree with or diverge from national and sub-national statistics. A comparative understanding of these production estimating methods could inform improved integration of model and EO methods.

Recommendation 2: A Global Retrospective Experiment was recommended at a 5' spatial grid, focused on forecasting wheat and maize production. The experiment would compare model and satellite-derived production estimates from 2001-2014, a period which includes multiple extreme weather events. The production estimates would be evaluated against a database of 'best available' sub-national production estimates (developed in Recommendation 1).

It was noted that to-date global satellite data sets have primarily been developed from coarse-resolution optical satellite systems (c. 250m-8km), but that recent advances in data acquisition and processing are enabling the development of global moderate-resolution data sets (c. 30m). Global moderate-resolution data will permit improved mapping of crop type and crop area essential for regional model implementation. Higher temporal frequency from multiple moderate-resolution satellites may also provide a better characterization of agronomic growth stages, which would improve modeling of crop production.

Recommendation 3: Utilize international moderate-resolution observations to generate improved global agricultural data sets on cropland distribution and crop type and test w gridded crop models at regional scales.

Test Site Cooperation

Both programs are developing networks of test sites for collecting field data to be used for method inter-comparison and improvement. It was felt that there was considerable mutual benefit to be gained from establishing a minimum dataset for the test sites, along with standards and protocols for data collection and sharing, which would be implemented at all sites.

Recommendation 4: Establish an initiative to identify a minimum dataset and metadata standards for site data and to share data between GEOGLAM and AgMIP. A near-term opportunity for developing this cooperation was identified at the SIGMA-JECAM Meeting planned in Europe in November 2015.

Recommendation 5: Conduct an experiment to hindcast and forecast within-season crop yields at several well-instrumented test sites, e.g., Michigan U.S., Argentina, China, Europe, Brazil.

Smallholder Agriculture Initiative

Much of the crop production modeling work to date has focused on major crops and crop-producing regions. Estimating crop production for food-insecure regions presents a considerable number of challenges in terms of their complex farming systems, high spatial variability, highly variable yield, diverse agricultural practices and poorly distributed meteorological data. The combined use of Earth observation and agricultural models targeting smallholder farming systems, could help overcome some of these challenges and that a concerted effort is needed in the context of improving smallholder livelihoods and food security.

Recommendation 6: Establish test sites for different smallholder cropping systems, e.g., maize-legume, sorghum-millet, with a common framework for data collection, building on on-going monitoring programs in East and West Africa and providing a focus for crop yield and production estimations.

Recommendation 7: Conduct pilot study at one or more sites to investigate impacts of pests, disease, and extreme temperatures and precipitation events on yield estimation and how they might be monitored and modeled.

Methods and Technique Development

There are a number of methodological challenges to integrating EO (satellite and *in-situ*) in crop models associated with utilizing products at different spatial and temporal scales and accuracies and with model uncertainties and error propagation. Attention needs to be given to the utility, usability, and availability of data. Model assumptions need to be clearly articulated as well as the conditions for their applicability. The integration of EO and crop models for estimating within-season production remains primarily a research activity, although a number of methods being developed hold considerable promise.

Recommendation 8: Conduct an intensive field campaign across a number of field sites to evaluate the use of remote sensing methodologies to estimate parameters, crop yield, and production including planting date, crop type, water use, crop growth, phenology, and weather forcing. As well as test the use of experimental EO products in crop models that focus on estimating within-season production, e.g., ground water, evapotranspiration, soil moisture, biomass, water-use type, and chlorophyll fluorescence.

Conclusions

There was an overall consensus from the workshop that increased cooperation between the two international programs would be mutually beneficial, with the initial focus on joint activities related to global data and analyses, test site cooperation, smallholder agriculture, and methods and technique development. Both programs recognized the need for a distributed approach for funding international cooperation with most support coming from national funding agencies. The international test site and the experiment frameworks proposed above would enable multiple international groups and countries to participate with their own agency funding. It was also recognized that the Smallholder Agriculture Initiative would provide an opportunity for international funding, with funds set aside for developing country practitioner and scientist participation.

The participants agreed that international meeting opportunities and venues should be identified to further discussion and elaboration of the collaborative activities. Such sessions could take advantage of larger international workshops and conferences, such as the Fall Meeting of the American Geophysical Union Meeting in San Francisco, CA ,USA, where both programs often have special sessions.

The workshop concluded that the focus of proposed joint activities should be on developing capabilities that meet the needs of and enhance operational agricultural production monitoring systems. The intent is to reduce the gap between what is now feasible and what is currently being used operationally. The effectiveness of this 'operational research and development' depends on responding to the needs of those involved in operational monitoring and current decision support systems. The GEOGLAM-AgMIP collaboration, through its joint activities developed in conjunction with its user community, has the potential to improve current decision support systems for agricultural production monitoring and forecasting.

Workshop Co-conveners

Chris Justice (UMD, US), Cynthia Rosenzweig (NASA, US), Debra Peters (USDA, US)

Program Organizing Committee

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Meeting Report

Objectives of the Workshop

One of the greatest challenges for agricultural monitoring globally is improved forecasts and within-season estimates of crop production. The goal of the Joint GEOGLAM/AgMIP Workshop was to examine ways to improve within season crop production forecasts at multiple scales, from sites to regions to the entire globe.

The workshop was developed jointly and attended by the members of two international communities that are leaders in monitoring and forecasting crop production: **GEOGLAM**, the Group on Earth Observations (GEO) Global Agricultural Monitoring Initiative (http://www.earthobservations.org/geoglam), which has traditionally focused on Earth observation data from ground and space to monitor seasonal regional-to-global agricultural production. **AgMIP**, the Agricultural Model Intercomparison and Improvement Project (http://www.agmip.org/), which uses modeling techniques to conduct regional and global assessments and forecasts of climate impacts on crop production.

The workshop was attended by scientists from 10 countries around the world, from both the GEOGLAM and AgMIP communities, ensuring an international perspective on agricultural monitoring and modeling. During the workshop, a research agenda was developed for the immediate, medium, and long term, covering multiple scales and themes of inquiry. Collaborations between these two large international programs are expected to make important contributions to the challenges of understanding global food supply and responses to a changing climate, leading to improved forecasts that will help reduce the impacts of short-term shocks in the weather system to the global food supply.

The meeting was officially opened by **Ann Bartuska**, Deputy Under Secretary for Research, Education & Economics at the USDA, and **Sally Schneider**, Deputy Administrator, National Program Staff Natural Resources & Sustainable Agricultural Systems at USDA Agricultural Research Service. Chris Justice (UMD) introduced the objectives of the meeting.

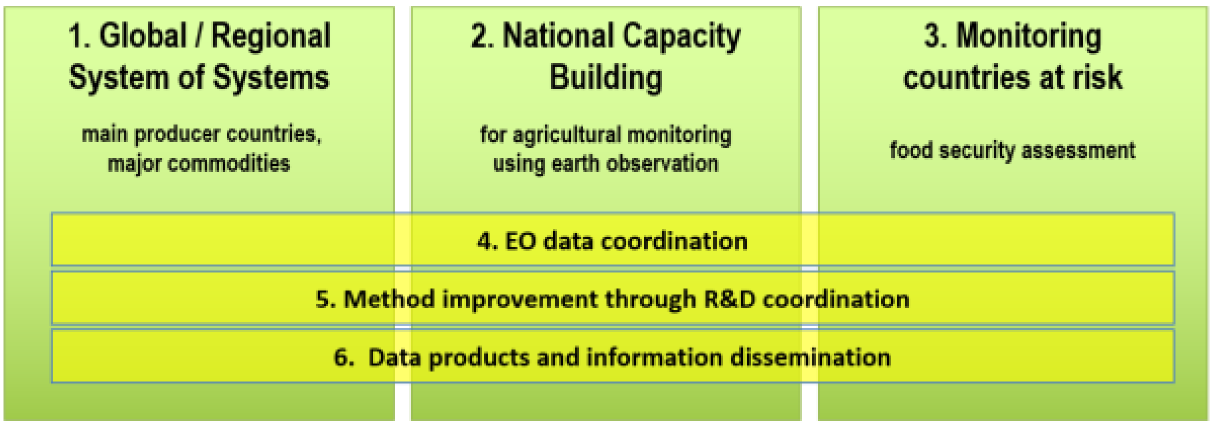
Context: The GEOGLAM and AgMIP Programs

Ian Jarvis (Agriculture and Agrifood Canada, JECAM lead and GEOGLAM Component 5 co-lead) presented an introduction to the GEOGLAM program, while **Cynthia Rosenzweig** (NASA Goddard Institute for Space Studies, Co-PI for AgMIP) presented the overview of the AgMIP program.

GEOGLAM was launched by the Group of Twenty (G20) Agriculture Ministers in June 2011, in Paris jointly with the Agricultural Market Information System (AMIS; www.amis-outlook.org) in response to growing calls for improved agricultural information to help stabilize markets. The GEOGLAM initiative builds on the activities developed under the GEO Agricultural Monitoring Task, initiated in 2007. The main objective of GEOGLAM is to reinforce the international community's capacity to produce and disseminate relevant, timely, and accurate information on agricultural conditions and production at national, regional, and global scales using Earth observation data. This information generation and dissemination is achieved by:

- Enhancing national agricultural reporting systems through capacity-building that integrates satellite observations with ground-based monitoring systems
- Establishing an international network of research organizations and practitioners that focuses on agricultural research in support of operational monitoring (JECAM; www.jecam.org)
- Harmonizing the global agricultural monitoring system through exchange of information on methods and coordination of satellite observations from diverse sources.

Toward meeting these GEOGLAM is organized into three main components, and three cross-cutting components:



As a crucial portion of its Global/Regional Component, GEOGLAM has since 2013 been providing AMIS with a monthly synthesis of the conditions of the world's major crops (wheat, maize, rice, soybeans) in the 27 major producing countries representing over 80% of global production and trade via its AMIS Crop Monitor (www.geoglam-crop-monitor.org). Regionally, Component 1 also includes the Asia-RiCE (Rice Crop Estimation and Monitoring; www.asia-rice.org) activity, which is a multi-national project led by Japan (JAXA) with collaborations in ASEAN+3 countries and India that aims to ensure rice-producing regions receive the full benefit of the GEOGLAM initiative. It has two levels of analysis: regional, utilizing agro-meteorological data; and local, to estimate rice crop area and production using satellite and ground data resources.

Component 2 of GEOGLAM focuses on supporting national and regional institutions to develop agricultural monitoring capacities through the use of Earth observations and modeling. Most countries have an agricultural monitoring system in place, but the level of uptake and use of Earth observations is highly variable among countries. This component provides technical and institutional training, training of trainers, methodological guidelines and tools, facilitated access to Earth observations including meteorological data, and expert advice and support. Early examples of Component 2 activities include the development of a Global Agricultural Monitoring system in Argentina as well as in Pakistan, where a multi-agency initiative has been undertaken to carry out training workshops and field campaigns and to develop a range of spatial tools and systems for monitoring.

Building on the successes of the Global Crop Monitor, GEOGLAM is developing its Early Warning Crop Monitor under Component 3, which will monitor livelihood-sustaining crop production and watch for early warnings of crop failures in countries at-risk. Countries at-risk are characterized by subsistence agriculture and pastoralism, and typically are under-monitored due to gaps in climate station networks, persistent cloud cover (a barrier for optical imaging), and insufficient field data collection. Appropriate satellite remote sensing and models can fill these knowledge gaps, and these will be used to develop the Early Warning Crop Monitor.

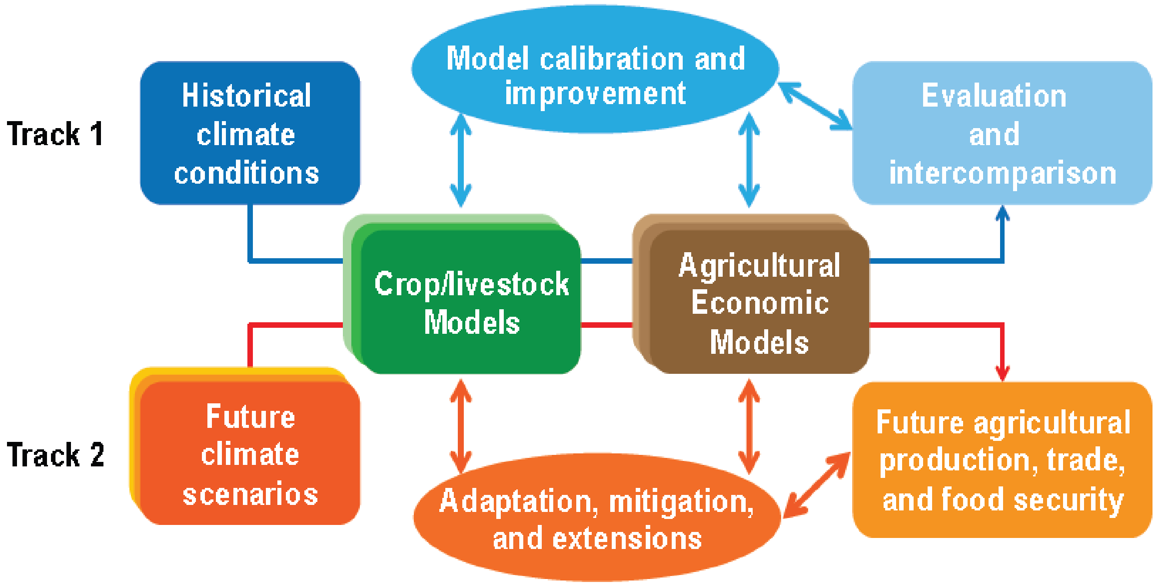
Common and crucial to these three main components is the development of 'best-practices' for monitoring the heterogeneous global agricultural landscape. The testing of new satellite data streams and the development of new monitoring methodologies are carried out in Component 5 through the Joint Experiment for Cropland Assessment and Monitoring (www.jecam.org) and Stimulating Innovation for Global Monitoring of Agriculture (www.geoglam-sigma.info) initiatives. Both activities comprise a number of test sites where field data are routinely collected and minimum EO datasets are acquired to allow for intercomparison between sites and monitoring activities. The provision of EO datasets for JECAM and other GEOGLAM activities are secured through Component 4, which coordinates space-based data through collaboration with the Committee on Earth Observation Satellites (www.ceos.org). Since 2012, the CEOS Ad Hoc Working Group for GEOGLAM has been developing EO requirements for monitoring, working to fulfill these requirements with international space agency data, and piloting data services prototypes to ensure the timely dissemination of high-quality EO to GEOGLAM partners around the world.

In sum, GEOGLAM is a coordination activity, which seeks to support, strengthen, and synergize existing monitoring efforts, to develop capacities at the national and global level, and to coordinate and disseminate data and information to global partners. It is executed through its Community of Practice that includes ministries of agriculture, space agencies, universities, and members of industry.

AgMIP was founded in 2010. Its mission is to improve substantially the characterization of world food security as affected by climate variability and change, and to enhance adaptation capacity in both developing and developed countries. The objectives of AgMIP are to:

- Incorporate state-of-the-art climate, crop/livestock, and agricultural economic model improvements into coordinated multi-model regional and global assessments of climate impacts and adaptation and other key aspects of the food system.
- Utilize multiple models, scenarios, locations, crops/livestock, and participants to explore uncertainty and the impact of data and methodological choices.
- Collaborate with regional experts in agronomy, animal sciences, economics, and climate to build a strong basis for model applications, addressing key climate-related questions and sustainable intensification farming systems.
- Improve scientific and adaptive capacity in modeling for major agricultural regions in the developing and developed world, with a focus on vulnerable regions.
- Improve agricultural data and enhance data-sharing based on their intercomparison and evaluation using best scientific practices.
- Develop modeling frameworks to identify and evaluate promising adaptation technologies and policies and to prioritize strategies.

AgMIP brings together world leaders in climate, crop, livestock, and economic modeling to form the necessary framework to understand climate impacts on food security. That framework is based on a two-track science approach:



Track 1 focuses on model intercomparison and improvement, and Track 2 focuses on climate change multi-model assessment. AgMIP crosscutting science themes include uncertainty, aggregation and scaling, and representative agricultural pathways. To accomplish this scientific approach, AgMIP's work is carried out by four teams: Climate, Crop Modeling, Economics, and Information Technology.

There are now over 700 members of the AgMIP global community of science. AgMIP has built a dynamic and innovative international community of agricultural researchers to enable more robust agricultural-sector decision-making from local to global scales. One of AgMIP's biggest successes has been its ability to demonstrate goodwill and honest collaboration across previously competing modeling groups, providing a productive space to undertake challenging research endeavors. AgMIP Global Workshops anchor this community and facilitate collaboration to set agendas, design protocols for AgMIP activities, and encourage in-kind contributions to unravel the most difficult challenges in food-security modeling.

AgMIP has engaged stakeholders and researchers to assess climate impacts on food security and plan for a more resilient future. AgMIP has built a cutting-edge assessment framework on both global and regional scales, which links climate, crops, livestock, and economics to help decision-makers better understand how climate change will reverberate through complex agricultural systems and markets. Prior to AgMIP, the majority of studies on the impacts of climate change on the agricultural sector utilized only a single crop model, did not address economic implications or the potential for adaptation, and featured methodological differences that severely limited comparison or aggregation of studies. AgMIP's approach eliminates these shortcomings and increases the rigor of scientific information that can aid in stakeholder decisions.

AgMIP also enables, supports, and provides oversight for a range of initiatives. These include global economic assessments and global crop modeling activities (via AgGRID, the AgMIP GRIDded Crop Modeling Initiative), the development of next-generation models incorporating enhanced economic and environmental interactions, data and tools to facilitate multi-model and multi-discipline assessments, activities to understand and improve existing crop and livestock models, cross-cutting themes to help interpret agricultural model results for decision-making, and efforts to include the wider network of crop modelers around the world for future assessments (via C3MP, the Coordinated Climate-Crop Modeling Project). To fulfill its mission, AgMIP is carrying out these initiatives on global and regional scales. Results from these initiatives contributed to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. They provide important context for national and regional stakeholders interpreting climate change risks, further state-of-the-art global food-security assessments and agricultural models, and deliver important inputs, such as commodity prices, into regional integrated assessments.

AgMIP has now launched regional projects on six continents and is building a global program to formalize collaboration and decision-making between AgMIP and regional leaders. AgMIP's Science Integration and Coordination Office at Columbia University spearheads interactions with national agricultural ministries, international development agencies, and research teams, which in turn lead to interactions with stakeholders and decision-makers across multiple scales. Building on these interactions, AgMIP is organizing coordinated global and regional assessments of climate change impacts on the food system and the development of the next generation of agricultural models that can be used to develop and evaluate sustainable technologies.

Remote Sensing, Crop Models, and In Situ Data

A series of presentations were given, establishing the state of the science for crop production estimation and modeling utilizing *in situ* and EO-based data (Chair: **Mark Walbridge**, USDA).

The first state of the science presentation was given by **Jim Jones** (University of Florida) in place of Senthold Asseng (UFL), and provided an overview of the crop production models used in the AgMIP program. Dr. Jones demonstrated the multi-crop model ensemble approach utilized within AgMIP. The median output of models run in the ensemble approach was found to be a better predictor of yield and crop growth than any single model on its own. Further, multi-model ensembles reduce uncertainty, allowing the highest certainty yield estimations to be scaled-up to country and global production. A major question weaving through this research is, "How much of a simulated yield or yield change is due to the chosen crop model?" as opposed to other input drivers such as climate, cultivar choice, management or input base data. While discussing seasonal yield forecasts, Dr. Jones noted that they are probabilistic and require skillful seasonal climate forecasts and physiological-based crop simulation models. Climate forecasting information can be used to improve the reliability of yield forecasts, but the success of the approach varies by location and also with the reliability of the climate forecasts themselves. Despite the success of multi-crop model ensembles, ensemble seasonal climate forecasts are currently under investigated, highlighting a necessary avenue of research.

Dr. Jones pointed to some important research papers about seasonal forecasting, model testing, and multi-model ensembles, including the recent papers by Asseng et al. (2013, 2014, and 2015) in *Nature Climate Change*, Martre et al. (2014), *Global Change Biology*, Bassu et al. (2014) in *Global Change Biology*, and Li et al. (2014) in *Global Change Biology*.

The next talk, given by **Belen Franch** (UMD), described the current status of the use of Earth observations for crop monitoring and yield forecasting, which at present largely relies on coarse spatial resolution (250m – 1km), and frequently acquired satellite data. It generally works better at broad scales of large, homogeneous agricultural areas. Dr. Franch described three main groups of techniques (after Atzberger et al., 2013):

1. *Qualitative crop monitoring*, as is currently employed in the GEOGLAM Global Crop Monitor, USAID Famine Early Warning Systems Network (FEWSNET), Joint Research Centre's Monitoring Agricultural Resources (MARS) Project of the European Commission, and Chinese Academy of Sciences (RADI/CAS) CropWatch;

2. *Quantitative crop yield forecasts using regression models* based on EO-based vegetation indices (e.g., maximum normalized difference vegetation index (NDVI) of the season (Becker-Reshef et al., 2010), temporal NDVI integration (Pinter et al., 1981; Tucker et al., 1983; Goward et al., 1987; Doraiswamy et al. 2005, Meroni et al., 2013), senescence rate (Baret and Guyot, 1986), Land surface temperature (LST) and NDVI (Johnson, 2014)) or using mixed remote sensing and bio-climatic indicators (e.g., spatio-temporal rainfall distribution (Potdar et al., 1999), environmental information (Rasmussen et al., 1998), and actual evapotranspiration (Rojas et al., 2007));
3. *Quantitative yield forecasts using (mechanistic and dynamic) crop growth models*, wherein models describe the primary physiological mechanisms of crop growth and their interactions with the environmental driving variables (temperature, precipitation), and remotely sensed EO data are used to parameterize, initialize, re-calibrate, re-initialize, force, and update the models (e.g., CERES (Jones et al., 1986), WOFOST (Supit et al., 1994), OILCROPSUN (Villalobos et al., 1996), CROPSYST (Stöckle et al., 2003), STICS (Brisson et al., 1998), and GRAMI (Maas1992; Atzberger et al., 2001)).

Dr. Franch provided examples of a regression-based yield forecasting method for winter wheat from her work and that of Becker-Reshef et al. (2010). Both methods are based on the strong correlation between NDVI peak and resultant yield, with Franch et al. (2015) improving the timeliness of winter wheat yield forecasting by including an additional parameter of growing degree days, thereby enabling an accurate forecast of yield approximately 6 weeks before the peak.

Each approach has advantages and disadvantages, but common across all is that models tend to be localized and non-transferable, difficult to scale up/down, incapable of representing impacts of events that affect yields but not biomass, and dependent upon ground-based data for training, validation, and parameterization (e.g. planted area). Further, there are issues that confront satellite-based EO particularly: mixed pixels, cloud occultation (for optical systems), appropriate temporal resolution, and data quality, access, and continuity. However, with improved temporal frequency and quality of fine-to-moderate (<100m) spatial resolution data (both in the passive optical (visible through thermal infrared) and the active SAR (synthetic aperture radar) domain) soon to be available, this will provide an avenue for improved qualitative and quantitative crop yield forecasts and monitoring.

Bringing the focus back "down to Earth," **Richard Ferguson** (University of Nebraska) presented on in-situ data for crop production estimation, providing a review of the "proximally sensed" field data that are collected at different points during the growing season and utilized in crop growth research and for crop monitoring in a precision agriculture context. While focusing on irrigated maize, Dr. Ferguson discussed the collection of soil samples, nutrient uptake at different vegetative stages, climatic data (air and soil temperature, precipitation, photosynthetically active radiation (PAR), growing degree days (GDD), etc.), canopy status (VI-based), leaf area and biomass accumulation, water use, and nitrogen stress using hand-held devices, mounted devices, and unmanned aerial vehicles. He showed examples of destructive plant sampling at physiological maturity to understand nutrient content and agronomic efficiency with different plant management strategies, which is a practical input for crop modeling and for farmers, informing within-season management adaptations.

Following these three state-of-the-science review presentations were six short presentations on approaches for integrating Earth observations in crop models for within season forecasts (Chair: **Cesar Izaurralde**, UMD).

Hendrik Boogaard (Alterra, NL) discussed the use of satellite-based Earth observations for regional yield forecasting drawing on experience of the European Commission Joint Research Center MARS System, AgMIP, and the European Union SIGMA project. Dr. Boogaard stated that EO data are useful for monitoring and crop yield forecasting as they can assess actual state or key driving variables of crop yield, such as rainfall, radiation, cropland locations, and spatio-temporally variable crop calendars. They can provide updates as the season progresses with near-real time information, but do require large areal coverage, frequent within-season temporal coverage, and a high degree of availability and access to an historical archive in order to cover the range of interannual climatic variability and continuity. To accomplish broad coverage with high temporal resolution, the trade-off is often the use of coarse spatial resolution EO, which results in mixed pixels. Where high-resolution data are available, there are considerable costs and limited availability of data, highlighting the need to find a balance between complexity and sensitivity while taking account of data availability, quality, and timeliness. Additionally, Dr. Boogaard stated that the assimilation of these EO data into models is demanding, and requires further development of protocols and guidance.

Jasmeet Judge (UFL) discussed the integration of remote sensing observations in crop models. Dr. Judge demonstrated the assimilation of active and passive microwave sensing-based soil moisture into crop growth models, which can be used to improve crop yield estimates. She utilizes satellite data at multiple spatio-temporal scales, and through the example of a case study in the La Plata Basin in Brazil, she highlighted the importance of spatial scaling of remotely sensed datasets to match the scale of crop models.

Aston Chipanshi (AAFC, Canada) presented on the Integrated Canadian Crop Yield Forecasting (ICCYF) system, which integrates satellite and in-situ data to provide in-season (mid-August) and post-season yield outlooks for major crops (spring wheat, durum wheat, barley, canola, grain corn, and soybean) across the agricultural landscape of Canada. The ICCYF system is a statistics and GIS-based forecasting system that takes historical agro-climates, NDVI, and yield information together with near real-time agro-climate and NDVI inputs to forecast 80% yield ranges and medians. The system captures the general trend of yield variation but fails to capture extreme years.

David Lobell (Stanford) presented a scalable satellite-based crop yield mapper, which integrates satellite data with crop models for field-scale estimation. Dr. Lobell's goal has been to derive yield in areas that are data poor, and develop a method that is robust beyond very local and season-specific calibrations. To this end, his team has developed a simple method: 1) utilize weather information and crop models (e.g., APSIM) to simulate hundreds of hypothetical fields based on different sowing dates, sowing densities, soil moisture, cultivar choice, and nitrogen rates, 2) convert the simulated LAI to a metric observable from remote sensing (currently using Green Chlorophyll Index (Gitelson et al.), 3) train regressions that will predict simulated yields from weather and simulated VI, and 4) apply these regressions to the available observations from fine-to-moderate spatial resolution systems (e.g., Landsat, SkyBox, etc.). This approach has largely been developed and tested using hind-casting with good results for maize and soybean so far, although future plans include within-season forecasting, transferring the method to other regions, and analysis using different sensors.

Bruno Basso (Michigan State University) presented on the assessment and simulation of crop yield variability at the field scale, with a particular focus on biophysical models. Dr. Basso highlighted the importance of simulating the soil water balance, as rainfall amount and distribution are among the most important factors affecting crop yield and its variability space and time. He also detailed the use of UAVs to collect within-field information on spatial variation in biomass, while drawing attention to the limitation of LAI and NDVI as model forcers, due to their rapid rate of change (LAI) and saturation issues (NDVI).

Closing out the session was **Joshua Elliott** (University of Chicago and Columbia University), who described the AgMIP GRIDded Crop Modeling Initiative (AgGRID). In its first phase, the Global Gridded Crop Model Intercomparison (GGCMI) has intercompared results from ~15 models and ~11 countries, each for 4-12 crops, with full protocols recently published in *Geoscientific Model Development* (Elliott et al., 2015) including a full, open archive to model input forcing data. The goals of the GGCMI are to understand model processes, accelerate model improvement, and develop lightweight statistical emulators to improve downstream model coupling and analysis. Advantages of the global gridded approach include: consistency across scales, between regions, and over time; easy aggregation to decision-relevant units; and connection to diverse economic models and analyses; while weaknesses of the approach lie in sparse data availability, limitations on complexity of model scenarios, and calibration challenges. Dr. Elliott showed that major improvements could be made by incorporating improved evapotranspiration datasets, improved land use representation and accounting (cropping index, water use type, land management practices – and their evolution over time), and better spatially explicit information on growing season timing (crop calendars). He pointed out that the difference between model runs is at least as important as how you set up and execute the models, highlighting the underlying importance of input data quality. This highlighted an avenue for collaboration between AgMIP and GEOGLAM, as spatially explicit datasets of this type are now being produced from remotely sensed information.

When these introductory talks were completed, **Jim Jones** (UFL) and **Pierre Defourny** (Catholic University of Louvain, Belgium) led a discussion on identifying critical issues for the two communities with respect to within-season crop forecasting and the research that underpins it. Often discussed is the issue of scale: there is a mismatch between the process scale and that of *in situ* observations, as well as that of the pixel and model output. Further, research areas include how spatial variability in climate is represented at the pixel level, and whether the scale of the AgMIP Sentinel and JECAM test sites are representative of broader areas. Further to the point of test sites, Dr. Jones noted they ought to harmonize their key variables, develop *in situ* observation protocols, and ensure long-term data consistency and continuity for the provision of high-quality reference data to be later used in validation exercises.

A discussion ensued on the two-way relationship between crop models and EO-derived models: crop models can be used to train EO-derived yield models, to derive key variables, and to support EO retrieval, while EO-derived data can provide crop type area and distribution information, cropland phenology, and land use characterization (and its uncertainty) to be used in crop models. There was an acknowledgement that protocols for parameter and variable definitions, in situ data collection, data management, model validation are all very much needed by both communities. This productive discussion paved the way for a breakout group and the resulting international research agenda.

International Research Agenda

On the second day, the attendees broke into four groups focusing on global fields and remote sensing model integration experiments, test site data and synergies, smallholder agricultural systems, and “nuts and bolts” of method, model, and technique development. Each group was asked to develop research questions and plans for new product outputs in each of these thematic areas, focusing the discussion through broader guiding questions of *How can AgMIP help GEOGLAM? How can GEOGLAM help AgMIP? What can be achieved only in tandem?* The rapporteurs for each group were tasked with developing immediate actions that could take place without new funding, the mid-term “low-hanging fruit” opportunities for collaboration between the communities, and the longer-term research agenda.

Global Data and Remote Sensing Model Integration Experiment (Co-Chaired by Alex Ruane and Alyssa Whitcraft)

The global group's discussion centered primarily on the priority gridded datasets for AgMIP and the potential of remote sensing to generate them (as well as a recognition of a need to compile the best-available datasets – EO-based, ground-based, etc.). These included yield reference data, soil information, crop calendar data, crop type distribution maps, cropping intensity layers (available within season, and including a description of which crops are being grown in which order), irrigated area distribution, irrigation timing distribution, precipitation, temperature, solar radiation at surface, evapotranspiration, fertilizer utilization, and leaf area index. There was also a brief discussion of the potential benefits in recognizing where simulations may capture variability missed in satellite-derived yield estimates and vice versa.

Immediate Actions:

1. AgMIP to formulate a spreadsheet of their input products, spatial resolutions and estimated accuracies, and desired spatial resolutions and accuracies, and for GEOGLAM to respond by evaluating existing EO-based datasets for use in global AgMIP model simulations.
2. AgMIP to provide best-available global gridded soils data to be used as ancillary data in GEOGLAM monitoring activities.

Low-Hanging Fruit:

1. Intercomparison of Priority and Best-Available Datasets (Currently Available):
    a. Annual historical yield/production reference datasets (sun-national)
    b. Cropland area (ideally produced within season)
    c. Crop type distribution (ideally within season)
    d. Crop calendars (SOS (AgMIP definition: planting) and EOS (AgMIP definition: maturity) as a first cut)
    e. Water use type and timing (irrigated, rainfed, paddy)
    f. Cropping intensity (count and characterization)
2. Priority Datasets Coming Online:
    a. Evapotranspiration
    b. Leaf Area Index
    c. Soil Moisture (remote sensing-based) and other soil variables
    d. Solar radiation at the surface
    e. Precipitation data from GPM
    f. Land Surface Temperature

Longer-Term Research Agenda

1. Global experiment comparing and validating satellite- and model-derived yield estimates (brief sketch is provided but it was recognized that this would require further discussion for a detailed design of the experiment):
    a. Recent historical forecasts at 5 minute horizontal resolution, focus on maize and wheat
    b. Should include some years with extreme events in order to evaluate ability of EO and crop models to capture them, validate with available production and yield observations.
    c. Compare satellite-derived yield estimates to model estimates over MODIS record (2001-2014), examine ways to better integrate EO and crop models
    d. Improve harvest index for different crops and different areas

    e. Improve validation datasets – national and sub-national production estimates
2. Annual within-season crop type and crop area products, at ~30 m
3. Within-season phenology (agronomic stages e.g. heading, silking, tillering)
    a. Potential detection from space; to be evaluated post-Sentinel 2a/b launches
4. Link crop growth and carbon budget models; gross primary productivity (GPP)
5. Within-season crop production predictions using models constrained/initialized with EO

Test Site Data and Remote Sensing-Model Integration (Co-chairs: Ian Jarvis and Bruno Basso)

GEOGLAM has many test sites through its JECAM initiative and the EC SIGMA project, while AgMIP has a number of well-established Sentinel Sites with field observations and C3MP sites where models have been specifically calibrated.. The breakout group discussed ways of synergizing the test site activities and filling gaps in data collected at each site, and discussed what each initiative can lend to crop monitoring and modeling that the other cannot. It was recognized that GEOGLAM can provide a great deal of information over a very broad space, including valuable insight during the early stages of crop development and also as validation for models. Meanwhile, AgMIP is capable of modeling crop conditions over long time spans, including those periods and years for which EO data are not available, as well as simulating deep soil conditions and biological processes that determine outcomes. Additionally, AgMIP models are able to compensate for the situations where EO data utility is limited by saturation at high LAI values or cloud contamination. AgMIP models can also provide more information on uncertainties of the yield estimation, which is crucial information for policy-makers. The group further discussed minimum datasets across the test sites, and developed overarching research questions that can be approached at the test site scale.

Minimum Datasets

The group discussed JECAM's recent initiative to develop minimum dataset standards and protocols, for both remote sensing and in situ data, for gathering information on/towards estimates of LAI, ground cover, phenology, crop area, crop type, and crop conditions. This breakout group proposed to identify a set of JECAM-AgMIP sites and identify gaps and opportunities for nested sampling and scalable measurements. The group indicated that it would be beneficial to test the sampling protocol initially for a few sites where there is overlap between JECAM and AgMIP Sentinel Sites (e.g., KBS Michigan US, Argentina, China, Europe Brazil) based on established methods. Further, following activities already underway within JECAM through its Space Data Management System (SDMS – developed by NASA for JECAM), the group indicated a need to develop data management standards. Lessons and parallels for JECAM may also be drawn from the AgMIP Sentinel Site Pyramid process by which agricultural field trials are classified according to their ability to provide minimum datasets required for accurate simulation of various processes. This tiered system allows field experimentalists to design trials that maximize the potential utility of observations for crop modeling studies of potential management and cultivars. Related overarching research questions included:

Overarching Research Questions

- What is the minimum dataset suitable to link crop models to EO?
- How can we best represent the scale issue between ground truth measurements, crop models, and satellite imagery?

- Is there an optimal field or sampling size? Does this vary by target application? Can we utilize broad observational regions for point-based modeling studies?
- How do we incorporate crop models into Earth observations and use them to scale up from local to regional outlooks?
- Can we identify target sampling sites using the remote sensing-based spatial-temporal approach used for yield mapping (stable vs. unstable zones), linking this approach to crop models to understand possible cause of yield uncertainties?

Actions:

- Exchange datasets between GEOGLAM and AgMIP, and compare data formats
- Plan experiment at 2-3 test sites where representatives from both programs can utilize shared data to hindcast and forecast within season yields at agreed upon test sites (e.g., Michigan, Ukraine, Argentina, Brazil, China, Burkina Faso, Mali)
- Develop a joint GEOGLAM-AgMIP working group on minimum datasets and metadata – potential opportunity at JECAM/SIGMA meeting in Europe in November 2015.

Smallholder Agricultural Systems Initiative (Pierre Defourny and Alisa Coffin)

Many modeling and monitoring activities focus on large production systems and major crops due to the important role they play in global food supply and markets. However, smallholder systems and second-tier crops are very important for livelihoods and food security, and they are often exposed to different drivers, stressors, vulnerabilities, and decision-making systems than are larger production systems. This group discussed how GEOGLAM and AgMIP might collaborate to better monitor and forecast these systems.

Guiding Questions:

- What are the uncertainties in quantitative production estimation in smallholder farming systems?
    - To be supported by validation test bed sites for different cropping systems (e.g., maize-legume, sorghum-millet systems) – Action: select sites based on:
        - The suitability of existing or ongoing monitoring/data collection sites (AFSYS, VITAL SIGNS, JECAM, Sentinel Sites, household survey sites, East Africa and West Africa sites), particularly for those regions most vulnerable to climate variability and change.
        - The opportunity to establish regional teams from AgMIP and GEOGLAM
    - Common framework for data collection across test sites
- How do we improve knowledge of disease and pest modeling and monitoring in smallholder systems?
    - Action: conduct GEOGLAM-AgMIP pilot study in one or more sites (e.g., Tanzania, Burkina Faso, Mali) with special attention to pest and disease impacts monitoring.

Immediate Actions

- Use remote sensing to see how smallholder crops respond to extreme events that are not yet part of the AgMIP models, e.g., flooding, pest outbreaks, high temperatures, etc.
- Share best datasets available for modeling applications (see group 1 Global Data recommendations)

- Characterize the smallholder farming systems in the regions where there are AgMIP and JECAM sites.
- Conduct retrospective analysis and summary of GEOGLAM monthly monitoring output to detect/assess trends and patterns, and learn how to harmonize with AgMIP model simulations in smallholder farming systems.

Low-Hanging Fruit

- How AgMIP can benefit from GEOGLAM:
  - Crop area estimates and spatial variability of smallholder regions
  - Cropping system delineation to assess the transformation of crop allocation and practices of smallholder regions
- How GEOGLAM can benefit from AgMIP:
  - Gain understanding in crop production variability of smallholder regions
  - Explain the transformation from perennial cropping systems to annual systems as an adaptation to uncertainty brought about by (climate change-associated) extreme events.

Long Term Research

Monitoring and understanding of cropping system transformations in response to climate change and associated impact to ecosystem services across a region (e.g. water, soil erosion, forest production, etc.) with focus on smallholder systems.

Methods and Technique Development - “Nuts and Bolts” (Jasmeet Judge and Prasad Bandaru)

This group approached their discussion of methods and techniques for monitoring, modeling, and data integration/assimilation by identifying overarching issues and recommendations for how to reconcile them. Issues included:

- The utility, usability, and availability of data:
  - Not all necessary data are acquired, and those which has been acquired are not always available.
  - There is a discrepancy between crop model needs and data availability due to data latency (delay between data acquisition and delivery to users).
  - Remote sensing-based observations are not consistently validated or evaluated.
- The integration of remote sensing-based and *in situ* observations with crop models:
  - How to combine datasets, information, model results, etc. that are at various spatial and temporal resolutions?
  - There is a need to quantify uncertainties in the data and crop models, and to understand how error propagates through models.
  - Assimilation of remote sensing-based data into crop models.

The group recommended the following:

- Reconcile and evaluate existing methodologies that relate remote sensing observations to biophysical characteristics through a joint experiment with nested scales to verify both EO and crop model outcomes.
- Clearly articulate the assumptions within each crop model, as well as their conditions for applicability and their predictability at the outset of all uses.

- Review and compare existing methodologies of:
    - Assimilating remote sensing and *in situ* observations with crop models
    - Scaling and merging disparate datasets
    - Quantifying uncertainties in data and models, and error propagation in linked models.
- Reconcile crop model input requirements with remote sensing and *in situ* data that exist and are available.
- Evaluate extensibility of existing remote sensing methodologies to estimate biophysical parameters and yield, including:
    - Yield and production (quantitative and qualitative estimates)
    - Within-season crop information:
        - Planting date, crop type map, water use type, crop growth, phenology, field characteristics (soil, management practices), weather forcing.

    It was noted that this would translate into an intensive field campaign that could be conducted at field sites and could be linked to the JECAM-AgMIP sentinel site activities described by group 2 on Test Sites.
- Develop standardized best practices for data acquisition (potential collaboration with Component 4 of GEOGLAM) and integration of remote sensing and models.
- Include in crop models additional remote sensing observations such as crop ground water, chlorophyll florescence, evapotranspiration, soil moisture, crop phenology, biomass, and water-use type (irrigated vs. rainfed).

Summary of Actions and Priorities

Common to all of the actions recommended is the focus of the GEOGLAM-AgMIP collaboration on research-to-operations, with the goal of reducing the gap between the two as much as possible. Further, it was affirmed that as the international research agenda unrolls, it is necessary wherever possible to engage the various stakeholders (monitoring system practitioners and decision-makers) in scoping the research and evaluating the findings.

Both programs recognized the need for a distributed approach for funding international cooperation with most support coming from national funding agencies. The proposed international test sites and the experiment frameworks would enable multiple international players to participate with their own agency funding. It was also recognized that the Smallholder Agriculture Initiative could provide an opportunity for international funding, with funds set aside for developing country practitioner and scientist participation. The participants agreed that international meeting opportunities and venues could be identified to further discussion and elaboration of the collaborative activities.

Beyond this initial meeting of these two communities, the following steps are necessary to continue momentum and to ensure success:

- Circulate the workshop report to attendees and broader communities of practice for input, and deliver the final version to the GEOGLAM Advisory Committee and AgMIP Steering Committee for help in identifying funding sources for program collaboration.
- Identify topic leads and workshop venues for further developing implementation of immediate actions, low-hanging fruit, and longer-term global experiments.
- Foster regular discussions between the GEOGLAM and AgMIP Component Leads, and identify opportunities for continued collaboration, e.g., through invited participation in program meetings and joint organized sessions at international conferences.

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