Summary of

CRC Workshop on
Life Cycle Analysis of Transportation Fuels

Argonne National Laboratory
October 15-17, 2013

A. Introduction

On October 15-17, 2013, the Coordinating Research Council (CRC) hosted a workshop at Argonne National Laboratory outside of Chicago, Illinois, which focused on technical issues associated with life cycle analysis (LCA) of transportation fuels, with particular emphasis on biofuels. The workshop was co-sponsored by API, Argonne National Laboratory, CONCAWE, Canadian Fuels Association, National Biodiesel Board, Renewable Fuels Association, South Coast Air Quality Management District, US Department of Agriculture, US Department of Energy, and the University of Michigan Energy Institute.

The following goals were established for the workshop:

- Outline technical needs arising out of policy actions and the ability of LCA to meet those needs.
- Identify research results and activities that have come to light in the past two years that have helped to close data gaps previously outlined as outstanding issues.
- Identify data gaps, areas of uncertainties, validation/verification, model transparency, and data quality issues.
- Establish priorities for directed research to narrow knowledge gaps and gather experts' opinions on where scarce research dollars would best be spent.

More than 100 representatives from government, industry, academia, and non-governmental organizations (NGOs) attended the workshop. Twenty presentations were given, organized into four Technical Sessions. Additionally, an Opening Session provided background information about CRC, and gave context for this 3rd LCA Workshop by summarizing the previous two workshops. Also, two Open Forum Discussion Sessions were held to help identify high-priority issues related to LCA of transportation fuels, and engage in further discussion of these issues.

This summary report highlights the topics discussed in each session as well as the knowledge gaps identified by the speakers, the session chairs, and through interaction with the workshop participants. Most of the abstracts and workshop presentations are available for download from the CRC website.[*] This report is organized into the following sections: (1) a brief listing of overall workshop highlights, (2) short summaries of each session, including the information gaps and data needs that were defined, and (3) summary descriptions of each presentation.

[*] *See* http://www.crcao.org/workshops/

B. Overall Workshop Highlights

Given below are brief overall highlights from the workshop. This list is not comprehensive, but attempts to capture the most significant take-home messages, common themes that emerged, and conclusions where there appeared to be some degree of consensus.

- Considerable progress has been made during the past two years (since the previous workshop) in LCA of transportation fuels. Significant updates have been made to several of the models and underlying databases that are used in these assessments, resulting in a higher degree of confidence in some aspects of model outcomes. However, despite these improvements, many of the major uncertainty problems highlighted in previous workshops still remain. These uncertainties need to be considered when assessing the GHG impacts of any transportation fuel.

- There appears to be increasing acknowledgement that different LCA modeling approaches have been developed for different purposes. Consequently, there is less call for harmonization of the models. However, there remains strong interest in clear definition of model inputs, transparent application of the models, and better description of uncertainties when reporting model results.

- The issue of co-product allocation, while clearly important, did not receive as much attention as in previous workshops. This now appears to be regarded as just one of many influential differences among various modeling approaches. As with all important modeling inputs, the method of co-product allocation being used needs to be clearly stated and transparently applied when performing LCA studies.

- Considerable work is now being conducted to investigate reasons for disparate results from different LCA studies. Significant progress has been made in determining sensitivities of model outputs to changes in model inputs. This is improving understanding of the strengths and limitations of different approaches, and is helping to identify areas where more reliable data would be most useful.

- The topics of model variability and uncertainty continue to receive much attention. Increasing application of formal uncertainty analysis techniques is occurring, and is providing a more complete understanding of LCA model results in the form of probability distributions. Translation of these approaches into a regulatory context is still unclear.

- Considerable improvements appear to be happening in the area of LUC assessment. Greater spatial resolution now exists (in some locations) with respect to feedstocks, land types, crop productivities, and land conversion options. Overall, it appears that the extent of land use change to support biofuels policies is not as large as was thought a few years ago, although this remains an area of high uncertainty.

- The topic of indirect land use change (iLUC) remains controversial – both in principle and in application. In fuel regulatory applications, iLUC is still considered only in the US, although the EU (and other regions) continue to study the issues, and may implement iLUC-based regulations in the future. Largely as a consequence of improved LUC modeling (and other modeling enhancements mentioned above), the impact of iLUC on the total life-cycle carbon intensity of most biofuels does not appear to be as large as thought a few years ago, but still remains a significant and highly uncertain effect.

- Soil-based emissions of nitrous oxide (N_2O) are an important contributor to the total CI of some biofuels, and a significant source of overall uncertainty. Data limitations still prevent use of process-based biogeochemical models to estimate N_2O in many situations. However, a Global Nitrogen Oxide Calculator (GNOC) has been developed, which applies a higher spatial resolution than the simple IPCC Tier 1 N_2O approach.
- A better understanding of baseline CI values of fossil fuels, including their variability, is evolving. This is driven by more complete depictions of oil and gas production processes, and by better emissions data for these process steps. The rapid growth in hydraulic fracturing has increased concern about methane emissions associated with certain production activities, leading to more study in this area.

C. Session Summaries, Information Gaps and Data Needs

Session 1: Regulatory Environment/ New Policies Driving LCA Pathways and Methodologies

Session 1 highlighted the regulatory advancements being made in different regions. There remains a lack of harmonization throughout different jurisdictions in the areas of LCA definition and application. Although there is increased awareness of iLUC theory and quantification, at present, iLUC is only being applied in a regulatory sense within the US. However, the EU has been studying iLUC for some time, and is developing methodologies to potentially incorporate it into future regulations. Further efforts are still required to work towards a more uniform understanding of LCA model structures and the underlying data sources.

Session 2: LCA Methodology Development, Gaps and Uncertainties

Session 2 highlighted several areas of methodological differences, uncertainties and variabilities in application of LCA models. These differences can significantly influence the final predicted carbon intensity (CI) of a particular fuel. Based upon systematic comparisons of various modeling approaches, the underlying reasons for these differences are becoming better understood. Most important are real differences in model input assumptions – not simply model formulation errors. Further work could help narrow the range of uncertainties in some inputs. However, significant differences remain in model type (consequential vs. attributional), co-product allocation method, time period, geographic areas, and other aspects. Because different models serve different purposes, it seems unlikely (and even undesirable) to force convergence to a single "best modeling approach." However, it is important for each approach to be fully transparent with respect to input assumptions, supporting databases, and modeling methodologies used. Also, more efforts should be taken to systematically determine uncertainties in modeling results, and to report distributions of results rather than single point values.

Session 3: Advances in LCA of Biofuels

Session 3 highlighted several advancements that are occurring in LCA modeling of fuels. Increased spatial and temporal resolution of data inputs are leading to improved assessments of LUC, although further improvements in these areas are still required. A greater understanding of factors responsible for iLUC, and resulting GHG impacts, is developing, although significant uncertainties remain. For example, it was noted that significantly different iLUC CI values were indicated in this session for corn-derived ethanol scenarios, with Plevin reporting a mean value of 27 g/MJ and Tyner reporting 15 g/MJ. Soil N_2O emissions from biofuel-related agricultural activities continue to be an area of high uncertainty, although improvements have been made in reducing this uncertainty. A greater degree of model integration and collaboration is being pursued to improve overall assessments of biofuel LCA, although more needs to be done in this area too.

Session 4: Advances in LCA of Petroleum/Alternatives

Session 4 emphasized that LCAs of biofuels need to be viewed within the broader context of other fuels and energy sources used to establish baselines for comparison. Conventional gasoline and diesel fuel are usually considered reference points for determination of a biofuel's lifecycle GHG impacts, but there are significant uncertainties and variabilities in these reference points. GHG emissions associated with production of oil and gas are beginning to be defined with greater detail. This has revealed CI results that vary with the specific resource and technology being used. The expanding application of hydraulic fracturing has increased interest in better quantification of methane emissions associated with natural gas production. While initial measurements appear to agree reasonably well with the latest EPA inventories, additional work is necessary to characterize emissions from certain activities – particularly "liquid unloading" events, which can have large, but highly skewed emissions distributions.

D. Highlights and Learnings from Individual Presentations

Opening Session: Background of CRC LCA Workshops

Chairpersons: Brent Bailey (CRC) and Phil Heirigs (Chevron)

Brent Bailey (CRC) provided a brief history of CRC. Since its establishment as an independent organization in 1942, CRC has directed cooperative scientific research among industry (primarily the automobile and petroleum industries) and governmental bodies to develop optimum combinations of fuels, lubricants, and the equipment in which they are used. Environmental research began later, following establishment of CRC's Air Pollution Research Advisory Committee (APRAC) in 1968. Since the 1980's, CRC has organized and conducted a number of large experimental programs aimed at understanding the relationships between fuel composition and emissions, and the impact of these emissions upon air quality. The current activities regarding LCA of transportation fuels falls within the scope of the CRC charter, and the workshop follows the historical pattern of broad participation of stakeholders in CRC activities.

Phil Heirigs (Chevron) provided background information to explain CRC's current interest in LCA. Initial legislative/regulatory activities by the California Air Resources Board (CARB) began in 2007, calling for a 10% reduction in the carbon intensity (CI) of transportation fuels by 2020, measured on a full fuel cycle basis. Shortly thereafter, the US Congress established volumetric and greenhouse gas (GHG) reduction targets for renewable fuels, with the GHG emissions related to the full fuel lifecycle. In 2009, the EU adopted directives regarding renewable fuels, with determination of the GHG emissions impacts to consider life cycle aspects. In response to these legislative/regulatory actions, different assessment tools and assumptions have been developed and applied, resulting in different outcomes. Understanding these differences was the primary motivation for CRC's initial LCA Workshop in 2009. Mr.

Heirigs reviewed the important conclusions from the 1st and 2nd workshops, and noted that this 3rd LCA workshop was intended to continue exploration of the LCA issues identified previously, including LCA methodology development and applications, iLUC assessments, advancements in LCA of biofuels, and LCA of petroleum-derived and other alternative fuels.

Session 1: Regulatory Environment/ New Policies Driving LCA Pathways and Methodologies

Chairpersons: Jim Duffield (USDA), Bob Larson (US EPA), David Lax (API), and Mani Natarajan (Marathon Petroleum Co.)

The workshop's first session dealt with the regulatory framework and policy needs that drive much of the activity to improve and expand LCA modeling efforts. International regulatory perspectives were provided by Michael Rensing of the British Columbia (BC) Ministry of Energy and Mines, and by Luisa Marelli from the European Commission Joint Research Centre (EC-JRC). US EPA was unable to attend due to government travel restrictions associated with a government shutdown. CARB was also unable to attend, although presentation materials prepared by John Courtis were submitted, and are summarized below.

John Courtis (CARB) planned to provide an update on California's Low Carbon Fuel Standard (LCFS), which requires a 10% reduction of carbon intensity (CI) of the entire transportation fuel pool by 2020. CI, expressed as g $CO_{2\text{-}eq}$/MJ, is the measure of GHG emissions associated with producing, transporting, and consuming a particular fuel derived from a particular pathway. GHG emissions associated with indirect land use change (iLUC) are included in CARB's determination of CI for each biofuel pathway. There are now approximately 100 regulated parties (fuel suppliers) in California who are reporting and complying with the LCFS regulations. CARB continues to add new fuel pathways into the regulatory system, and is currently re-examining iLUC values for corn ethanol, sugarcane ethanol, and soy biodiesel. Overall, CARB believes the LCFS regulations are working well, and are having an indiscernible impact on fuel prices.

Michael Rensing (BC Ministry of Energy and Mines) described low carbon fuel requirements in Canada, with an emphasis on the BC situation. Throughout Canada, the GHGenius model is employed to assess LCA of transportation fuels, although different versions of the model are used by different Provinces. In BC, a 10% reduction in CI is required by 2020. At present, there is no consideration of iLUC in this determination. Credits or debits are calculated for various fuels that could be used in BC, although at present, only ethanol and biodiesel are commonly available. To achieve required future GHG reductions, other liquid fuels will need to be introduced, such as hydrogenation-derived renewable diesel (HDRD), and possibly alternatives such as natural gas and electricity.

Luisa Marelli (EC-JRC) presented an overview of European legislation and policy regarding LCA of biofuels. Two policy directives drive renewable fuel and sustainability requirements for the EU: the Renewable Energy Directive (RED; Directive 2009/28/EC) and the Fuel Quality Directive (FQD; Directive 98/70/EC). The RED requires that renewable fuels comprise 10% of all transport fuel within the EU; the FQD requires a 10% reduction in GHG intensity of fuels and energy used in road transport and non-road mobile machinery. The two directives also require a minimum life cycle GHG savings (compared to fossil baseline) of 35% -- increasing to 60% by 2018.

To avoid a disproportionate administrative burden for economic operators, a list of default "GHG savings" values is established in annexes of the RED and FQD for common production pathways. The JRC recently updated the input database used to calculate these default GHG emissions for all biofuel pathways specified in the directives. Although fuel providers are encouraged to declare actual emissions associated with their specific pathway, they may still choose to use established, default values. The directives also permit economic operators to mix default values for some parts and actual values for other parts of the fuel pathway in question, thus allowing them to choose a combination of default and actual values to declare the lowest emissions. (However, the default values for fuel production processes have a 40% conservative factor built in, which is intended to encourage fuel producers to use actual production data.) Major enhancements incorporated in the recent JRC update include the following:

- Addition of new fuel pathways (ethanol from barley and rye; FAME from coconut oil, jatropha, and waste cooking oil; hydrotreated vegetable oil; biomethane; and lignocellulosic fuels)
- Application of a new European electric energy mix (based on EU27 rather than EU15)
- Co-product allocation for bioliquids that are used to generate heat and electric power
- Development of an improved method for quantifying soil N_2O emissions associated with cultivation of biofuel feedstocks. (This new N_2O method was described in greater detail in a later presentation by Robert Edwards of JRC.)

At present, only direct emissions from production of the biofuels are considered in determining GHG reductions for biofuels in EU legislation. However, the European Commission issued a policy proposal aimed at incentivizing the transition to biofuels that do not cause land use change emissions by limiting the contribution of biofuels produced from food crops to 5%, and introducing iLUC emissions values per crop groups as reporting obligations. Preliminary iLUC values determined from application of the IFPRI-MIRAGE model for European fuel pathways are 12, 13, and 55 g $CO_{2\text{-eq}}$/MJ for grain-derived, sugar-derived, and vegetable oil-derived crops, respectively. Discussions are still on-going between the European Parliament and the national governments regarding these policies.

Session 2: LCA Methodology Development, Gaps and Uncertainties

Chairpersons: John DeCicco (U. Mich.), Chul Kim (Ford), Ken Rose (CONCAWE), and Geoff Cooper (RFA)

Session 2 provided various perspectives and updates about LCA model structures and operations. Key differences in model inputs and assumptions were identified, and the impacts they have on model outcomes were discussed. The session began with Don O'Connor of $(S\&T)^2$ who discussed model differences and variabilities, followed by Mike Griffin of Carnegie Mellon University (CMU) who discussed the issue of uncertainty, as applied to LCA. Bo Weidema of 2.0 LCA Consultants presented updates to European LCA methodologies, and Brian Murray of Duke University described the linkage between commodity markets and land use. The session concluded with Michael Wang of Argonne who presented updates to the widely-used US model called GREET.

Don O'Connor $(S\&T)^2$ discussed the research project, CRC-E-102, that he is currently conducting under sponsorship of CRC. The objectives of this study are to quantify sources of uncertainty and variability in selected LCA models being used to regulate fuels, and to define the factors responsible for major differences in model outputs. Four LCA models are included:

1. BioGrace, as being used in the EU's RED program
2. US EPA's modeling system as being used in the RFS program

3. GREET, as being used in CARB's LCFS program
4. GHGenius, as being used in BC's LCFS program and Alberta's RFS program

With each model, six fuel pathways are being evaluated: (1) gasoline/diesel from petroleum, (2) ethanol from corn, (3) ethanol from sugarcane, (4) cellulosic ethanol, (5) biodiesel/renewable diesel from soybeans, and (6) natural gas. Only direct GHG emissions are considered in this evaluation – no iLUC. Also, to allow for more straightforward comparisons in a common format, some minor modifications were made, such as defining the same modeling year and consistently using lower heating values (LHV) as the basis for energy content.

A series of results tables were presented to compare the CI values determined by each model for each stage of the life cycle (e.g. feedstock production, feedstock transport, and fuel production) as well as co-product allocation method and credits (where applicable). Several large differences in model outcomes were identified. For example, the overall corn ethanol CI value estimated by BioGrace is quite low, because of the large co-product credit for electrical power generation assumed in European ethanol production plants. On the other hand, BioGrace predicts the largest CI value for soybean-derived biodiesel because of high feedstock transportation emissions, resulting from shipping of soybeans from Brazil to Europe. The models gave quite different results for cellulosic ethanol, with GHGenius predicting the highest CI value, largely due to incorporation of more process chemicals used in the conversion of cellulosic feedstocks into ethanol. In summary, O'Connor concluded that there is significant variability among the models studied, and that the drivers of this variability are real – not just model "errors." The final report for this CRC-E-102 project will become available in the near future.

Mike Griffin (Carnegie Mellon Univ.) discussed uncertainty in LCA, and the implications this can have with respect to policy decisions. He differentiated two categories of uncertainty: (1) parametric (uncertainty about the value of empirical quantities) and (2) model (uncertainty about model functional form). Empirical quantities represent properties of the real world, which in principle, can be measured. Griffin described the ISO 14044 standard, which defines uncertainty analysis, and he recommended that this be applied to LCA studies. He presented LCA examples producing single point estimate results, ranges of results, and probability distribution results. Probability distributions are most useful in providing insights regarding the likelihood of achieving policy goals, and in understanding the robustness of the policy design.

Bo Weidema (2.0 LCA Consultants) discussed LCA methodology development in the EU, including efforts to deal with iLUC. The recent Product Environmental Footprint (PEF) guidelines from the EC call for consequential LCA modeling, but exclude iLUC. To support this modeling, an updated version of the Ecoinvent database has been developed. This now allows for direct comparison of consequential and attributional modeling based upon the same unit processes. Such a comparison highlights large GHG differences in the area of land use, with the consequential result being much higher than the attributional result. Further advancements include development of an updated version of ExioBase, which is a global Input/Output Table (IOT) that includes both physical and monetary parameters. (The earlier version was strictly a monetary database.) Use of ExioBase v2 in combination with Ecoinvent v3 provides a complete consequential modeling system that is consistent with the ISO 14040/44/49 standards. Weidema concluded that there has been a significant degree of harmonization in European LCA modeling principles, but that the topic of iLUC remains as an unresolved and controversial subject.

Brian Murray (Duke Univ.) described recent work focused on assessing iLUC of biofuels at various spatial scales. In general, the potential for iLUC effects increases as the geographic scale increases from regional to global. Several examples were presented to show the importance of integrating LCA with modeling of commodity markets and LUC. Through modeling exercises it was shown that the US RFS2 Program is effective in reducing net GHG emissions in the US, although global emissions may be neutral, or even increase slightly under some conditions. Results are sensitive to crop yields and other iLUC assumptions. From another study it was shown that having both the RFS2 Program and a subsidy for corn ethanol is duplicative. Murray concluded that the topic of iLUC effects from biofuel policies is too important to ignore, and it should be addressed through explicit connections between biofuel demand, commodity markets, and land use.

Michael Wang (Argonne NL) discussed recent updates to the GREET model, culminating in release of version GREET1_2013. Major changes in this new version include the following:

- Petroleum refinery efficiency is expressed as a function of crude quality and refinery complexity
- Updated efficiencies and emission factors are included for US power plants
- Updated methane leakage data are included for natural gas fuel pathways
- Marine fuel pathways and commercial vessel operations have been added
- Updated iLUC emissions are included as determined using the Carbon Calculator for Land Use Change (CCLUB) component in GREET
- Updated tailpipe emission factors for light-duty vehicles are incorporated from EPA's MOVES model

Wang presented several examples in which the new GREET1_2013 model was applied to investigate LCA sensitivities and results. For example, the GHG benefit of CNG vehicles compared to conventional gasoline vehicles depends upon methane leakage rates and assumed efficiencies of the CNG vehicles. Similarly, the GHG benefits of electric vehicles (EVs) depend upon the efficiency of the power plants being used. Use of EVs also has implications for other air pollutants. For example, Wang showed that battery electric vehicles (BEVs) charged by the average US electricity mix are less than 40% likely to increase total NOx emissions, and are less than 20% likely to increase urban NOx emissions.

Use of GREET to compare LCA GHG emissions of different US bioethanol pathways was discussed. Corn ethanol was determined to have a CI of ~65 g $CO_{2\text{-eq}}$/MJ (including iLUC) while sugarcane ethanol's CI was approximately 45 g $CO_{2\text{-eq}}$/MJ (including iLUC). The calculated CI values of ethanol from corn stover, switchgrass, and miscanthus were all much lower. Wang pointed out that N_2O emissions associated with crop growth are very significant (responsible for up to ¼ of GHG emissions for corn ethanol) but continue to have high uncertainty.

Session 3: Advances in LCA of Biofuels

Chairpersons: Jim Anderson (Ford), Jeff Farenback-Brateman (ExxonMobil), Luisa Marelli (JRC), Mani Natarajan (Marathon Petroleum Co.), and Don Scott (NBB)

Session 3 focused on recent advances in LCA of biofuels, with emphasis on improved LUC modeling through use of updated agro-economic datasets and model structures. Additional topics covered included collaboration/harmonization among models and modelers, efforts to establish sustainability criteria for bioenergy, and advancements in determining N_2O emission factors.

Wally Tyner (Purdue Univ.) discussed numerous recent changes made to the Global Trade and Analysis Project (GTAP) modeling framework and database, and implications this has with respect to LCA of biofuels. Overall, the underlying databases are becoming more detailed and regionally-specific with respect to feedstocks, land types, land conversion options, crop productivities, etc. For example, energy elasticities have been improved, a new land cover nesting structure was introduced to separate forest from cropland and pastureland, and corn oil is now separated in the ethanol production process. Another improvement involves determination of productivity when expanding croplands into forest and pastureland. Previously, a single value was used for productivity of new crops compared to existing crops (ETA value); now a process-based biogeochemistry model is used to calculate different ETA values according to agricultural ecological zone (AEZ) and geographic location. As a result of these and other improvements, the predicted amount of LUC required to support the 15 bgy corn ethanol RFS requirement has decreased from a value of 0.22 Ha/1000 gal in 2010 to 0.11 Ha/1000 gal in 2013 (both figures from Tyner's group). Tyner also presented data showing good correlation between harvested hectares and crop prices. Substantial increases in crop areas have occurred over the past decade, with almost all of this occurring outside of Europe and North America. Tyner concluded by explaining that in addition to uncertainties in determining the amount and location of iLUC, there is considerable uncertainty in land use emission factors used to calculate the overall GHG impacts of LUC.

Debo Oladosu (Oak Ridge NL) described use of a dynamic general equilibrium model to investigate iLUC implications of US biofuels policy. This model, called GTAP-DEPS (Dynamic Energy Policy Simulator) includes fossil fuel supply curves, and operates in a dynamic fashion over the period of 2001-2030; as opposed to the standard GTAP model, which is static for a particular year. Use of GTAP-DEPS predicts that the amount and type of LUC required to satisfy the RFS2 biofuels requirements change over this 30-year period. Initially, global LUC is positive, at 0.17 Ha/1000 gal of biofuel; but this decreases with time, becoming negative, at -0.13 Ha/1000 gal in 2018. This contraction results largely from assumptions of increased agricultural land efficiency and income effects of the biofuels policy.

David Laborde (IFPRI) described LCA modeling to evaluate the impacts of EU biofuel policy, using an updated version of the MIRAGE-Biof model. This is a global, dynamic, computable general equilibrium (CGE) model used to estimate changes in commodities, land use, and GHG emissions in response to changes in biofuels demand. Some of the recent changes made to this model since its inception in 2008 include improved sector disaggregation, improved accounting for co-products from ethanol and biodiesel production, treatment of crops and land use at the AEZ level, and others. Laborde presented several examples to illustrate the sensitivity of model outputs to a range of EU biofuel scenarios and input assumptions. With respect to first generation biofuels over a 20-year horizon, ethanol (from various feedstocks) can satisfy the goal of 50% reduction in life-cycle GHG emissions, while biodiesel (from various feedstocks) cannot satisfy this goal. The iLUC emissions associated with ethanol pathways to satisfy the RED mandate in 2020 were approximately 10 g $CO_{2\text{-eq}}$/MJ, while those associated with biodiesel were approximately 50 g $CO_{2\text{-eq}}$/MJ. (This assumes a biofuels share of 8.4% transport fuel in 2020, consistent with declarations of EU member states.) It was pointed out that although large amounts of land are needed to produce fuels that satisfy EU biofuel policies, relatively little new land is required. Sensitivity analyses showed very similar results, whether or not Europe instituted trade liberalization policies with respect to biofuels. Consideration of 2nd generation biofuels (from crop residues and dedicated energy crops) introduces many new options and uncertainties. Laborde presented preliminary modeling results for ethanol from wheat straw and corn stover that estimated very low iLUC emissions of about 4 g $CO_{2\text{-eq}}$/MJ.

Sonia Yeh (UC-Davis) described opportunities to employ model collaboration for improved assessment of biomass supplies and biofuels impacts. She began by defining four categories of modeling approaches currently being used: (1) economic computational general equilibrium, (2) partial equilibrium, (3) biophysical/economic engineering, and (4) integrated assessment. Each category has particular strengths and limitations. The objective of collaboration among these models is not to determine which approach is best, but to exploit the strengths of different approaches, thereby determining an overall better assessment of biomass and its impacts. Model collaboration can involve differing levels of engagement – from simple harmonizing of input data and scenarios, to complex integration by which inputs and outputs from one model drive (and are driven by) another model. Yeh presented three examples of where model collaboration can improve understanding and better address existing problems affecting LCA of biofuels:

1. Livestock production and its effects on availability of land and biomass feedstocks
2. Availability and use of agricultural and forest residues for bioenergy
3. Determining location, amount, and impacts of LUC that is induced by bioenergy policy

In a specific case, Yeh discussed modeling approaches to assess options for further development of biofuel feedstocks in Brazil. Incorporation of non-economic drivers in modeling (e.g., socio-economic and biophysical drivers) along with policy enforcement scenarios provides a basis for determining acceptable options for such development.

Stefan Unnasch (Life Cycle Associates) discussed a project he is currently conducting under CRC sponsorship, called Project E-88-3. The objectives of this project are to explain the structures and functions of models commonly used to assess LUC impacts of biofuels, and to compare/contrast the important drivers that affect LUC predictions. The four models included in this study are:

1. FASOM: Forest and Agricultural Sector Optimization Model
2. FAPRI: Food and Agricultural Research Institute model
3. GTAP: Global Trade Analysis Project
4. MIRAGE-Biof: Modeling International Relationships in Applied General Equilibrium

Unnasch described the general attributes of each model (general vs. partial equilibrium, geographic coverage, land cover type, time frames, land assumptions, etc.) as well as the approach used by each model in responding to a biofuel shock. No final results were presented, as the E-88-3 project is still underway. However, some of the parameters that are most influential in determining LUC estimates were identified, as shown below:

- Type and size of biofuel shock; also single vs. cumulative shocks
- Selection of land cover types – especially the amount of forest land
- Elasticities of crop supply/price and land substitution
- Biorefinery yields and co-products

Keith Kline (ORNL) discussed activities underway by the International Organization for Standardization (ISO) to develop "Sustainability Criteria for Bioenergy," (ISO 13065). The purpose of this proposed standard is to provide a more consistent basis on which to assess the sustainability of bioenergy. A Project Committee, called PC 248, is working to develop the detailed content of this proposed ISO standard. PC 248 consists of four Work Groups, which are addressing different aspects of sustainability criteria for bioenergy:

- WG1: cross-cutting issues – including terminology, traceability, and comparability
- WG2: GHG issues – including assessment methodologies and LCA approaches
- WG3: principles, criteria, and indicators of bioenergy sustainability
- WG4: indirect effects of bioenergy

The methodologies for assessing GHG emissions and carbon footprints of products are largely based on existing ISO standards 14040 and 14044. Dealing with indirect effects of bioenergy has been controversial, with no consensus yet emerging. At this point, the WG4 has concluded that: (1) the science on indirect effects is nascent and rapidly evolving, (2) model results are inconsistent and contradictory, and (3) iLUC is incompatible with a science-based International Standard designed to generate replicable results. A Project Committee draft report has been issued and reviewed. A revised version of this Committee report is expected in April, 2014. The next step would be development of a Draft International Standard (DIS). Lacking adequate support for this, development of an ISO Technical Specification may be pursued instead.

Richard Plevin (UC-Davis) presented an updated version of the GHG emissions model and underlying carbon stock database developed for CARB to estimate iLUC emissions associated with biofuels. A major improvement is finer disaggregation of carbon data to 245 countries x 18 AEZs. This allows for subsequent aggregation to match the 134 GTAP-8 regions, or other aggregation schemes. Another improvement is separate treatment of managed and unmanaged forest lands, in contrast to GTAP's uniform treatment, which overestimates GHG emissions from managed forests and underestimates the emissions from natural forests. The GHG emission model has also been improved in its treatment of N_2O, and in assessment of long-term sequestration of carbon in harvested wood products (HWP). The updated AEZ-emission factor model has now been developed in the Python programming language, which facilitates operation on large-scale computer clusters. Plevin presented examples of Monte Carlo simulations of the joint GTAP/carbon accounting model to investigate the model's sensitivities to various inputs. The overall iLUC GHG emissions for biofuels fall between 15 and 42 g $CO_{2\text{-eq}}$/MJ (95% confidence interval) with a mean value of 27 g $CO_{2\text{-eq}}$/MJ. Of the numerous parameters investigated, economic factors within GTAP (such as price-yield elasticities and land conversion options) were the largest contributors to overall variance.

Jerry Hatfield (USDA) presented (by phone) a discussion of N_2O emissions from agricultural soils, and efforts to monitor and mitigate these emissions. Better understanding of N_2O emissions is of considerable interest because of (1) the significant contribution of N_2O to total life-cycle GHG emissions of biofuels, (2) the relatively large variability and uncertainty of these emissions, and (3) the good potential to mitigate these emissions through land/agricultural management decisions. Hatfield described both soil-based and atmosphere-based methods for measuring N_2O emissions, and discussed the advantages and limitations of both. A complete understanding of N_2O from soils is difficult because these emissions are influenced by numerous factors – including soil type, moisture level, fertilizer type and application rate, crop type, and others. High temporal and spatial variability compound the problem. Data collected as part of a USDA Agricultural Research Service (ARS) program called GRACEnet (Greenhouse gas Reduction through Agricultural Carbon Enhancement) were presented and discussed. It is clear that N_2O emissions are influenced by soil water content, with spikes in N_2O flux observed to correspond with rainfall events. Seasonal/annual measurements were also compared with model-predicted values under different land management and crop rotation regimes. Measured N_2O fluxes (expressed as kg N_2O-N/ha) were much higher than those estimated using IPCC methods (especially the IPCC Tier 1 method). These differences were attributed in large part to the overall wetter conditions that existed during the GRACEnet program (in the US Midwest) than anticipated in the IPCC methodology.

Robert Edwards (JRC) described the development and use of JRC's Global Nitrogen Oxide Calculator (GNOC) in assessing life-cycle GHG emissions of biofuels attributed to N_2O. For most agriculturally-derived biofuels, the contribution of N_2O to total GHG emissions is large, but highly uncertain. While it is convenient to use the IPCC Tier 1 methodology to calculate N_2O emissions as part of a biofuels LCA study, the IPCC approach was intended only to provide national-level inventory reporting under the Kyoto Agreement. IPCC Tier 1 only considers fertilizer nitrogen inputs when calculating annual N_2O emissions, ignoring known effects of soil and climate. The GNOC is an on-line tool that can be used to estimate soil N_2O emissions from crop cultivation anywhere in the world. It is based on the same database of empirical N_2O measurements as the IPCC Tier 1 approach, but it considers several more input variables that influence N_2O emissions, such as crop type, soil type, and climate properties. Consequently, it is much more reliable for smaller geographic areas, and for assessing impacts of mitigation measures. When averaged over a large region, results of GNOC are consistent with IPCC. JRC has used the GNOC tool to estimate N_2O emissions from several biofuel pathways. Edwards presented examples of N_2O from soy-based biofuels originating in Argentina, USA, Canada, and China. In most cases, measured N_2O emissions were much higher than estimates from GNOC, but were in closer agreement after adding the nitrogen contribution from below-ground residues, which is not included in the IPCC protocol for national-level inventory reporting.

Session 4: Advances in LCA of Petroleum/Alternatives

Chairpersons: Phil Heirigs (Chevron), David Lax (API), Heather MacLean (Univ. of Toronto), and Michael Wang (Argonne)

Session 4 addressed advances that have been made with respect to LCA of petroleum and other non-biofuel alternatives. The four presentations in this session focused on GHG emissions associated with oil production and refining (both conventional oil and oil sands), GHGs associated with natural gas production (including hydraulic fracturing), and LCA assessments of fuels used in future vehicle technologies.

Adam Brandt (Stanford University) discussed development of the Oil Production Greenhouse gas Emission Estimator (OPGEE), which is an engineering-based, open-source LCA tool for estimating GHG emissions from oil production operations. This includes emissions from the production, surface processing, and transport of petroleum from the well-to-refinery (WTR). OPGEE was developed – and is still being enhanced – to determine CI values for petroleum-derived fuels as part of California's LCFS regulations. GHG emissions vary widely from one oil field to another, and are affected by many operational parameters, such as water/oil ratios, gas/oil ratios, enhanced oil recovery measures, depth of well, and others. The most important driver is flaring – both flaring rate and flaring efficiency. OPGEE has been used to calculate a CI value for baseline gasoline used in California. To do this, 270 crude oil producing fields and crude blends were modeled. Results showed CI values ranging from below 2 to above 30 g $CO_{2\text{-eq}}$/MJ, with a California production-weighted value of 11.4 g $CO_{2\text{-eq}}$/MJ. (The GREET national average default value is 6.9 g $CO_{2\text{-eq}}$/MJ.) Brandt is currently comparing OPGEE with other LCA models, and is expanding the application to a broader range of oil fields.

Joule Bergerson (Univ. of Calgary) described on-going work within the Alberta project called LCA for Oil Sands Technology (LCAOST). The overall objective of this project is to improve scientific understanding of the life-cycle implications of current and developing oil sands technologies, to support choices about future natural resource investments, and drive future research and development activities. The GreenHouse gas emission Oil Sands Technology (GHOST) model has been developed and applied to estimate emissions associated with the recovery, extraction, and upgrading of oil sands resources. This Excel-based software tool is optimized for the Alberta Oil Sands Region. It characterizes life-cycle energy use and GHG emissions associated with existing oil sands technologies – not future technologies. GHOST model results shown for various scenarios indicated well-to-wheel (WTW) CI values of approximately 90-115 g $CO_{2\text{-eq}}$/MJ gasoline. As part of the LCAOST Project, a new refinery model was also developed, as refining of oil sands-derived crude oil was not adequately represented by previous LCA models. Results from application of this new model showed CI values (for the refining component) of approximately 4-14 g $CO_{2\text{-eq}}$/MJ crude oil.

David Allen (Univ. of Texas at Austin) described recent experimental measurements of methane emissions associated with natural gas production at sites involving hydraulic fracturing. This study, which was sponsored by a consortium of environmental groups and natural gas producers, sampled 190 on-shore natural gas sites in four broad locations: Appalachia, Rocky Mountains, Midcontinent, and Gulf Coast. These sites included 150 routine production well sites (489 individual wells), 27 wells with completion flowback, 9 liquid unloading events, and 4 well workovers. Results showed that at the routine production wells, emissions from pneumatic controllers and equipment leaks were somewhat higher than EPA's natural gas emissions projections; however, completion flowback emissions were lower than previously estimated by EPA. Emissions from liquid unloading were highly variable, with 4 of the 9 measured unloadings being responsible for 95% of the total emissions. Allen concluded that more sampling and measurements of liquid unloading is necessary to properly account for this category of methane emissions. Assuming the measurements made in this study are representative of the national situation, a total inventory of methane emissions from natural gas production was calculated to be 2.3 x 10^3 Gg/yr. This is in good agreement with EPA's most recent inventory (2011) figure of 2.5 x 10^3 Gg/yr, but is considerably lower than EPA's prior (2010) inventory figure of 6.0 x 10^3 Gg/yr.

Heiko Maas (Ford Motor Company) presented updates to the joint JRC, EUCAR and CONCAWE (JEC) well-to-wheels (WTW) GHG assessments of light-duty European vehicles. The first WTW study was completed in 2004; Version 4 will be completed by the end of 2013. For the tank-to-wheel (TTW) component, the vehicle platform has been updated from 2002 to 2010, with projections for future configurations in 2020. The propulsion systems have been expanded to include a number of hybrid and electric concepts. The New European Driving Cycle (NEDC) was applied to gasoline vehicles, and the UNECE R101 cycle was applied to the electrified vehicles. On the well-to-tank (WTT) side, updates have been made to fuel pathways, soil N_2O emissions have been improved, and the European electrical grid has been updated. Maas presented a few draft results of full WTW GHG emissions for several cases with both 2010 and 2020 vehicles. In the 2010 case, the highest emissions came from gasoline spark ignition (SI) vehicles, at 175 g $CO_{2\text{-}eq}$/km. SI vehicles fueled with CNG and LPG both had WTW emissions levels of approximately 150 g $CO_{2\text{-}eq}$/km, as did diesel compression ignition (CI) vehicles. Plug-in hybrid electric vehicles (PHEV) and range-extended electric vehicles (REEV) had emissions of approximately 110 and 100 g $CO_{2\text{-}eq}$/km, respectively. Full battery electric vehicles (BEV) had GHG emissions of 75 g $CO_{2\text{-}eq}$/km, assuming the electricity came from the 2009 European electric power mix. All of these life-cycle WTW emission levels are reduced by about 30% in 2020, due largely to assumed improvements in powertrain efficiency.

Open Forum Discussions

Two Open Forum Discussion Sessions were held to further engage all participants in discussion of topics of specific interest. Both sessions were moderated by S. Kent Hoekman of the Desert Research Institute (DRI), with assistance from the Session co-chairs, John DeCicco (Univ. of Michigan) and Jeremy Martin (Union of Concerned Scientists). During both sessions, free-flowing discussions touched on many topics. Some of the main points covered are combined and summarized below.

- There was considerable discussion regarding the rapid pace of development in LCA of fuels. Concerns were expressed that major business decisions based upon today's understanding may be jeopardized by later changes in LCA requirements and results. Some thought it best to wait for the science of LCA (and especially iLUC) to "settle down" before getting locked-in to a particular approach. Some participants expressed the need and benefits of moving forward with LCA regulations, even though uncertainties may exist. Others felt that the extent of uncertainty involved in LCA raises questions regarding its suitability as a compliance method for fuels regulation.
- It was discussed that different biofuel regulations have different purposes, hence the difficulty (or impossibility) of achieving total harmonization. Some regulations are focused only on GHG reductions, while others are also concerned with use of renewable resources, rural development, carbon intensity, energy independence, jobs, and economic benefits, to name a few. This leads to different "scoring systems," some of which include political factors, not just scientific factors. Some thought that the LCFS approach may be the most "fuel neutral," as it is strictly focused on GHG reductions by means of CI control.
- The topics of variability and uncertainty received considerable discussion. Some emphasized the importance of distinguishing between modeling uncertainty, which may be reduced by better/more information (reducible uncertainty) and system variability, which may be an unchangeable reality of diverse fuel pathways.
- There was some consensus about the importance of evaluating and reporting the variability and uncertainty of LCA studies. Several indicated the merits of conducting formal uncertainty analyses (Monte Carlo or other techniques) to better understand the range, or probability of results. How to incorporate this information into a regulatory setting is not clear.

- Some emphasized the need to blend LCA science and policy together in a way that creates a workable global approach. Perhaps current LCA methods are (or will become) workable in Europe and North America, but what about China and India, which will eventually dominate the motor vehicle market. The size of biofuels programs, and the rate at which they are implemented, are also important.
- Several participants emphasized the importance of having a simple process for LCA of fuels. If it becomes too complex, many loopholes will develop, which will diminish the effectiveness of the program. Some thought that defining a specific CI value for a particular fuel pathway implies more certainty than warranted. Perhaps it would be better (and simpler) to develop a broad ranking of fuel pathways, and combine those that have similar CI values into common "bins." Others pointed out that there will always be controversy about those cases that are "close to the line" that separates one bin from another.
- During the 2nd Open Forum Discussion, results from an opinion survey of the participants were presented as a way to foster further discussion of LCA-related topics. A wide diversity of opinions was apparent. With respect to the overall concept of LCA for fuels, there was general agreement that LCA approaches can provide results that are qualitatively useful, but there were mixed opinions about the quantitative reliability of these approaches in a regulatory sense. With respect to iLUC issues, most respondents believe the concept of iLUC has become better defined, understood, and accepted. However, opinions were mixed as to whether current modeling approaches provide reliable assessments of GHG emissions resulting from iLUC.
- Survey questions regarding LCA of transportation fuels were also posed in three general categories:

    1. Degree of progress (in specific LCA technical areas) over the past few years
    2. Need for further improvement in specific areas
    3. Priority areas requiring additional work

  Of the 12 specific areas identified under category 1 above, the degree of progress was deemed highest in co-product allocation and evaluation of feedstocks and processing pathways. The degree of progress was judged lowest in harmonization of LCA methods and data to support fuels LCA. The need for further improvement was deemed highest for reliability of LUC assessments, and assessments of iLUC emissions. With respect to prioritization of areas for further work, many areas were regarded as being of high priority. Among the highest priority items were (1) increase harmonization of different data sets to support LCA, (2) improve quantification of LCA uncertainty/variability, and (3) reduce the uncertainty of iLUC assessments.

APPENDIX I

Glossary of Terms Used During the Workshop

AEZ	Agricultural Ecological Zone
ALCA	Attributional Life Cycle Assessment
API	American Petroleum Institute
BC	British Columbia
CARB	California Air Resources Board
CARD	Center for Agricultural and Rural Development
CCLUB	Carbon Calculator for Land Use change for Biofuels
CGE	Computable General-Equilibrium
CI	Carbon Intensity; also Compression Ignition
CLCA	Consequential Life Cycle Assessment
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
$CO_{2,eq}$	Mass of a specified GHG expressed as a mass of CO_2 having equivalent GWP
CONCAWE	CONservation of Clean Air and Water in Europe
CRC	Coordinating Research Council
DEPS	Dynamic Energy Policy Simulator
DNDC	De-Nitrification De-Composition (model for N_2O emissions)
DOE	U.S. Department of Energy
DRI	Desert Research Institute
EC	European Commission
EER	Energy Efficiency Ratio
EF	Emission Factor
e-GRID	Emissions & Generation Resource Integrated Database
EIO-LCA	Economic Input-Output- Life Cycle Assessment Model
EOR	Enhanced Oil Recovery
EPA	(US) Environmental Protection Agency
EU	European Union
EV	Electric Vehicle
ExioBase	Multi-regional supply and use input/output database
FAME	Fatty Acid Methyl Ester (biodiesel)
FAO	Food and Agricultural Organization
FAPRI	The Food and Agricultural Policy Research Institute
FASOM	The Forest and Agricultural Sector Optimization Model
FORCARB	U.S. Forest Carbon Budget Model
FQD	Fuel Quality Directive
g $CO_{2,eq}$ MJ^{-1}	grams of CO_2, equivalents per MJ of fuel
GEMIS	Global Emission Model for Integrated Systems
GHG	Greenhouse Gas
GHGenius	LCA model used in Canada
GHOST	Green House gas emission Oil Sand Technology (GHG emissions model)
GLOBBIOM	Global Biomass Optimization Model
GNOC	Global Nitrogen Oxide Calculator
GRACE	Greenhouse gas Reduction through Agricultural Carbon Enhancement

GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GTAP	Global Trade and Analysis Project
GWP	Global Warming Potential
HCICO	High Carbon Intensity Crude Oil
HDRD	Hydrogenation-Derived Renewable Diesel
HWP	Harvested Wood Products
HWSD	Harmonized World Soil Database
IAM	Integrated Assessment Model
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
ILUC	Indirect (or Induced) Land Use Change
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JEC	JRC, EUCAR and CONCAWE
JRC	(EC) Joint Research Centre
LCA	Life Cycle Assessment
LCAOST	Life Cycle Assessment of Oil Sands Technologies
LCFS	Low Carbon Fuel Standard
LEM	Life Cycle Emissions Model
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LUC	Land use change
MIRAGE	Modeling International Relationships in Applied General Equilibrium
MODIS	Moderate Resolution Imaging Spectroradiometer
MOVES	Motor Vehicle Emission Simulator (EPA model)
N_2O	Nitrous Oxide
NBB	National Biodiesel Board
NPV	Net present value
NREL	National Renewable Energy Laboratory
OPGEE	Oil Production Greenhouse gas Emission Estimator
PEF	Product Environmental Footprint
PHEV	Plug-in Hybrid Electric Vehicle
RED	Renewable Energy Directive
REEV	Range Extended Electric Vehicle
RFS2	Renewable Fuels Standard
SCAQMD	(California) South Coast Air Quality Management District
SI	Spark Ignition
SOC	Soil Organic Carbon
SSA	System Sensitivity Analysis
TEM	Terrestrial Ecosystem Model
TTW	Tank-to-Wheels
USDA	U.S. Department of Agriculture
WTW	Well-to-Wheels
WTR	Well-to-Refinery
WTT	Well-to-Tank