CarMan: Next-Generation Carbon Management Analysis

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1 Introduction

The concentration of atmospheric carbon dioxide (CO_2) will continue to increase in the 21st century unless there are drastic changes in the way we produce and use energy—specifically the way we manage carbon. Although the effects of rising atmospheric CO_2 concentration on the global climate are uncertain, many scientists agree that a doubling of the concentration could have serious adverse effects. Consistent national and international strategies that will reduce net CO_2 emissions are needed to stem these effects. In general, these strategies, and the policies implementing them, will need to recognize the complex and interwoven linkages among the technological, economic, and biophysical components of what has been referred to as "carbon management". Specifically, solutions are needed that will reduce emissions without damaging economic well-being or creating new environmental problems. Studies suggest that such solutions are achievable, but that considerable understanding and evaluation is needed to identify effective groups of technologies, or technology portfolios (DOE, 1997a,b, 1999). Accordingly, we are developing an advanced science-based analytical system (CarMan) that will provide for the comprehensive analysis of proposed carbon management technologies and policies, including carbon sequestration.

Carbon management is the management of carbon in the production and utilization of energy and management of the global carbon cycle to reduce *net* anthropogenic emissions of carbon-based greenhouse gases (e.g., CO_2 and methane). The complexity of the carbon management problem is illustrated by Figure 1. It involves multiple perspectives and interactions among diverse components of several different systems (including global biogeochemistry and international economics). To adequately evaluate the effectiveness of multiple CO_2-reduction options within such a complex physical, economic and social environment requires a tool, a model, to evaluate and optimize the operation of each element of the system. The model and the analysis must consider how each element could be influenced by economic, environmental, and social variables with varying degrees of uncertainty and risk. The linkages between elements of the carbon management problem are many and complex, and actions in any sector can be expected to have implications for many others. Integrated assessment modeling

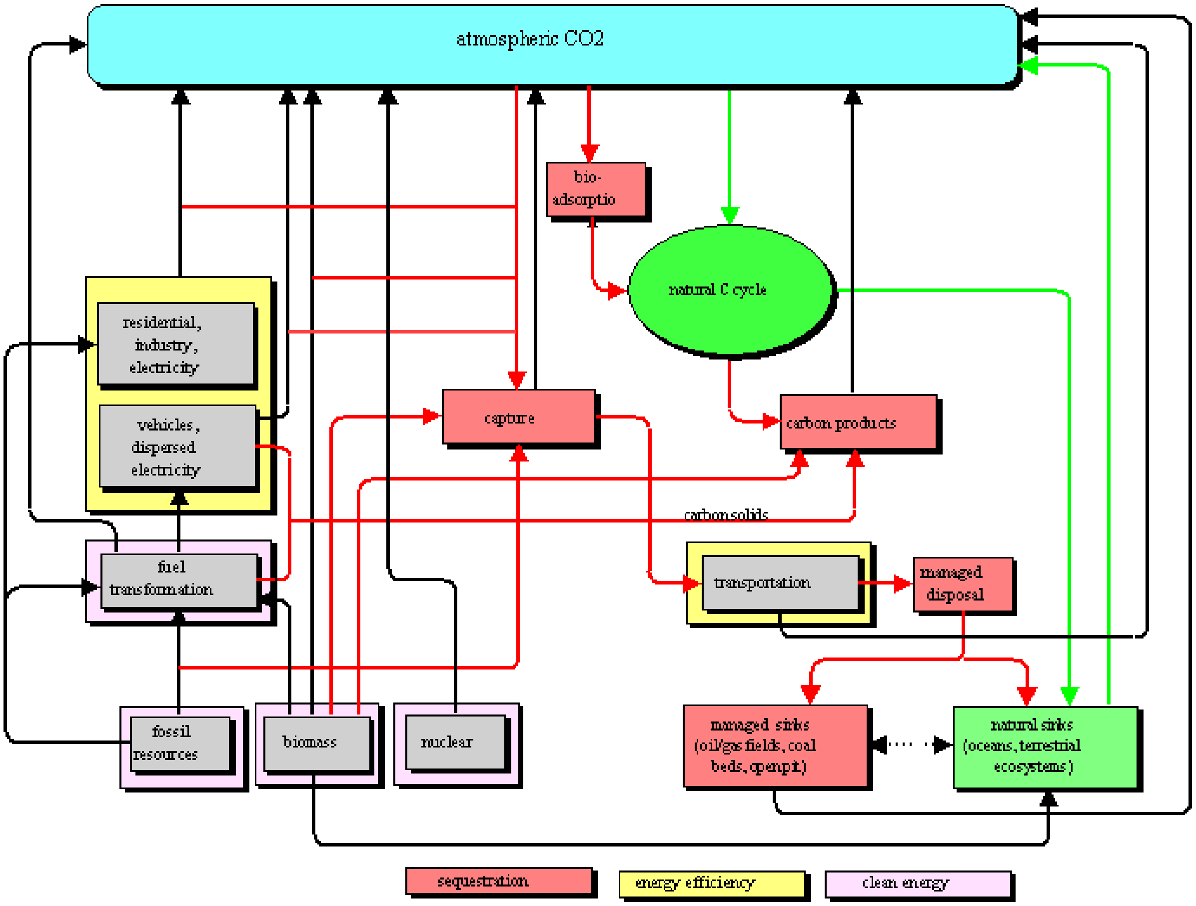

Figure 1: One representation of the complexity of the carbon management problem. Note that this diagram does not include the additional complication of linkages with the economic sector of carbon management.

(Weyant et al., 1996) addresses comparable issues and challenges, and carbon management analysis can fruitfully be considered a specialized application of integrated assessment.

Because carbon management is complex and inherently multidisciplinary, science "gaps" are pervasive in existing approaches for evaluating options to reduce CO_2 emissions (i.e., the *thoroughness* criteria proposed by the National Energy Technology Laboratory). These "gaps" seem to occur most frequently at the interfaces between disciplines and between systems and subsystems, in the feedbacks among diverse elements, and between elements operating and modeled at different time and space scales. We found that none of the 22 analytical approaches to carbon emissions cited by the Intergovernmental Panel on Climate Change (IPCC) and the National Research Council (NRC) meets the basic requirements of a science-based carbon-management analysis system (Houghton et al., 1995; NRC, 1999). For example, carbon emission-economic analysis approaches often have little or no analytical capability at national scales (using coarse geographical regions instead). Many approaches have little or no ability to evaluate the effects of emission reductions on most ecological or geophysical systems. Furthermore, many approaches use overly simplified science calculations, base their carbon emission projections on limited greenhouse gas emission scenarios, and do not incorporate adequate representation of carbon flows within their analytical structure (Schellnhuber, 1997).

In the past 15 years, knowledge of the global carbon fluxes and the processes regulating atmospheric CO_2 concentrations has expanded (Sarmiento and Bender, 1994; Schimel, 1995; CCSP, 1999). Nevertheless, serious deficiencies remain in understanding how the global carbon cycle fits into carbon management (Houghton et al., 1995). Understanding of the large-scale exchange of carbon between the atmosphere and terrestrial ecosystems, for example, is incomplete. There is a need to know how carbon sequestration in vegetation and soils can serve as a carbon management strategy (Lal et al., 1998; Rosenberg et al., 1999). Similarly, the basic mechanisms of long-term carbon storage in oceans and geological formations are not well understood (Holloway, 1997; Brewer et al., 1999). Current best understanding of the carbon cycle needs to be integrated with energy, technology, and economic facets of carbon management in a consistent fashion and in a functional analytical framework (DOE, 1999).

Current integrated assessment models frequently incorporate climate and global carbon cycle models developed by the earth science/biogeochemical community during the 1980s and early 1990s. Transfer of the consensus understanding of the earth system captured by those models from the earth science community to the integrated assessment community is appropriate and useful. However, we are now experiencing the conception and gestation of a second wave of knowledge and model transfer. One in which newer, more complicated and sophisticated earth system models (including atmospheric general circulation models and coupled ocean-atmosphere-terrestrial carbon cycle models) will be integrated into the next generation of carbon management and integrated assessment models.

Jae Edmonds (Pacific Northwest National Laboratory), who developed two widely used integrated assessment models, maintains that carbon management should be treated as a risk management problem and should provide uncertainty estimates for all calculated parameters (Jae Edmonds, personal communication, 2000) He and others believe that, without such estimates, making decisions about appropriate technologies will be problematic. Edmonds also believes that development and inclusion of a complete, balanced carbon cycle (including natural fluxes and industrial fluxes) in an analytical framework is critical to developing scientifically credible projections and full life-cycle analyses of multiple CO_2-reduction technologies (Jae Edmonds, personal communication, 2000).

There is no single pathway to achieve CO_2-emission reductions of the required magnitude in an appropriate timeframe (e.g., by 2100). Moreover, large present and future uncertainties in the effectiveness, costs, and risks of proposed technologies and pathways make it imprudent to place all "eggs" into a single or limited technology "basket". Portfolios of technologies, pathways, and policies will be required. Consequently, technology portfolio analysis is needed as part of carbon management analysis. Portfolio analysis has been identified as a pressing need by major Department of Energy (DOE) National Laboratory reports on carbon management (DOE, 1997a,b, 1999; IWG-EECET, 2000).

2 Objective

From our review of carbon management science and discussions with those involved in carbon management analysis and integrated assessment, we have identified three critical or priority areas requiring additional research and development. These areas are: (1) a complete accounting of carbon dynamics within the natural and industrial carbon cycle, including explicit representation of carbon sequestration in global carbon cycle models; (2) a life-cycle-based risk management framework for identifying and evaluating portfolios of technologies to achieve carbon management goals, and (3) error and uncertainty analysis of biophysical, technological, and economic components of the analysis.

These three areas of research form the core of our ongoing activity to contribute to the development of the next generation of carbon management analysis. In this paper we describe our approach to achieving these objectives, briefly report on our progress to date, and point towards future activities.

3 Approach

3.1 Carbon Cycle Modeling

It is widely recognized that representations of the carbon cycle in existing integrated assessments of carbon management are highly simplified. Simplified carbon cycle calculations are sometimes justified as a compromise with computational demands (e.g., Wigley, 1993), but the risk of oversimplifying the carbon cycle introduces uncertainty and a potential source of error into carbon management analysis. In any case, the increasing availability of high-performance computational resources at the DOE National Laboratories provides a means of overcoming this constraint.

Oversimplified representations of terrestrial ecosystem sources and sinks and land-use (deforestation) emissions are of special concern. A recent Energy Modeling Form (EMF) energy model intercomparison concluded, for example, that differences in the representation of terrestrial sinks and land-use (deforestation) emissions contributed to differences in the emission pathways needed to achieve a 550 ppmv stabilization target (Halsnaes et al., 1999).

The simplified carbon cycle models in extant carbon management analyses are particularly limited for extensive consideration of carbon sequestration technologies. For example, the carbon cycle model (Wigley, 1993) in MAGICC (Hulme et al., 2000) used by MiniCAM (Edmonds et al., 1994; Scott et al., 1999), ESCAPE (Hulme et al., 1995) and others (e.g., Riahi and Roehrl, 2000) describes net primary production (NPP) and CO_2 fertilization of terrestrial vegetation with a simple rectangular hyperbolic form. Future net land-use emissions are specified by IPCC scenarios (and thus cannot respond to changes in land-use as a part of carbon management). Oceanic uptake is determined using the convolution integral representation of the Maier-Reimer and Hasselman (1987) ocean general circulation carbon cycle model (and hence cannot represent residence time and leakage of CO_2 injected into the deep ocean). The carbon cycle model is globally aggregated and does not reflect geographical variation in response to changing climate and rising atmospheric CO_2. These simplifications do not represent current best understanding of the global carbon cycle, and they limit the ability of the model to represent carbon sequestration technologies. The next generation of carbon management analyses will require improved process-based representations of the carbon cycle (CCSP, 1999; Post et al., 1999). We are working to develop this improved carbon cycle for carbon management, and to thus fill one of the big science "gaps" in carbon management analysis.

Our first step towards a carbon cycle for carbon management analysis is to implement a terrestrial biosphere module. To represent terrestrial ecosystems in the global carbon cycle and to address questions of terrestrial carbon sequestration, we are coupling a process-based model of geographically-distributed carbon sources and sinks in natural ecosystems (GTEC 2.0) with a model of national carbon emissions and storage accompanying land-use change (LUCSE). The former is a revision of GTEC 1.0 (King et al., 1997; Post et al., 1997) with explicit ecophysiological modeling of hourly CO_2 flux and daily NPP replacing a statistical model of annual NPP. The latter is a regional land-use emissions model (King et al., 1995) modified to generate global land-use CO_2 emissions by country (Boden and King, 1998).

The coupling of these models at a common national resolution will be achieved by implementing a flux management scheme that aggregates the geographically-distributed, grid-cell fluxes of the natural ecosystem into fluxes by country. The "flux manager" will also be responsible for tracking the shifting of land from natural ecosystems to disturbed or managed ecosystems, and for insuring global conservation of land area and the conservation of carbon mass in the transfer between models. The country-scale coupling of these models provides a natural interface with the national and regional resolution of integrated assessment models. The country fluxes and storages of the coupled terrestrial module can be aggregated if necessary to provide coupling with regionally-disaggregated socio-economic models and data utilized in many integrated assessment models.

Components of the coupled model are being explicitly revised to simulate carbon sequestration practices. For example, the soil organic matter dynamics in the terrestrial ecosystem model of GTEC 2.0 is being revised to better simulate no-till agriculture. The land-use emissions model will be adapted for carbon management analysis by expanding the types of land-use change included in the model to include land-use explicitly associated with carbon management and sequestration (e.g., biomass plantations, agricultural management for soil carbon sequestration). The full life-cycle carbon accounting found in the GORCAM model of carbon in managed forests (Schlamadinger and Marland, 1996) will also be incorporated into the land-use emissions model.

The coupled terrestrial carbon model will be responsive to future changes in climate and atmospheric CO_2, and it will be capable of simulating the manipulation of vegetation and soil processes that are part of proposed terrestrial carbon sequestration practices. Carbon dioxide emissions from the coupled model will also be responsive to future changes in land-use, including those associated with carbon sequestration practices. The model will account for the fate of all carbon impacted by land-use change, including biomass energy and wood products, for example, and will thus provide for full life cycle carbon accounting of carbon sequestration practices. Minimally, the land-use/land-management changes will be defined by scenarios of change (ha yr^{-1}) provided to the model as time-dependent input data. We will investigate, however, whether the future land-use changes can be better generated by a land-use change model driven by an energy-economic model.

The next step is to couple the terrestrial module described above with atmosphere, ocean, and geologic modules to provide a whole global carbon cycle model for carbon management analysis. This will involve:

1. Disaggregation of the traditional fossil-fuel emissions flow from "industry" to atmosphere to allow for the direct flow of CO_2 from energy/industrial sectors to non-atmospheric carbon reservoirs. For example, the model will represent the flow of carbon captured from coal-fired electric-power plants to the deep ocean via injection pipelines. It will also represent the flux of CO_2 to the atmosphere from individual energy sources/economic sectors rather than as a single "fossil-fuel" flux.
2. Representation of ocean carbon uptake and storage in the deep ocean. Ultimately, the next generation of carbon management analyses will include complete ocean carbon cycling and three-dimensional transport. However, as a bridge to that goal, we plan to identify the ocean general circulation carbon cycle model recognized as best in class and adopt the convolution integral from that model for estimating oceanic CO_2 uptake. We will also extract estimates of deep-ocean residence time and leakage to the surface ocean and atmosphere from that model for purposes of simulating deep ocean carbon sequestration.
3. The addition of explicit geological-formation reservoirs in the carbon cycle model to provide for the simulation, analysis and assessment of geological sequestration. It will be necessary to identify the size and location (to country resolution) of potential reservoirs and to estimate rates of leakage from those reservoirs.

3.2 A Risk Management Framework and Portfolio Analysis

As noted above, risk analysis needs to be an integral part of carbon management analysis. Consequently, we plan to create a life-cycle-based risk management framework for carbon management. As recognized in the 11-lab study (DOE, 1997b), understanding the risk attributes of the technology pathways is essential to making informed technology portfolio decisions. That study took the first steps. We will fill knowledge gaps and advance a risk-based framework for life cycle analysis of CO_2 emission reduction technologies that includes ecological risk, human health risk, technical risk, and other important risk factors. Based on Oak Ridge National Laboratory's historical contribution to frameworks for ecological risk assessment for the Environmental Protection Agency (EPA) and life cycle analysis for the DOE-EM program, we hope to create a comprehensive framework for risk management for carbon management that has the potential to be similarly adopted by DOE.

Many diverse aspects of risk need to be considered and assessed in a coherent framework. These include human health risk (which may be estimated as expected mortality and morbidity); economic risk (which may be estimated as the expected loss of investment in a failed technology); social risk (e.g., the risk of floods, famine, pestilence, etc.); ecological risk (which may have many different endpoints of interest, e.g., loss of an ecosystem or species); and technical risk (for which we have no standard, accepted methods and endpoints). Each of these risks will be considered using life-cycle analysis principles. For example, "ecological risk" refers to the total cradle-to-grave environmental impacts of a technology pathway, and the measure for ecological risk will incorporate the total resource consumption and environmental burdens of the technology pathway over its entire life cycle. We have identified several key areas of research needed to develop a comprehensive life-cycle based risk management framework for carbon management analysis:

1. For risk measures that lack accepted methods and endpoints (e.g., technical risk), the scope of concerns and data input requirements for those risk measures must be defined.

2. Complex relationships among risk measures must be better understood. For example, there are significant interactions between human health and ecological impacts, and the correlations between human health risk and ecological risk are poorly understood.

3. Methods to make the measures of risk commensurate are needed. For example, methodologies such as contingent valuation and conjoint analysis can, in come cases, be used to place a dollar value on avoiding environmental damages. Methods that integrate human and ecological concerns into a single metric that represents overall "quality of life" or "well-being" or "integrity" of the system are also needed.

4. A covariance matrix that describes the correlations among attributes within and between technologies of a carbon management portfolio must be developed. Then, using the covariance matrix and user-specified inputs on the relative importance of different attributes, a user-specific composite index $R_c = f(R_1, ..., R_n)$ needs to be derived, where R_c is a combined or composite measure of risk, $R_i (i = 1, n)$ are the measures of risk for individual attributes, and f is some, yet to be determined, integrating function.

We also plan to introduce temporal considerations into risk and portfolio analyses of carbon management pathways. Temporal considerations are important because of the possibility of learning, and because the carbon management problem is characterized by a long planning horizon, great uncertainty, and limited reversibility of action. Learning may occur through the resolution of uncertainty from the passage of time, and through decisions, experiments, and research. Three examples illustrate why consideration of temporal aspects is so important for carbon management. First, in cases in which there is the possibility for learning if a decision is delayed and in which there may be negative, irreversible consequences of the decision, a decision-maker may choose to delay action. As a second example, actions that seek to reduce risk sooner may be more desirable than a robust portfolio of actions constructed as insurance against all possible contingencies. Third, actions that create or preserve options and enhance flexibility may be highly desirable for carbon management. We seek to identify and develop methods that can introduce these considerations into carbon management analysis. For example, we plan to investigate decision-theoretic concepts such as the expected value of perfect information, the expected value of research, and the importance of the sequential resolution of uncertainty and decisions to determine their applicability to the carbon management problem.

And lastly, we plan to develop methods for portfolio selection for carbon management. Rather than identify an individual "optimum" technology, next generation carbon management analysis will utilize portfolio analysis to suggest optimal strategies in terms of optimal portfolios of technologies to achieve CO_2 emission reduction goals and other objectives. Decision makers must make informed decisions on selecting a portfolio of technologies, where the appropriate distribution of investments is complex, due to varying levels of risk, resource requirements, and interaction among the proposed technology pathways.

While portfolio analysis for simple problems is well established, portfolio analysis for carbon management presents several research challenges. First, as typically implemented (e.g., for financial investment decisions), portfolio theory is applied to static choice problems in which the outcomes are measured in dollars. In the case of carbon management, however, we have a dynamic choice problem in which the outcomes are measured in many different, incommensurate, ways (e.g., a technology produces financial risk measured in dollars, risk to human life, and risk to ecosystems). Second, the use of historical covariances as estimates of expected covariances is problematic because a) history may lack information about specific technology pathways, and b) the number of periods of relevant data may be too small. Third, the risk measures are often correlated (e.g. human health risk and ecological risk). Fourth, the technology pathways themselves are correlated. Advances in portfolio analysis will be needed to adequately address the problems associated with optimizing portfolios of technology pathways.

3.3 Error and Uncertainty Analysis

It goes virtually without saying that next generation carbon management analysis should include estimates of error and uncertainty in input and should report outcomes with ranges or confidence intervals (Scott et al., 1999). The variability in model input and output is an integral part of the risk and portfolio analyses. Moreover, reporting the quantitative uncertainty surrounding model results more accurately reflects existing knowledge and makes for better input to policy and decision making. Statistically-based Monte Carlo methods using Latin hypercube sampling and repeated simulations are extremely flexible. They are routinely used with simulation models to report output parameters as a range of values with an associated probability distribution. However, because of the size of the carbon management problem (e.g., number and diversity of inputs and outputs, computational demands of large models), the suitability of these methods may be limited and new methods needed for carbon management analysis. Nevertheless, we are investigating the requirements and feasibility of using Monte Carlo methods for error and uncertainty analysis of next generation carbon management models. At the same time we plan to explore novel approaches to error and uncertainty analysis, such as moment propagation and interval computation, that do not carry the computational burden of Monte Carlo approaches.

4 Accomplishments

Our research began in earnest at the end of 2000. To date, we have developed the flux management scheme for coupling models at a common national resolution. Using that "flux manager" we have completed the initial linkage of the geographically-distributed model of natural ecosystem carbon flux (GTEC 2.0) with the model of CO_2 emissions from land-use change (LUCSE) (Section 3.1).

We have initiated our review of methods of portfolio analysis responsive to the challenges posed by the carbon management problem (Section 3.2). Further development of the life-cycle based risk management framework for carbon management analysis awaits the results of that review.

We have outlined a method for using Monte Carlo techniques and Latin hypercube sampling for error and uncertainty analysis of the coupled terrestrial models (Section 3.3). GTEC 2.0 is computationally demanding and is coded and designed to run on a high-performance parallel computer. Our design for error and uncertainty analysis of the coupled models accounts for that implementation, but does not avoid the need for 200 plus iterations of an already computationally intensive model.

5 Future Activities

In the very near term, concepts of full life-cycle carbon accounting and carbon sequestration pathways will be added to the coupled terrestrial carbon module. The terrestrial module will be then be linked with a geological sequestration module and a simple ocean module, all linked in common to an atmospheric module, to form a whole system global carbon model for carbon management analysis. The model will explicitly include the necessary links and elements to investigate terrestrial, geological, and oceanic carbon sequestration pathways.

Once the carbon cycle model is completed and running, it will be incorporated into a new version of the MiniCAM integrated assessment model (Edmonds et al., 1994; Scott et al., 1999). This coupling will be done in collaboration with Jae Edmonds and others at Pacific Northwest National Laboratory, and it serves as a test-bed for our carbon-cycle improvements for carbon management analysis. A standard carbon management analysis will be performed using the original and revised MiniCAM, and the results compared to determine the impact of the improved carbon cycle on carbon management analysis. Carbon management strategies involving sequestration will be most affected, and will likely alter the contribution of sequestration options to the technology portfolio. Small differences can have significant consequences. For example, a 15-10 GtC/yr global sequestration in terrestrial ecosystems could approach a 2.5-5.0 GtC/yr flux to the atmosphere after 50 years.

"Test-bedding" of our carbon cycle model will be followed with other joint tasks to perform life cycle analysis of individual technologies and evaluate technology portfolios. These joint tasks will utilize our advances in portfolio analysis and exercise our life-cycle based risk analysis framework.

Our ongoing research responds to the national need for an improved capability to evaluate CO_2 reduction options through a risk assessment framework incorporating state-of-the-art understanding of the global carbon cycle. It addresses critical, immediate science needs identified by those engaged in identifying technology options. Much work remains to be done to implement our research plan and achieve our near term goals. Even greater challenges lie ahead as the respective communities come together to continue the infusion of earth system science and integrated assessment that will form the next generation of carbon management analysis.

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