BioEarth: A Regional Biosphere-Relevant Earth System Model to Inform Agricultural and Natural Resource Management Decisions

J.C. Adam · J.C.·Stephens · S.H. Chung · M.P. Brady · R.D. Evans · C.E. Kruger · B.K. Lamb · M.L. Liu · C.O. Stöckle · J.K. Vaughan · K. Rajagopalan · J.A. Harrison · C.L. Tague · A. Kalyanaraman · Y. Chen · A. Guenther · F.Y. Leung · L.R. Leung · A.B. Perleberg · J. Yoder · E. Allen · S. Anderson · B. Chandrasekharan · K. Malek · T. Mullis · C. Miller · T. Nergui · J. Poinsatte · J. Reyes · J. Zhu · J.S. Choate · X. Jiang · R. Nelson · J.H. Yoon · G.G. Yorgey · K. Johnson · K.J. Chinnayakanahalli · A.F. Hamlet · B. Nijssen

Abstract As managers of agricultural and natural resources are confronted with uncertainties in global change impacts, the complexities associated with the interconnected cycling of nitrogen, carbon, and water present daunting management challenges. Existing models provide detailed information on specific sub-systems (e.g., land, air, water, and economics). An increasing awareness of the unintended consequences of management decisions resulting from interconnectedness of these sub-systems, however, necessitates coupled regional earth system models (EaSMs). Decision makers' needs and priorities can be integrated into the model design and development processes to enhance decision-making relevance and "usability" of EaSMs. ***BioEarth*** is a current research initiative with a focus on the U.S. Pacific Northwest region that explores the coupling of multiple stand-alone EaSMs to generate usable information for resource decision-making. Direct engagement between model developers and non-academic stakeholders involved in resource and environmental management decisions throughout

J.C. Adam (✉),S.H. Chung, B.K. Lamb, M.L. Liu, J.K. Vaughan, K. Rajagopalan, F.Y. Leung, T. Nergui, J. Reyes
Civil and Environmental Engineering, Washington State University, Pullman, WA 99164
email: jcadam@wsu.edu

J.C. Stephens
Environmental Science & Policy, IDCE, Clark University, Worcester, MA 01610

M.P. Brady, J. Yoder, B. Chandrasekharan
School of Economics, Washington State University, Pullman, WA 99164

the model development process is a critical component of this effort. BioEarth utilizes a bottom-up approach for its land surface model that preserves fine spatial-scale sensitivities and lateral hydrologic connectivity, which makes it unique among many regional EaSMs. This paper describes the BioEarth initiative and highlights opportunities and challenges associated with coupling multiple stand-alone models to generate usable information for agricultural and natural resource decision-making.

1. Introduction

The underutilization of climate science information for decision making is increasingly being acknowledged (Weaver et al. 2013), and novel approaches to increase the "usability" of climate science are being encouraged. Different types of research projects are emerging that are designed to close the gap between climate science information that is deemed useable by scientists versus that by non-academic societal actors (Lemos et al. 2012). Societal actors involved in agricultural and natural resource decision-making are confronted with uncertainties in global change impacts and the interconnected challenges of managing nitrogen (N), carbon (C), and water (H_2O). However, most climate change impact work relies on models that only simulate specific sub-systems (e.g., land, air, water, and economics). Complex interconnections among these sub-systems are often poorly understood and difficult to conceptualize, thus resource management decisions made with the best intentions can lead to negative unintended consequences. To better understand interconnections among sub-systems, coupled earth system models (EaSMs) are essential. To enhance decision-making relevance and *usability* of existing and developing EaSMs, these models need to be capable of quantifying the impacts of specific management practices such that model outputs can be communicated in a manner that is relevant to decision-makers.

R.D. Evans, S. Anderson, J. Poinsatte
School of Biological Sciences, Washington State University, Pullman, WA 99164

C.E. Kruger
Center for Sustaining Agriculture and Natural Resources, Washington State University, Wenatchee WA 98801

C.O. Stöckle, K. Malek, R. Nelson
Biological Systems Engineering, Washington State University, Pullman, WA 99164

J.A. Harrison, C. Miller
School of the Environment, Washington State University, Vancouver, WA 98686

EaSMs have evolved in recent years by incorporation of biogeochemical processes and vegetation dynamics in climate models (Washington et al. 2009). Currently, many EaSMs are being further developed to resolve coupled human and natural systems (CHANS), including representation of resource management activities. The Community Earth System Model (CESM; www2.cesm.ucar.edu) and the Platform for Regional Integrated Modeling and Analysis (PRIMA; Krakunas et al., this issue) are two EaSMs where progress is being made in this direction. CAM-chem, the Community Atmosphere Model (CAM) in CESM, has been developed to study the interactions between climate and atmospheric chemistry, thus allowing for the analysis of the impact of climate change on air quality (Lamarque et al. 2012). The Community Land Model (CLM) (Lawrence et al. 2011), the land surface model for CESM, has recently been developed to represent some agricultural and water management activities (e.g., Drewniak et al. 2012). Including economic decision making in EaSMs is starting to emerge; computable partial and general equilibrium models (CGE) and, increasingly, agent-based models (ABM) have been connected to biophysical models (Harou et al. 2009; Rowan et al. 2011) allowing for better representation of CHANS when captured in an EaSM framework.

C.L. Tague, J. Zhu, J.S. Choate
Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106

A. Kalyanaraman, T. Mullis
School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA 99164

Y. Chen
Agricultural and Resource Economics, Oregon State University Corvallis, OR 97331

A. Guenther, X. Jiang
Atmospheric Chemistry Division, National Center for Atmospheric Research, Boulder, CO 80301

L.R. Leung, J.H. Yoon
Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, WA 99352

A.B. Perleberg,
Chelan County Extension, Washington State University, Wenatchee, WA 98801

E. Allen
School of the Environment, Washington State University, Pullman, WA 99164

G.G. Yorgey
Center for Sustaining Agriculture and Natural Resources, Washington State University West, Seattle WA 98164

Although tremendous progress is being made towards resolving resource management activities in integrated models, funding and decision-making agencies (e.g., the U.S. Department of Agriculture) as well as scientists (e.g., Reid et al., 2010) are calling for additional advancements to quantify impacts on and feedbacks from ecological, agricultural, and other human systems; and effectively communicate model results for informing decisions. Resolving EaSMs at finer spatial and temporal scales is instrumental to making these advancements (Liu et al., 2007). Regional EaSMs have greater potential than those at global scales to improve both the technical understanding of complex interconnected environmental processes (including the role that humans play in these processes) and the relevance of information for decision-making (Giorgi 1995). For relevance to land-use decision-making, inter-annual to decadal time-scales are critical (Smith 2011). While planting decisions occur annually, farm-level irrigation infrastructure and machinery generally have investment pay-back periods of about a decade, and perennial crops have an investment term of 3-30 years. Many U.S. state planning agencies operate on a 20-year time horizon. Capturing shorter time-scale variability in EaSMs is also important because it is necessary for managers to adapt to variability and extremes of decision-relevant variables in addition to changes in the mean (Katz and Brown, 1992).

BioEarth is a research initiative designed to explore the coupling of multiple stand-alone models within a modular EaSM framework to generate usable information for agricultural and natural resource decision-making at the regional scale**.** This project focuses on the U.S. Pacific Northwest (PNW) region and is a modular framework that integrates atmospheric, terrestrial, aquatic, and economic models. BioEarth utilizes a bottom-up approach for its land surface model that preserves fine spatial-scale sensitivities and lateral hydrologic connectivity, which makes it unique among many regional EaSMs. Our economics modeling utilizes a two-pronged approach that allows for both rich economic analysis through CGE and a more integrated biophysical-economic approach through the spatially-explicit ABM, which also allows for consideration of non-economic information such as social norms. Modeled decisions are

K. Johnson
Department of Animal Sciences, Washington State University, Pullman, WA 99164

K.J. Chinnayakanahalli
State of Washington Water Research Center, Washington State University, Pullman, WA 99164

A.F. Hamlet
Civil and Environmental Engineering and Earth Sciences, University of Notre Dame, Notre Dame, IN 46556

B. Nijssen
Civil and Environmental Engineering, University of Washington, Seattle, WA 98195

sensitive to changes in decadal-scale variability as well as long-term changes. Direct engagement with non-academic stakeholders throughout the model development process is a critical component of this effort. This project can benefit the broader scientific community by supporting and informing other regional modeling efforts that seek to integrate sub-systems with complex interconnections and produce useable climate science information to decision-makers.

The objectives of this paper are to 1) provide an overview of the goals and overall design of the BioEarth project, 2) describe the integrated modeling approach, 3) explain the development and implementation of the stakeholder engagement process, and 4) highlight the emerging opportunities associated with this ambitious initiative. This paper is written in the same spirit as other overview papers (e.g., Kampe et al. 2010) that seek to provide the broad context of a large project, rather than results for specific research questions.

2. Overview of BioEarth

2.1 Project Goal

The overarching goal of the BioEarth project is to improve understanding of the interactions between coupled C:N:H_2O dynamics and human actions at regional and decadal scales under global change to 1) better understand the role that resource management actions have in impacting earth system dynamics, and 2) inform resource managers about the consequences of their decisions on the earth system, with a particular focus on quantifying environmental feedbacks and ecological and environmental tradeoffs. The BioEarth framework enables users to quantify the impacts of human decisions on greenhouse gases and other atmospheric pollutants, water quantity and quality, terrestrial ecosystem health, and economics through simulating the management of cropping systems (e.g., crop selection, irrigation, fertilization, and residue management), forested ecosystems (e.g., thinning and restoration), rangeland ecosystems (e.g., grazing and restoration), water supply management (e.g., reservoirs, water rights curtailment, and water transfers), and air quality (e.g., regulation of emissions of pollutant and pollutant precursors from cars, power plants, and industrial facilities). This information, when combined with other more focused decision-support tools and the constraints and priorities of a decision-maker, allows for improved decision-making.

2.2 Study Domain

The BioEarth project focuses on the PNW region of the U.S. (Figure 1). As the fourth largest river in North America (as measured by flow), the Columbia River Basin (CRB) drains complex topography with the Cascade and Rocky Mountain Ranges surrounding

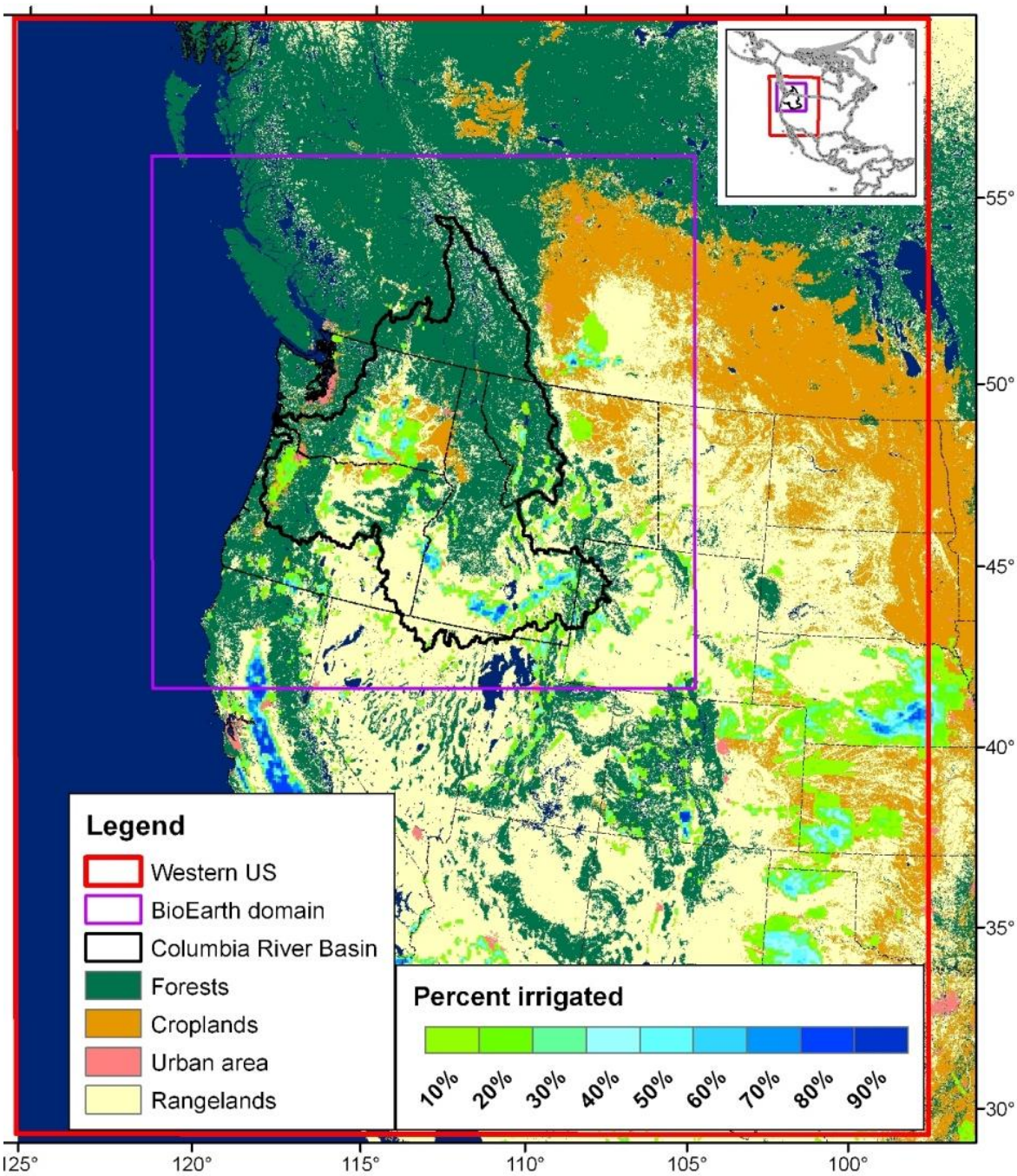

Fig. 1 Map of the BioEarth domain within the PNW region (purple rectangle) nested within the larger western U.S. domain (red rectangle) for physical atmospheric (WRF model) and land surface processes only. The economic and aquatic model components (streamflow routing, reservoirs, and nutrient export) are implemented only within the CRB (black outline). The land cover data are a combination of sources, including the 2011 USDA Cropland Data Layer and irrigation data from Ozdogan and Gutman (2008).

coastal areas and the Snake River Plain. The region has extensive and diverse agricultural lands interspersed with heavily populated urban areas and surrounded by largely untransformed ecosystems; these lands provide a vast array of agricultural and natural resources. Much of the diversity in resources is due to the large gradient in climate across the basin. Winter-dominated precipitation and cold winters result in large seasonal storage of water in the snowpack, providing a natural reservoir that supports summer water needs but that is vulnerable to warming (Mote et al. 2003). Storm patterns are closely tied to the jet stream position and sensitive to long-term circulation patterns, including the El Niño Southern Oscillation and the Pacific Decadal Oscillation. These climate patterns affect temperature (Mote et al. 2003), precipitation (Wang et al. 2009), ecosystem exchange (Wharton et al. 2009), and forest fire regimes (Kitzberger et al. 2007). The PNW is also influenced by long-range import of air pollutants from Asia (Jaffe et al. 1999). Global change is expected to impact ecosystems through warming, perturbations to precipitation patterns, changes in extreme meteorological events, and increased transport from Asian sources. Concurrent steady increases in human population are applying pressures on environmental quality with continued demand for environmental services. The sum of these effects presents a complex array of uncertainties to public decision-makers struggling to address all of these issues. The diversity of resources and complexity of issues in this region make it an ideal test-bed for the BioEarth framework for eventual application over other regions of the world.

3. The BioEarth Modeling Framework

3.1 Overview of Framework

The challenge of the BioEarth project is to develop a framework that can be used to understand and quantify the interactions between N, C, and H_2O dynamics, including their responses to changes in climatic characteristics, the socioeconomic environment, and resource management activities at spatio-temporal scales relevant for decision-making. An integrated system is necessary to comprehensively capture the impacts of a change, thereby uncovering unanticipated responses and feedbacks (Liu et al., 2007). The model is developed via integration of existing model components; by choosing among the most sophisticated models, the integrated modeling framework will continually improve as each component develops. Each of the stand-alone models within the framework is an open-source community model in continuous development, allowing the BioEarth framework to benefit from the model development efforts of the larger scientific community. This framework encompasses atmospheric, terrestrial, aquatic, and economic model components with varying levels of integration (Fig. 2). Regional economic

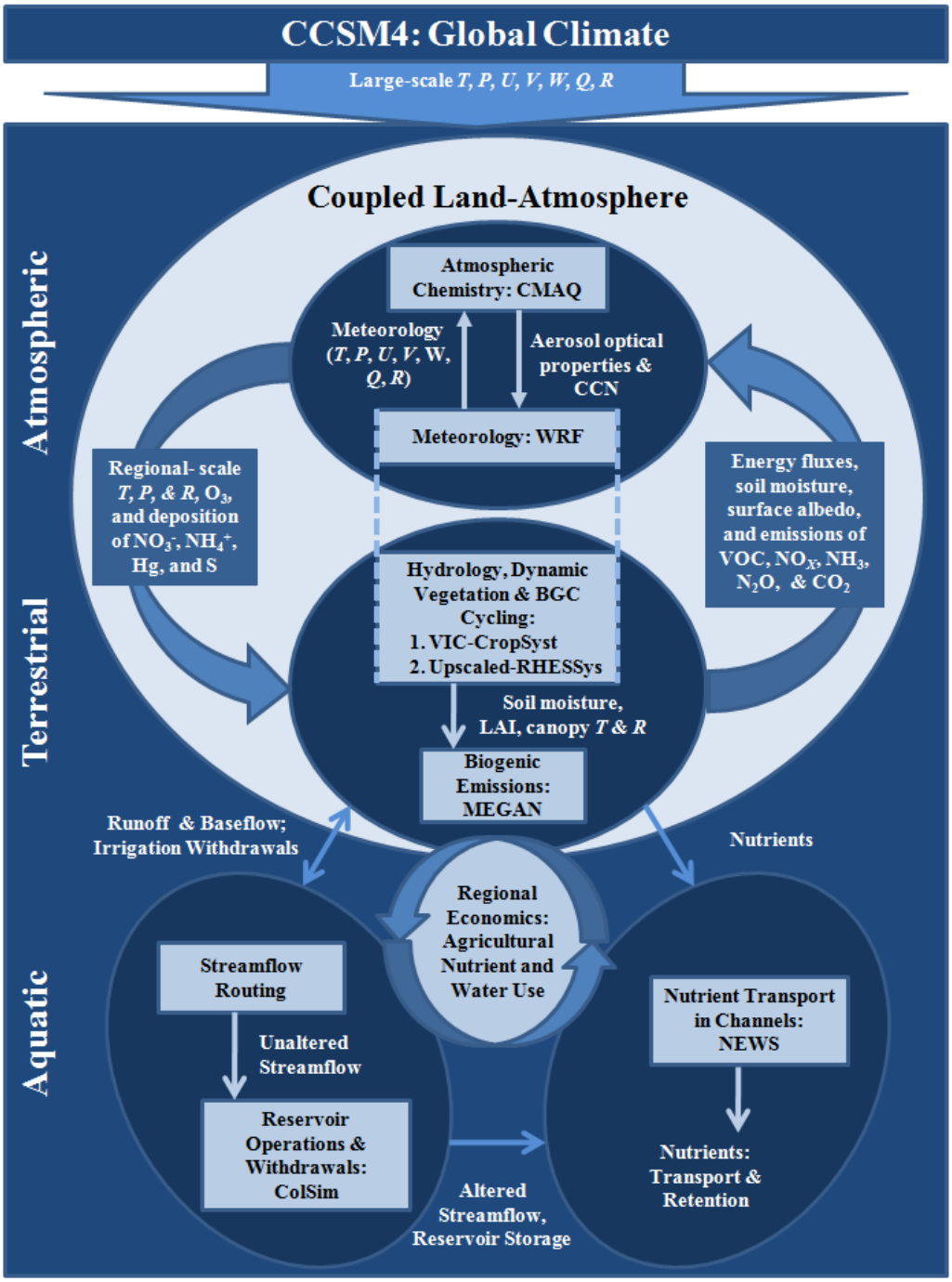

Fig. 2 Linkages between the atmospheric, terrestrial, aquatic, and economic components that comprise the BioEarth model. Descriptions of each of the stand-alone models are given in Table 1. Detailed here are some of the variables that are passed between stand-alone models: *T*=temperature, *P*=precipitation, *U*,*V*,*W*=wind speed components, *Q*=water mixing ratio, *R*=radiation, CCN=cloud condensation nuclei, O_3=ozone, NO_3^-=nitrate, NH_4^+=ammonium, Hg=mercury, S=sulfur, VOC=volatile organic compounds, NO_x=NO + NO_2=nitric oxide + nitrogen dioxide, NH_3=ammonia, N_2O=nitrous oxide, CO_2=carbon dioxide, LAI=leaf area index.

Table 1 Descriptions for each of the stand-alone models shown in Figure 2.

Earth System Component	Stand Alone Model	Key References
Global Climate: CCSM4	Community Climate System Model-4; Future WRF simulations are driven by archived CCSM4 output for the Intergovernmental Panel on Climate Change's Fifth Assessment Report.	(Gent et al. 2011)
Atmospheric Chemistry: CMAQ	The Community Multiscale Air Quality; CMAQ is a photochemical transport model that is used to simulate air quality and atmospheric deposition. The model accounts for chemical interactions for compounds in gas, aqueous, and aerosol phases and is driven by meteorology, which governs transport, deposition, and chemical reactions in the atmosphere. CMAQ is implemented over the PNW domain in Fig. 1.	(Byun and Schere 2006)
Meteorology : WRF	Weather Research and Forecasting; WRF is a mesoscale meteorological model that solves the Navier-Stokes equation for atmospheric dynamics and includes physics parameterizations to represent short- and long-wave radiation, planetary boundary layer, sub-grid eddy diffusion, convection, cloud microphysics, and land surface processes. WRF is implemented over the western U.S. domain (Fig. 1) at a spatial resolution of 12 km.	(Skamarock et al. 2008)
Macro-Scale Land Surface Hydrology: VIC	Variable Infiltration Capacity; VIC was developed for large-scale land-atmosphere interaction water quantity applications ($1/16^{th}$ - 2°), in which sub-grid variability is based on statistical relationships. VIC accounts for key moisture and energy fluxes between the land surface and the atmosphere. VIC is implemented over the western U.S. domain (Fig. 1) at a spatial resolution of 12 km.	(Liang et al. 1994)
Cropland Biogeochemistry and Dynamic Vegetation: CropSyst	Cropping Systems; CropSyst is a multi-crop model that simulates soil water budgets, nutrient budgets, C cycling, crop growth and yield, residue production, and other parameters under user-defined management options (including rotations, tillage, fertilization, and irrigation scheduling).	(Stockle et al. 2003)
Forest and Grassland Ecohydrology and Dynamic Vegetation: RHESSys	Regional Hydro-Ecologic Simulation System; RHESSys is a mechanistic catchment-scale model designed to simulate climate and land-use change impacts on ecosystem C and nutrient cycling and hydrology. RHESSys links well-established models of vegetation growth, nutrient uptake, and soil biogeochemistry with a fully-distributed hydrologic model that includes lateral surface and subsurface hydrologic connectivity. RHESSys also simulates resource competition between plant species, and plant mortality.	(Tague and Band 2004)
Biogenic Emissions: MEGAN	Model of Emissions of Gases and Aerosols from Nature; MEGAN is driven by land cover and environmental conditions supplied by WRF and the land surface models, and provides biogenic emissions as inputs to CMAQ.	(Guenther 2012)

Water Management: ColSim	Columbia River Simulation Model; ColSim considers the physical characteristics of the CRB water management system (reservoirs, run-of-river dams, diversions, and return flows) and its reservoir operating policies to generate reservoir rule curves as a function of operating policy. ColSim is adapted for BioEarth to include irrigation withdrawals and a water rights curtailment process.	(Hamlet and Lettenmaier 1999)
Nutrient Export in Rivers: NEWS	Nutrient Export from Water(S)heds; In BioEarth, NEWS takes as input simulated hydrologic and nutrient fluxes, and is utilized to predict annual average nutrient fluxes, sources, and sinks for various forms of nutrients and C at the sub-basin scale.	(Seitzinger et al. 2005)

analysis is linked to the terrestrial and aquatic components; the circular arrows in Figure 2 represent CHANS feedbacks. Exogenous to the BioEarth framework are water regulatory institutions and other environmental policies, the environmental and economic impacts and trade-offs of which can be quantified. Each of these stand-alone models is described in Table 1; economic models are described in §3.6.

3.2 Overview of Coupling and Integration Strategy

Varying levels of integration from one-way (a.k.a., “offline”) to two-way (a.k.a., “online” or “full”) coupling exist in the fully-developed BioEarth framework. The atmospheric and terrestrial models can either be linked offline or fully-coupled at 30- to 60-minute time-steps. Many of the other components of BioEarth are coupled at longer time-steps (e.g., water rights curtailment decisions occur weekly). The Kepler scientific workflow toolkit (kepler-project.org) is utilized for implementing and automating BioEarth workflows.

BioEarth has a modular framework and is designed such that only some of the components may be utilized for the specific research question under investigation. In determining which components to include, our goal is to match the level of model integration to the interconnectivity of the decision process under investigation. The level of integration needed for informing specific management activities is partially determined through feedback from our stakeholders (see §4). This approach minimizes model complexity and computational resources while still capturing key interactions. Furthermore, incorporating too much complexity (for a specific question) into an integrated model can have negative consequences. As an example, coupling a land surface model to an atmospheric model can result in large biases and reduced performance in informing management decisions, as compared to driving a land surface model with observed meteorology or with bias-corrected atmospheric model output (Liu et al., submitted). This loss of accuracy may prohibit a coupled model’s usefulness for specific management decisions. Regardless of the complexity of the model chosen for

each application, when a coupled model is used for informing decision-making, rigorous testing is required to evaluate model results and enhance the usability of model outputs.

3.3 Land-Atmosphere Coupling and Atmospheric Model Integration

WRF has several options for each physics component. For BioEarth, we include two additional land surface options for coupling to WRF to simulate land-atmosphere interactions: 1) VIC-CropSyst, and 2) Upscaled-RHESSys (see §3.4). We take advantage of the CESM flux coupler that facilitates coupling of earth system components to allow data exchange between WRF and the land surface models. This approach provides flexibility for the atmospheric and land surface models to be applied on their own grids and spatial resolutions. This is particularly important for coupling WRF to Upscaled-RHESSys which runs on variably-sized watershed units rather than grid-cell units. For coupling with an atmospheric model, VIC requires code restructuring to adopt a space-before-time data structure so that state variables for all grid-cells are updated before advancing to the next time step, which has been accomplished in other projects (Leung et al., 2011). The BioEarth project utilizes this modified version of VIC but with modifications and updates at the University of Washington through the Regional Arctic System Model (RASM) project (Maslowski et al. 2012).

For applications involving atmospheric chemistry, the CMAQ model can either be run offline from or fully-coupled to WRF. The fully coupled version accounts for radiative feedbacks between chemistry and physics by considering ozone effects on long-wave radiation and aerosol effects on both short- and long-wave radiation (Wong et al., 2012). For BioEarth, the CESM framework is adapted to pass hydrologic information to MEGAN to determine biogenic emissions needed by CMAQ.

3.4 Terrestrial Model Integration

The modular nature of the BioEarth framework allows users to apply the land surface model most appropriate for each research question. Two unique land surface models are in development for BioEarth: 1) VIC-CropSyst primarily for applications involving intensely-managed cropping systems, and 2) Upscaled-RHESSys primarily for applications involving less intensely-managed forest and rangeland ecosystems, but eventually with capabilities to handle cropping systems.

VIC and RHESSys were originally developed for different scales and applications. VIC was developed as a land surface model that can be used with atmospheric models and includes detailed process-based parameterizations for water and energy fluxes with the flexibility to run at sub-daily time-steps, both of which are necessary for atmospheric coupling (Liang et al., 1994). Like all macro-scale land surface models, VIC is coarse in its representation of lateral hydrologic processes. To reduce computation time and avoid

breaking model assumptions, grid-cells are necessarily large (~10^7-10^{10} m^2), and sub-grid heterogeneity in, e.g., land cover, elevation, saturated extent, and snow cover is represented implicitly in space through empirical relationships (Figure 3). Lateral fluxes are not specifically simulated within VIC while a post-process is available for streamflow routing. Conversely, while RHESSys is less detailed than VIC in representing vertical fluxes, it is highly detailed in space, capturing surface/subsurface lateral flow between neighboring patches (~10^1-10^4 m^2). In the following paragraphs, we describe the development of the two BioEarth land surface models which are based on VIC and RHESSys, with elements of CropSyst. While Upscaled-RHESSys simulations can be more computationally demanding than VIC-CropSyst, lateral flow and characterization of the complex structure of landscapes allows it to better capture the hydrologic connectivity that impact, e.g., ecological hot-spots in terms of coupled C:N:H_2O dynamics. In summary, VIC-CropSyst's strength lies in capturing land-atmosphere interactions, particularly as related to agricultural activities; Upscaled-RHESSys' strength lies in capturing hydro-ecological processes that are governed by fine-scale spatial heterogeneities and lateral hydrologic connectivity.

3.4.1 Development of VIC-CropSyst

In the integrated VIC-CropSyst model, CropSyst is embedded into VIC as a sub-model simulating vegetation dynamics and biogeochemistry, providing the model's capacity to investigate interactions between hydrology and agro-ecological systems. VIC simulates hydrologic processes with the exception of transpiration. It is improved to simulate crop-specific potential evapotranspiration; irrigation technology-specific evaporative losses; vertical drainage of moisture through tightly-spaced soil moisture layers; and humidity following irrigation. CropSyst models transpiration, crop yield, nutrient leaching, and greenhouse gas emissions, which are provided as inputs to the economic, atmospheric, and aquatic models.

Because of its coarse spatial resolution, VIC-CropSyst does not resolve individual farms, as specific crop types are represented implicitly as sub-grid classes within a grid-cell; i.e., within each grid-cell, a particular crop is assigned a percentage of the grid-cell area and its location and extent are treated as non-spatial elements (Figure 3). Modeled variables are often aggregated over the sub-grids to produce a grid-cell average prior to subsequent analysis. In terms of decision support, VIC-CropSyst's strength lies in producing information as to the broader implications of widespread changes in irrigation, fertilization, or crop management decisions; in addition to being a powerful tool for large-scale studies of land-atmosphere interactions.

3.4.2 Development of Upscaled-RHESSys

Upscaled-RHESSys includes several additional developments for inclusion in the BioEarth framework.

1) RHESSys is modified to better represent biogeochemical processes occurring in rangeland and cultivated cropping systems through an integrated C allocation scheme taking into account both resource limitation and plant growth, dynamic C:N ratios in leaves, inclusion of a C and N pool that represents the regenerative (or harvested) portion of the crop, biomass removal mechanisms related to harvesting and grazing, and other additional capabilities to simulate hydro-ecological responses to forest, rangeland, and cropping systems management.

2) To couple RHESSys as a land surface sub-model to WRF, it is adapted to run at the same temporal scale as WRF, and its full energy budget is refined to simulate subsurface thermodynamics, radiation transfer through the canopy, and energy balance-driven snow processes.

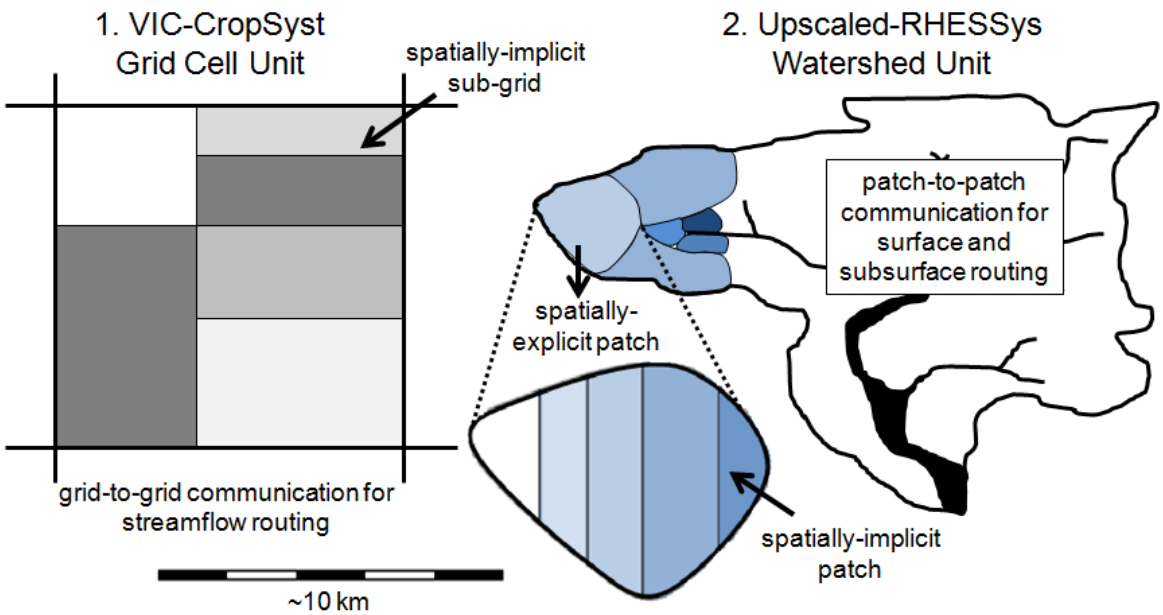

Fig. 3. Comparison of the Upscaled-RHESSys watershed unit to the VIC-CropSyst grid-cell unit. The Upscaled-RHESSys approach is considered "bottom-up" because its native spatial resolution is high; fine-resolution spatial heterogeneities are more fully captured than VIC because the watershed units are comprised of fine-resolution spatially-explicit patches, which are in turn comprised of spatially-implicit or "aspatial" patches. The sizes of the explicit and implicit patches within Upscaled-RHESSys are determined through model sensitivity experiments across biomes. Alternatively, the VIC-CropSyst approach is considered "top-down" because VIC was originally developed for global-scale applications at relatively coarse resolutions. VIC grid-cells should not be implemented at resolutions typically implemented by RHESSys because lateral hydrologic connectivity does not exist between cells.

3) To reduce compute time, RHESSys is adapted to allow for larger patch sizes by incorporating within-patch heterogeneity through non-spatial elements analogous to VIC

sub-grids (i.e., "embedded aspatial patches"). Therefore, we combine aspatial approaches used in hydrologic models such as VIC with explicit hydrologic routing approaches used in models such as the Distributed Hydrology Soil-Vegetation Model (DHSVM; Wigmosta et al., 1994). We argue that this approach will be substantially more efficient but will still allow users to represent differences that arise due to lateral connectivity and spatial heterogeneity in watershed hydrology and ecosystem dynamics. Figure 3 illustrates the differences between Upscaled-RHESSys watershed units and the VIC-CropSyst grid-cell units.

3.5 Aquatic Model Integration

The water resources of the CRB are heavily managed and this human alteration of the hydrologic cycle needs to be considered to better estimate seasonal available water supply. We take a two-pronged approach involving 1) an offline reservoir model (ColSim) that has detailed information on reservoir operating rules and, 2) a generic store-and-release algorithm that can be fully-coupled with the hydrologic model. The generic algorithm will estimate storage and releases either based on time-series results from the offline reservoir model or on empirical calculations similar to Voisin et al. (2013) or Biemans et al. (2011). This two-pronged approach gives the flexibility of choosing the framework best suited to a specific question.

NEWS sub-models have been successfully applied at sub-basin spatial scales (e.g., Harrison et al., 2010) for various forms of C and nutrients. In BioEarth, NEWS is utilized and evaluated for sub-basins within the CRB to predict seasonal fluxes, sources, and sinks for various forms (inorganic/organic, particulate/dissolved) of N and C. NEWS takes as input simulated hydrologic and N fluxes from the terrestrial models, meteorological information from WRF, and water storage from the reservoir model.

3.6 Economic Model Integration

The purpose of integrating economic models into mechanistic biophysical models is to base human action and their influences on biogeochemical cycles (e.g., from land use, nutrient loading, and irrigation) on microeconomic foundations rather than on arbitrary rules (Harou, et al., 2009). A two-pronged approach is taken to model economic behavior by utilizing 1) a CGE model of the regional economy and 2) an ABM. While both work from a foundation of economically-optimizing decision-makers, they differ significantly in terms of temporal/spatial disaggregation and model structure. The CGE and ABM models are run separately but are integrated on annual time-steps. Multiple groups have applied CGE modeling of regional economies to represent agricultural production (for a review, see Harou et al. 2009). CGE modeling is suited for capturing the complex array of possible economic responses to changing conditions, including

input/output substitution and investment. Hydrologic models inform water availability, and crop growth models are used to parameterize crop production functions for varying levels of deficit irrigation under a range of atmospheric conditions. Input use determined by the CGE model defines the timing of water use and other inputs, including fertilizers that can be fed back into other models. Sub-regions are differentiated by their parameterization and constraints, which is usually important for representing production in irrigated agriculture where water is a limiting resource.

In many instances the lack of spatial resolution in CGE models becomes problematic. While the development of sub-regions within the regional CGE model can account for spatial heterogeneity in growing conditions and resource constraints, they usually involve a significant level of spatial aggregation and are ill-suited towards modeling spatially-dependent decision-making. This is an important limitation because of the extensive spatial interactions that result from moving water around in time and space as a result of farm-level adaptation, water transfers, or any other changes in water management. This weakness provides the motivation for the development of an ABM to represent economic decision-making.

ABM allows for improved modeling of nutrient use and water quality impacts by more precisely locating each agent in space relative to water systems; and it is possible to separate the region of study into grid-cells that match those of the biophysical models. This allows for full coupling between human and environmental models. Adoption of approaches like ABM among economists remains small relative to more accepted economic modeling frameworks because they typically require a more simplistic representation of economic decision-making. However, they are becoming more common as recognition of the importance of spatial interactions has grown (Irwin 2010). Increased funding for interdisciplinary research and computing power are also encouraging increased use of ABM. Literature in computational finance (LeBaron 2000) and in analyzing collective action problems (Berger et al. 2007) also demonstrates increased value of the ABM approach.

4. Stakeholder Engagement Process and Communication Research

Earth system modelers and other earth scientists are now more than ever asked to consider not only the scientific credibility and adequacy of their work, but also its salience to the needs of the public and its legitimacy among stakeholders beyond their scientific peers (Cash et al. 2003). Creating more opportunities for interactions among scientists and potential users of climate information is an approach to produce scientific information that is also actionable. In response, EaSM research initiatives have begun to explicitly integrate novel approaches for stakeholder engagement into the modeling process. This is often conceptualized as merely communication of research results after a project is completed (Green et al. 2009). Increasingly, the value of engaging with

stakeholders during the process of knowledge production is recognized, but such engagement is limited in practice (Callon 1999, Phillipson et al. 2012).

The project's communication research and extension team provides multiple vital functions including being responsible for the coordination and implementation of stakeholder engagement throughout the duration of the project by facilitating interactive communication between the model developers and non-academic practitioners. In addition, this team is conducting communication research to improve understanding of interactions among stakeholders and model developers. Through surveys and interviews, the communication research component of the project is documenting and analyzing stakeholders' and scientists' perceptions over the course of the project concerning their respective roles in model development and application (Allen et al. 2013).

4.1 Design and Implementation of Interactive Communication

For stakeholders to be engaged in the model development process, opportunities for stakeholders to influence the research questions addressed within model development must be created, and communication between researchers and stakeholders must be bi-directional. A series of stakeholder advisory workshops are occurring during the second and third years of the project, focusing on management issues of critical concern to the region including N and C management, water availability, water quality, forest and rangeland management, and air quality. Individuals who could benefit from using model results to inform their decision-making are the project's targeted stakeholders. These individuals include representatives from industry, government agencies (federal, state, local and tribal), environmental organizations, and other advocacy organizations. Stakeholder advisory workshops organized around specific resource management issues are designed to allow for in-depth discussion of stakeholders' issue-specific information needs and preferences for how model outputs, complexity, and uncertainty might be best communicated. During the final two years of the project, an additional set of larger stakeholder meetings are planned to expand awareness and understanding of the potential relevance and utility of the model to a wider audience of resource managers and policy makers.

The goals of the stakeholder advisory meetings are multiple:

1. Elicit stakeholders' insights and perspectives to inform potential mitigation and adaptation strategies and scenarios that could be explored by using the integrated model.

2. Communicate the potential value and utility of the model to stakeholders and provide them with an enhanced understanding of the model development process, complexity, and uncertainty of outputs.

3. Establish positive, productive relationships and enhance mutual understanding between a broad range of stakeholders and the modeling team.

4. Increase researchers' understanding of the factors driving resource management decisions and the information needs of decision-makers, and help the modeling team understand how stakeholders prioritize various environmental and economic concerns.

4.2 Communications Research: An Integral part of BioEarth

In addition to facilitating communication among modelers and stakeholders, the communication team is analyzing the perceptions and understandings of stakeholders and scientists throughout the research process using surveys and interviews. The evolution of perceptions of these individuals regarding the stakeholder engagement process and of the utility and relevance of the model to decision-making is tracked throughout the five-year project.

As stakeholder engagement in environmental modeling is increasingly expected by funding agencies, understanding the range of perceptions on the value of stakeholder engagement can help facilitate productive interactions. Acknowledging this, the BioEarth communications research team began with analysis of the scientists' perspectives on stakeholder engagement during the first year of the project (Allen et al. 2013). Results demonstrate a broad range of perceptions about the value of the stakeholder engagement process and varying expectations for the production of decision-relevant information within BioEarth. Researchers who anticipate the model to be relevant to policy decision-making rank communication with stakeholders as a central challenge in the project, while those researchers who are thinking about the model as something primarily relevant to academic audiences tend to focus on technical challenges associated with model integration rather than the model's practical or social relevance. The communications team is continuing to conduct surveys and interviews with researchers and stakeholders to understand their perspectives on model development and the stakeholder engagement process.

5. The Way Forward for BioEarth

One goal of the BioEarth project is to move an integrated modeling project along the continuum from generating primarily scientific knowledge to *also* producing actionable information that can inform decision-making. Because of its high degree of integration, BioEarth's strength is in providing a fuller context of land use decision-making at the regional scale. The BioEarth framework can highlight environmental and economic trade-offs among different management scenarios to inform a variety of decision-makers with different priorities, concerns, and constraints.

BioEarth has several unique aspects that enable movement along this continuum. It is designed as modular and flexible framework, enabling the degree of model integration to match the decision process under investigation. Throughout the project period, we engage

non-academic stakeholders to inform model design and development, and we perform communications research to analyze both stakeholders' and model developers' perceptions on the usefulness of the model development and its output. In addition, BioEarth can be viewed as one attempt to operationalize the notion of projection rather than prediction. A challenge associated with utilizing models to inform decisions in a future climate is in predicting future conditions. While improvements toward enhanced predictability is important, environmental modeling communities are embarking on a paradigm shift in the purpose and intent of models, moving from the conventional view of "predict then act" to a more nuanced view of "seeking robust solutions" (Weaver et al. 2013). This paradigm shift represents an acceptance of the compounding uncertainties associated with the interconnected complexities of earth system change and the unpredictability of how humans will respond to these changes. Modelers increasingly acknowledge that, rather than predicting the future, models are valuable in providing information about different future scenarios (or projections) as a way to assess vulnerabilities (Lempert 2012). Finally, the social and technical learning anticipated from this project involves broad potential for contributing and reinforcing the nascent paradigm shift in expectations for environmental modeling with regard to relevance and utility of the modeling process. Lessons learned from researchers and stakeholders involved in BioEarth could be useful for other environmental modeling projects.

The BioEarth project is currently halfway through its initial five-year funding period, by the end of which our goal is to have a rigorously-tested framework that includes the primary linkages between model components; a foundation that we can continue to build on over time. Some achievements to date include development of a detailed land cover dataset to be used for all component models; design of a tool for building and automating modular workflows; development, implementation, and testing of WRF-VIC; implementation and operationalization of CMAQ; completion, testing and application of the VIC-CropSyst integrated model; refinement, development, and initial upscaling of RHESSys over forested and grassland ecosystems; application of the NEWS dissolved inorganic nitrogen model by driving it with output from BioEarth's terrestrial models; initial implementation of the CGE model using crop response curves generated by VIC-CropSyst; completion of the initial survey of scientists' perceptions on stakeholder engagement; and completion of the first two stakeholder workshops, with outputs that are informing further model development and scenarios. Multiple model integration challenges remain to be solved before the foundation for this framework is complete, although enough of this modular framework already exists that we have begun implementing specific applications and running scenarios, the outputs of which are being provided to our stakeholder advisory group for feedback.

Our intent is that the BioEarth project will continue to evolve over the long term, increasing its generation of both scientific knowledge and actionable information. We

continue to extend our collaboration network and seek additional funds to incorporate missing processes (such as deep groundwater dynamics, fire behavior, or biotic disturbance) and to apply and rigorously test the model for specific applications. As BioEarth is composed primarily of mechanistic models, it can be readily applied in other regions and will be a powerful tool for exploring the water-energy-food-climate nexus. The BioEarth framework is flexible in that it can accommodate highly detailed information only available in specific regions (such as water rights, instream flow rules, and reservoir operations) or it can use simplified rules where this information is not available, lending itself well to application in developing countries. Finally, the stakeholder advisory process is evolving. The multiplicity of decisions that are relevant to the model scope complicate this process, and we are continuing to develop ways to learn from our stakeholder advisors to improve the model as well as communication about the model output, complexity, and uncertainty.

Acknowledgments This research is funded from the Department of Agriculture, National Institute of Food and Agriculture grant number 2011-67003-30346. Funding for Dr. Nijssen's contribution to this project is from the Regional Arctic Systems Model (RASM) through Department of Energy grant number DE-SC0006856. The authors would like to thank our peer reviewers and our stakeholders who have contributed invaluable insights to the BioEarth Project. Finally, we thank three anonymous reviewers whose comments helped to improve this manuscript.

References

Allen, E., Kruger, C., Leung, F.-Y., Stephens, J.C., 2013. Diverse Perceptions of Stakeholder Engagement within an Environmental Modeling Research Team. J. Environ. Stud. Sci. 3, 343–356.

Berger, T., Birner, R., Díaz, J., McCarthy, N., Wittmer, H., 2007. Capturing the complexity of water uses and water users within a multi-agent framework, in: Craswell, E., Bonnell, M., Bossio, D., Demuth, S., Giesen, N.V.D. (Eds.), Integrated Assessment of Water Resources and Global Change. Springer Netherlands, pp. 129–148.

Biemans, H., Haddeland, I., Kabat, P., Ludwig, F., Hutjes, R.W.A., Heinke, J., von Bloh, W., Gerten, D., 2011. Impact of reservoirs on river discharge and irrigation water supply during the 20th century. Water Resour. Res. 47, *W03509, doi:10.1029/2009WR008929.*

Byun, D., Schere, K.L., 2006. Review of the Governing Equations, Computational Algorithms, and Other Components of the Models-3 Community Multiscale Air Quality (CMAQ) Modeling System. Appl. Mech. Rev. 59, 51–77.

Callon, M., 1999. The Role of Lay People in the Production and Dissemination of Scientific Knowledge. Sci. Technol. Soc. 4, 81–94.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. 100, 8086–8091.

Drewniak, B., Song, J., Prell, J., Kotamarthi, V.R., Jacob, R., 2013. Modeling agriculture in the Community Land Model. Geosci. Model Dev. 6, 495–515.

Dumont, E., Harrison, J.A., Kroeze, C., Bakker, E.J., Seitzinger, S.P., 2005. Global distribution and sources of dissolved inorganic nitrogen export to the coastal zone: Results from a spatially explicit, global model. Glob. Biogeochem. Cycles 19, *GB4S02, doi:10.1029/2005GB002488.*

Gent, P.R., Danabasoglu, G., Donner, L.J., Holland, M.M., Hunke, E.C., Jayne, S.R., Lawrence, D.M., Neale, R.B., Rasch, P.J., Vertenstein, M., Worley, P.H., Yang, Z.-L., Zhang, M., 2011. The Community Climate System Model Version 4. J. Clim. 24, 4973–4991.

Giorgi, F., 1995. Perspectives for regional earth system modeling. Glob. Planet. Change 10, 23–42.

Green, L.W., Glasgow, R.E., Atkins, D., Stange, K., 2009. Making Evidence from Research More Relevant, Useful, and Actionable in Policy, Program Planning, and Practice: Slips "Twixt Cup and Lip". Am. J. Prev. Med. 37, S187–S191.

Guenther, A.B., Jiang, X., Heald, C.L., Sakulyanontvittaya, T., Duhl, T., Emmons, L.K., Wang, X., 2012. The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions. Geosci. Model Dev. 5, 1471–1492.

Hamlet, A.F., Lettenmaier, D.P., 1999. Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin1. JAWRA J. Am. Water Resour. Assoc. 35, 1597–1623.

Harou, J.J., Pulido-Velazquez, M., Rosenberg, D.E., Medellín-Azuara, J., Lund, J.R., Howitt, R.E., 2009. Hydro-economic models: Concepts, design, applications, and future prospects. J. Hydrol. 375, 627–643.

Harrison, J.A., Bouwman, A.F., Mayorga, E., Seitzinger, S., 2010. Magnitudes and sources of dissolved inorganic phosphorus inputs to surface fresh waters and the coastal zone: A new global model. Glob. Biogeochem. Cycles 24, GB1003, doi:10.1029/2009GB003590.

Irwin, E.G., 2010. New Directions for Urban Economic Models of Land Use Change: Incorporating Spatial Dynamics and Heterogeneity. J. Reg. Sci. 50, 65–91.

Jaffe, D., Anderson, T., Covert, D., Kotchenruther, R., Trost, B., Danielson, J., Simpson, W., Berntsen, T., Karlsdottir, S., Blake, D., Harris, J., Carmichael, G., Uno, I., 1999. Transport of Asian air pollution to North America. Geophys. Res. Lett. 26, 711–714.

Kampe, T.U., Johnson, B.R., Kuester, M., Keller, M., 2010. NEON: the first continental-scale ecological observatory with airborne remote sensing of vegetation canopy biochemistry and structure. J. Appl. Remote Sens. 4, 043510–043510–24.

Katz, R.W., Brown, B.G., 1992. Extreme events in a changing climate: Variability is more important than averages. Clim. Change 21, 289–302.

Kitzberger, T., Brown, P.M., Heyerdahl, E.K., Swetnam, T.W., Veblen, T.T., 2007. Contingent Pacific–Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proc. Natl. Acad. Sci. 104, 543–548.

Lamarque, J.-F., Emmons, L.K., Hess, P.G., Kinnison, D.E., Tilmes, S., Vitt, F., Heald, C.L., Holland, E.A., Lauritzen, P.H., Neu, J., Orlando, J.J., Rasch, P.J., Tyndall, G.K., 2012.

CAM-chem: description and evaluation of interactive atmospheric chemistry in the Community Earth System Model. Geosci. Model Dev. 5, 369–411.

Lawrence, D.M., Oleson, K.W., Flanner, M.G., Thornton, P.E., Swenson, S.C., Lawrence, P.J., Zeng, X., Yang, Z.-L., Levis, S., Sakaguchi, K., Bonan, G.B., Slater, A.G., 2011. Parameterization improvements and functional and structural advances in Version 4 of the Community Land Model. J. Adv. Model. Earth Syst. 3.

LeBaron, B., n.d. Agent-Based Computational Finance: Suggested Readings and Early Research (SSRN Scholarly Paper No. ID 224048). Social Science Research Network, Rochester, NY.

Lemos, M.C., Kirchhoff, C.J., Ramprasad, V., 2012. Narrowing the climate information usability gap. Nat. Clim. Change 2, 789–794.

Lempert, R., 2013. Scenarios that illuminate vulnerabilities and robust responses. Clim. Change 117, 627–646.

Leung, L.R., Huang, M., Qian, Y., Liang, X., 2011. Climate–soil–vegetation control on groundwater table dynamics and its feedbacks in a climate model. Clim. Dyn. 36, 57–81.

Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J. Geophys. Res. Atmospheres 99, 14415–14428.

Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., Taylor, W.W., 2007. Complexity of Coupled Human and Natural Systems. Science 317, 1513–1516.

Maslowski, W., Clement Kinney, J., Higgins, M., Roberts, A., 2012. The Future of Arctic Sea Ice. Annu. Rev. Earth Planet. Sci. 40, 625–654.

Mote, P.W., Parson, E.A., Hamlet, A.F., Keeton, W.S., Lettenmaier, D., Mantua, N., Miles, E.L., Peterson, D.W., Peterson, D.L., Slaughter, R., Snover, A.K., 2003. Preparing for Climatic Change: The Water, Salmon, and Forests of the Pacific Northwest. Clim. Change 61, 45–88.

Phillipson, J., Lowe, P., Proctor, A., Ruto, E., 2012. Stakeholder engagement and knowledge exchange in environmental research. J. Environ. Manage. 95, 56–65.

Reid, W.V., Chen, D., Goldfarb, L., Hackmann, H., Lee, Y.T., Mokhele, K., Ostrom, E., Raivio, K., Rockström, J., Schellnhuber, H.J., Whyte, A., 2010. Earth System Science for Global Sustainability: Grand Challenges. Science 330, 916–917.

Rowan, T.S.C., Maier, H.R., Connor, J., Dandy, G.C., 2011. An integrated dynamic modeling framework for investigating the impact of climate change and variability on irrigated agriculture. Water Resour. Res. 47 *7, W07520, doi:10.1029/2010WR010195.*

Skamarock, W.C., Klemp, J., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X.-Y., Wang, W., Powers, J., 2008. A Description of the Advanced Research WRF Version 3. .NCAR Tech. Note TN- 475_STR, 113 pp

Smith, M.S., Horrocks, L., Harvey, A., Hamilton, C., 2011. Rethinking adaptation for a 4°C world. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 369, 196–216.

Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18, 289–307.

Tague, C.L., Band, L.E., 2004. RHESSys: Regional Hydro-Ecologic Simulation System—An Object-Oriented Approach to Spatially Distributed Modeling of Carbon, Water, and Nutrient Cycling. Earth Interactions 8, 1–42.

Voisin, N., Li, H., Ward, D., Huang, M., Wigmosta, M., Leung, L.R., 2013. On an improved sub-regional water resources management representation for integration into earth system models. Hydrol. Earth Syst. Sci. Discuss. 10, 3501–3540.

Wang, S.-Y., Gillies, R.R., Jin, J., Hipps, L.E., 2009. Recent rainfall cycle in the Intermountain Region as a quadrature amplitude modulation from the Pacific decadal oscillation. Geophys. Res. Lett. 36, *L02705, doi:10.1029/2008GL036329.*

Washington, W.M., Buja, L., Craig, A., 2009. The computational future for climate and Earth system models: on the path to petaflop and beyond. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 367, 833–846.

Weaver, C.P., Lempert, R.J., Brown, C., Hall, J.A., Revell, D., Sarewitz, D., 2013. Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks. Wiley Interdiscip. Rev. Clim. Change 4, 39–60.

Wharton, S., Chasmer, L., Falk, M., Paw U, K.T., 2009. Strong links between teleconnections and ecosystem exchange found at a Pacific Northwest old-growth forest from flux tower and MODIS EVI data. Glob. Change Biol. 15, 2187–2205.

Wigmosta, M.S., Vail, L.W., Lettenmaier, D.P., 1994. A distributed hydrology-vegetation model for complex terrain. Water Resour. Res. 30, 1665–1679.

Wong, D.C., Pleim, J., Mathur, R., Binkowski, F., Otte, T., Gilliam, R., Pouliot, G., Xiu, A., Young, J.O., Kang, D., 2012. WRF-CMAQ two-way coupled system with aerosol feedback: software development and preliminary results. Geosci. Model Dev. 5, 299–312.