Workshop 1 Report
USDA-NIFA Next Generation Land-Use Change Methodology Project

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University of Illinois at Chicago

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Executive Summary

Land-use change (LUC) is a critical issue that drives the sustainability debate concerning biofuels. Given these concerns and the potential for increased ethanol blend levels in gasoline, expanded volumes of cellulosic biofuels, and growing markets for U.S. biofuels abroad, characterizing LUC is an important piece of evaluating and designing a bio-based economy. Currently, new data analysis techniques and new data sources, including high-resolution satellite imagery, is enabling new insights into LUC.

In April 2014, a workshop convened analysts seeking to evaluate LUC and policy makers who find utility in these estimates. The workshop provided an overview of the federal agency and stakeholder perspectives on LUC and recent advances in LUC data and analysis. Breakout sessions were designed to identify data gaps and outstanding research questions.

Federal agency participants from the United States and Canada highlighted the importance of a clear understanding of LUC to underpin policy and research approaches and the questions that persist that limit current estimates of LUC. Academic, private sector, and governmental researchers and program leaders from federal agencies discussed recent advances in the programs they oversee or research they are developing to improve LUC estimates. Participants in breakout sessions discussed ongoing data needs, new remote sensing tools, and the value of establishing data repositories. There is abundant interest in assigning causation to LUC, but this remains difficult as estimating LUC itself with reliable confidence intervals is under development.

Key takeaways from the workshop include the need of federal agencies to understand LUC to develop policies and maintain environmental health while building the bioeconomy. One key point was that LUC can result in landscapes with enhanced ecosystem services such as reducing runoff and increasing carbon stocks.

Workshop participants anticipated new data sources including new, higher-resolution satellites equipped with new sensors (e.g., moisture) that will enable improved LUC estimates and characterization of associated environmental effects. Data fusion (e.g., LiDAR and aerial imagery) approaches should continue to be developed as well as improved methods to quantify uncertainty in LUC estimates from a number of quantification approaches. Machine-learning-based techniques are essential to reduce manual effort in LUC quantification and to reduce error.

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1. Introduction: Workshop Motivation and Structure

When land undergoes changes in vegetation, usage, or management, the carbon stock on that land can change and, if carbon stocks from vegetation or the soil is lost, the outcome can be greenhouse gas (GHG) emissions. In fact, land use, land-use change and forestry (LULUCF) is a key factor influencing greenhouse gas (GHG) emissions.[1–3] Methods to characterize land use change (LUC) and associated GHG emissions remain an active area of research and it is abundantly clear given the importance of LUC's contribution to GHG emissions that advances in quantification of LUC by type and with increasing spatial resolution is critical to understanding LUC drivers, developing strategies to mitigate LUC GHG emissions, and, eventually devise methods to attribute LUC to individual sources. Two different types of LUC are generally evaluated in these characterizations: direct LUC and indirect LUC. Direct LUC is directly observable within a certain land parcel that changes, for example, from grassland to agriculture. Indirect LUC occurs as a result of other LUC that causes demand for land to be put into a different use or land cover than it had previously been. In the case of corn ethanol, for example, LUC has been estimated based on modeling[4,5] and remote sensing-based analyses[6] that increased demand for corn will lead to increased farmland producing corn, driving production of other crops to land that was previously forest, grassland, wetland, or in other uses or states in the United States and internationally.

Biofuels offer an opportunity to reduce the life-cycle GHG emissions of transportation fuels.[7,8] That expanded production of biofuels has and could continue to cause high amounts of LUC GHG emissions is an ongoing concern that drives the biofuels sustainability debate. Given these concerns and the ongoing discussions of increasing ethanol blending levels, expanding volumes of cellulosic biofuels, and growing markets for U.S. biofuels abroad, the ability to understand land-use change is an enduring issue.[9–11] Moreover, the availability of new data analysis techniques and new data sources, including high-resolution satellite imagery, is enabling new insights into LUC.

Spurred by these trends, the U.S. Department of Agriculture has supported Northwestern University, the University of Illinois at Chicago (UIC), and the University of Illinois at Urbana Champaign (UIUC) to develop a defensible, next-generation approach to quantifying and characterizing LUC. This approach will make use of survey-based agricultural statistics, remote sensing data, and, finally, high-resolution satellite imagery interpreted through machine learning techniques.

To be useful to the community, analysts in this area and, more broadly, biofuel stakeholders need to be engaged in the discussion around building this approach. The project team is therefore holding three stakeholder workshops over the course of this effort.

The inaugural workshop was held April 4, 2019 at UIC and provided an overview of the federal agency and stakeholder perspectives on LUC and recent advances in LUC data and analysis. Significant time was allocated for discussion of these topics and identification of research gaps. The following sections summarize presentations and breakout discussions.

2. Federal Agency Perspectives on Land Use Change (LUC)

At the workshop, three federal agencies contributed presentations regarding their agency's perspective on land use change. The first of these, the Bioenergy Technologies Office (BETO) of the Department of Energy (DOE) represented by Kristen Johnson, described the importance in understanding LUC in the context of bioenergy sustainability (Figure 1). Kristen pointed out that some LUC scenarios can be beneficial, increasing carbon stocks on land and potentially increasing ecosystem services such as reducing nitrate in soil water. Being able to identify with greater detail what types of LUC are occurring and, with greater spatial resolution, the locations of these changes, can improve estimates of LUC greenhouse gas (GHG) emissions that may be affiliated with increased bioenergy feedstock production. Furthermore, current approaches to estimating LUC do not capture land management change (LMC) which could occur at the subfield level include practices such as reduced tilling, planting of cover crops, or application of manure. Coupled with LUC, LMC has significant influence over life-cycle GHG emissions of bioenergy and bioproducts. BETO leverages Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) life cycle analysis (LCA) model to quantify LUC associated with bioenergy and bioproducts. Finally, a better understanding of current land use would inform identification of areas where biomass could be grown, increasing understanding of biomass potential that drives estimates of the amount of bioenergy and bioproducts that can be sustainably produced domestically. Overall, BETO is looking for ways to improve understanding of LUC because the office wants to identify LUC scenarios that are beneficial and could offer sustainability benefits and because LUC is part of the factors about bioenergy and bioproduct pathways that drive BETO investment decisions in R&D approaches. Yet, one particular ongoing challenge in evaluating LUC is attributing its occurrence to one or more drivers including, for example, expanded use of biofuels, weather effects such as drought, or policy drivers that influence food prices. Kristen emphasized that one key outcome of ongoing research to advance LUC characterization is improved ability to estimate LUC with greater specificity and clarity about type and location of LUC. Again, accurate LUC estimates are a significant driver in understanding the benefits of the bioeconomy; they merit ongoing improvement in methodology.

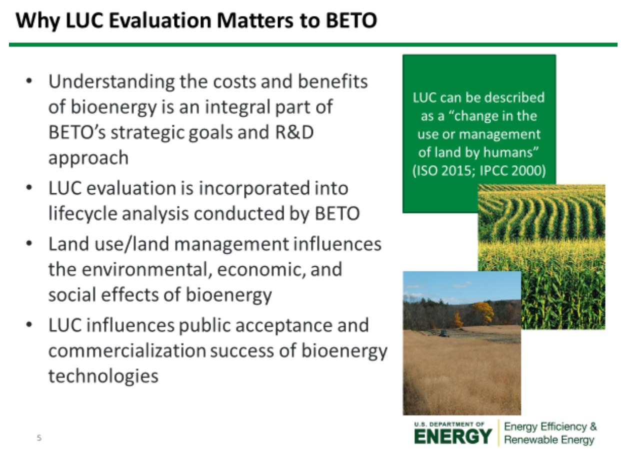


Figure 1. BETO motivation for characterizing LUC.

Chris Clark of the United States Environmental Protection Agency (EPA) indicated this agency continues to seek accurate characterization of LUC given the significant environmental effects LUC can have including on wildlife and water quality. He echoed Kristen's comments regarding the significant challenge of attributing LUC to any particular cause once it is characterized. In

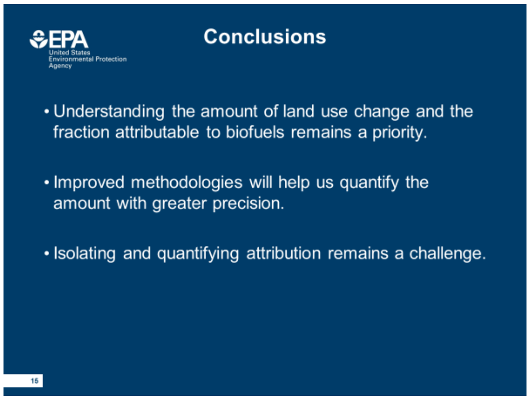


Figure 2. Chris Clark conclusions regarding LUC quantification.

the case of biofuels, it is especially difficult to tease out whether increased land in use for biofuel feedstock production is a result of specifically EPA's Renewable Fuel Standards (RFS). Raising a important question, he considered at what spatial scale LUC results are believable. Chris noted that a lack of ground-truthing limits the reliability of LUC estimates and pointed to the National Agricultural Imagery Program (NAIP) images as one way to ground truth although these images are not released annually for every state. Other ground truthing sources Chris mentioned included the National Resources Inventory and the Farm Services Agency common land unit data. He noted that the U.S. Forest Service has been pioneering methods to characterize LUC based on satellite imagery. Chris pointed out the need for evaluating systematic and unsystematic bias in LUC estimates. He concluded (Figure 2) that LUC characterization and attribution to biofuels remains a challenging priority for the agency.

The next presenter was from Natural Resources Canada (NRC). Devin O'Grady of NRC described his agency's efforts to develop the Canadian Clean Fuel Standard (CFS) which will take into account direct LUC. They are taking the European Union's Renewable Energy Directive (RED) as a starting point and are working to finalize sustainability criteria, considering how to treat imported biofuels and international biofuel certification schemes that include LUC.

Taken together, the discussions in this section highlight the ongoing importance of LUC characterization to federal energy and environmental agencies who would benefit from improved methods to characterize LUC.

3. Advances in Data and Analysis of Land Use Change

The second workshop session featured presentations from researchers working to improve LUC characterization or to develop or maintain data sets that can be used to understand LUC.

Keith Kline of Oak Ridge National Laboratory described his research into science-based assessments of the effects of bioenergy on land. He also emphasized the difficulty in attributing LUC to individual causes, pointing out that land scams are a driver of LUC that go

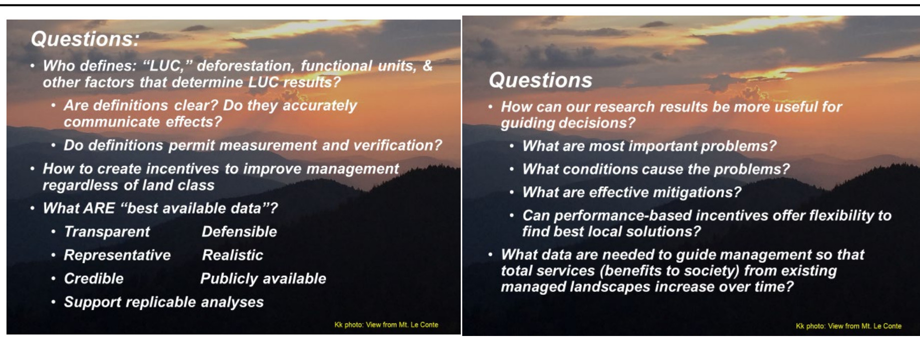
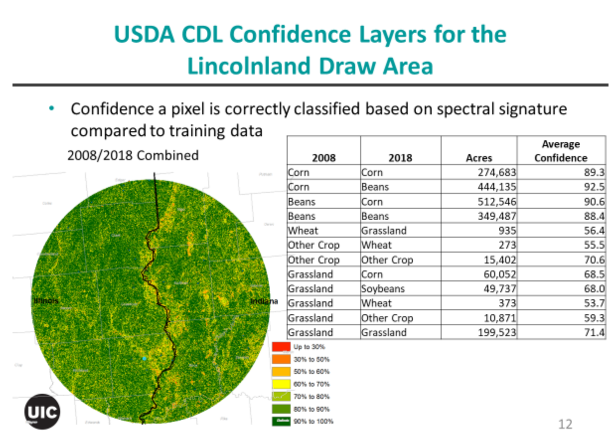


Figure 3. Research questions presented by Keith Kline.

unaccounted for in LUC studies. Among Keith's key messages were the need for consistent definitions of land types and of LUC itself. Furthermore, the baseline against which LUC is assessed is of critical importance and will undoubtedly influence results. He summarized key questions in quantifying LUC (Figure 3).



2008	2018	Acres	Average Confidence
Corn	Corn	274,683	89.3
Corn	Beans	444,135	92.5
Beans	Corn	512,546	90.6
Beans	Beans	349,487	88.4
Wheat	Grassland	935	56.4
Other Crop	Wheat	273	55.5
Other Crop	Other Crop	15,402	70.6
Grassland	Corn	60,052	68.5
Grassland	Soybeans	49,737	68.0
Grassland	Wheat	373	53.7
Grassland	Other Crop	10,871	59.3
Grassland	Grassland	199,523	71.4

Figure 4. CDL confidence estimates for corn, beans, other crops and grassland near the Lincoln Land Agri-Energy Plant in Illinois.

Ken Copenhaver of Cropgrower LLC presented results from a collaborative analysis among the University of Illinois at Chicago, Cropgrower, and Southern Illinois University at Edwardsville that has examined LUC around corn ethanol plants particularly in the U.S. Midwest. Effectively, the analysis seeks to establish the corn draw area of ethanol plants based on NAIP imagery and remote sensing data from the Cropland Data Layer (CDL) while identifying land in buffers, cover crops, and tillage. This type of analysis could therefore be used to evaluate LMC as described earlier. Importantly, this study seeks to quantify uncertainty in CDL classification of a pixel into individual land types in the form of a confidence estimate (Figure 4). Their analysis found that misclassification of land types is not uncommon with field edges frequently flagged as experiencing LUC and buffer strips also often subject to misclassification. Overall, this analysis effort is digging into characterizing uncertainty in LUC estimates and the methodologies applied and standards set will be of interest to the LUC evaluation community.

The next speaker was Patrick Willis of the United States Department of Agriculture National Agricultural Statistics Service (NASS). He described a number of USDA data products including the CDL, VegScape, and disaster analysis tools and noted that using spatial data in NASS is still a relatively new idea. The CDL itself has 11 years of continuous coverage and is developed based on satellite imagery and ancillary data such as the National Land Cover Dataset (NLCD) imperviousness and tree canopy data and state data. The CDL indicates land cover, but not land use. Ground referencing is also carried out and software tools such as decision tree software are applied to finalize land classifications in the CDL. The USDA uses these data internally to generate independent acreage estimates for U.S. major commodity crops through combining remote sensing imagery, Farm Service Agency data, and NASS survey data (June Area Survey). The USDA does not release survey segment data from the June Area Survey but releases land use strata maps.   Notably, the CDL contains classification accuracy data and full error/confusion matrices. Patrick noted that confidence layer data (Figure 5) are not a depiction of the accuracy of the assigned land use for a given pixel but is a measure of how well the classification fit within the rules set out in the decision tree.   There is significant consideration of how pixels has been classified over the 11 years of the CDL which can reduce survey costs and be used to impute missing survey data. The relationship between CDL and NLCD was also discussed; data processing techniques are similar but the CDL developers do not have access to NLCD validation data and so CDL cannot be used as an NLCD proxy. Notably, NLCD has a new shrubland layer. Also noted was that Sentinel 1 satellite data and the software that handles it are free. And, in the future, Sentinel 2 could enable higher resolution CDL data. Patrick discussed other data sets. For example, updated weekly, VegScape gives insight into vegetative cover and could be explored as a possible route to understanding LMC.

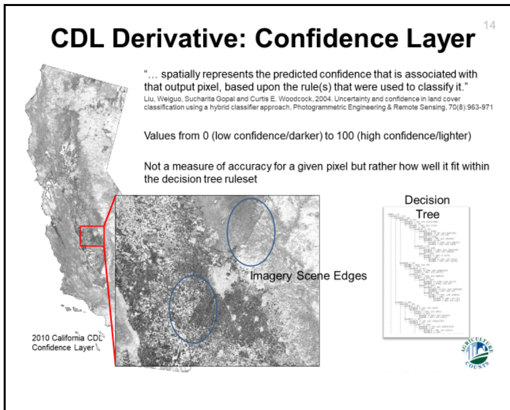


Figure 5. NASS produces a confidence layer as a CDL derivative

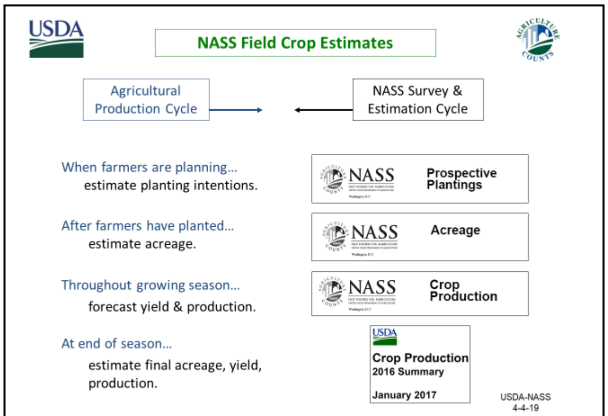


Figure 6. Field crop estimates are produced over the course of the season and will fluctuate given that farmers relaying their intentions for the year (Prospective Plantings) will not know about upcoming floods or droughts that will influence yields at the end of the season (Crop Production Summary).

Lance Honing from NASS spoke next about survey-based agricultural assessments. USDA NASS produces over 500 national reports annually in addition to over 9,000 state reports. NASS crop data derive from the Census of Agriculture, to which farmers are required to report, and administrative and remotely-sensed data. Additionally, USDA NASS collects data in four other voluntary surveys annually using mail, phone, internet and one-on-one interviews. The administrative data include certified acreage data from the Farm Service Agency in addition to data from the Risk Management Agency, Ag Marketing Service, administrative committees, and association check-off data. In using these data sources, analysts must understand the sources and quality of these data in addition to what the data represent to avoid misusing or mischaracterizing the data. Importantly, the timing of data collection is important to note as farmers relaying their intentions for the year will not know about upcoming floods or droughts that will influence yields at the end of the season (Figure 6). The CDL and NASS surveys are interrelated in that the CDL is used to verify what is being reported in the surveys. Lance reviewed recent data that illustrate changes in the amount of land producing corn and soy are the most notable drivers of changes in agricultural land area in the United States.

The next speaker, Tyler Lark, is from the University of Wisconsin and carries out research in geospatial analyses. Tyler reported that the use of CDL in academic research has been increasing over time with a 700% increase in Google Scholar citations since 2008 (Figure 7). Based on his work with the CDL, he presented several cautions and recommendations in working with this data source. For example, he pointed out that it is inadvisable to estimate area

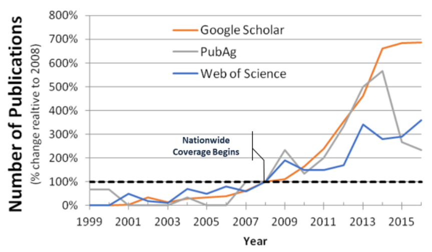


Figure 7. Research employing the CDL is increasing.

in a certain land cover by simple pixel counting, to measure incremental or pixel-level changes, and to attempt to identify land use. He cited best practices he and collaborators have developed including using all temporal data, using accuracy and confidence data, and validating with independent data. He further indicated that most misclassifications in using the CDL to identify LUC occur within cropland or non-cropland categories, and not between these two categories. His recent work with the CDL measuring eight years of conversion indicates a net increase in cropland of 6.6 million acres concentrated in the Dakotas, Iowa, Nebraska, and Missouri. His work is moving into evaluating the impacts of LUC including changes in irrigation and looking to attribute LUC to different causes including the Renewable Fuel Standard.

John Hogland of the United States Forest Service (USFS) reported on his research using NAIP imagery and LiDAR to characterize forests, understand woody biomass supply chains and costs, developing characterization techniques that leverage LiDAR, and considering issues of co-registration.[12] More specifically, Hogland presented RMRS Raster Utility, that is, a tool which provides the user with an intuitive Guided User Interface (GUI) to analyze remote sensing data. This tool allows for different types of sampling, and the sampled data can be mapped then to domains where useful information is extracted. Some examples of these transformations that RMRS Raster Utility supports are Normalized Difference Vegetation Index (NDVI), texture maps, or terrain Ruggedness index. Finally, different analyses can be performed on the mapped data. RMSR Raster Utility includes algorithms to carry out descriptive and exploratory analysis, hypothesis tests or clustering among others. His work offers the promise of leveraging NAIP imagery for understanding LUC and is an excellent foundation to continue to work from.

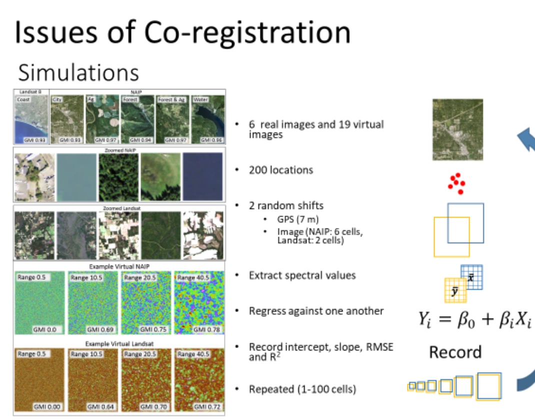


Figure 8. Hogland's work includes evaluating error that arises in co-registration approaches to characterizing landscapes

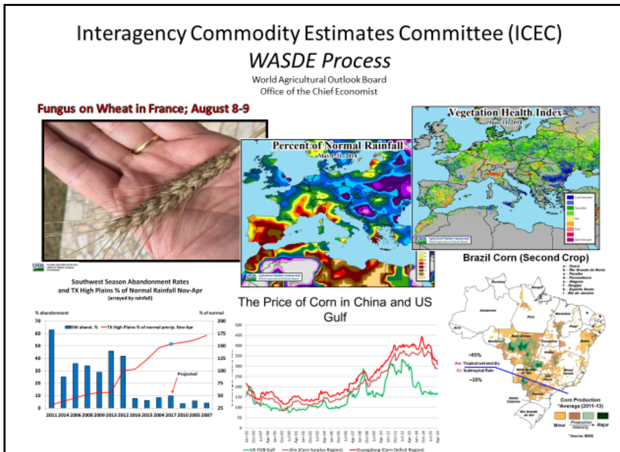


Figure 9. WASDE are based upon multiple data sources and influence agricultural markets.

The final speaker from USDA was Jan Lewandrowski, a senior economist who develops the World Agricultural Supply and Demand Estimates (WASDE). WASDE is an excellent example of an analysis that employs data fusion (Figure 9). It uses both NASS data for U.S. crop production forecasts but leverages other, non-survey based methods for regions outside the U.S such as data derived from satellite images, rainfall data, temperature data, and vegetation indicators. WASDE results influence markets. WASDE has objectives of providing unbiased, reliable, and timely information.

Pia Rothe from Global Risk Assessment Services (GRAS) reviewed a European perspective to remote sensing-based approaches to biomass certification. GRAS aims to evaluate whether biomass supply chains result in deforestation. EU legislation sets sustainability for biofuels and bioliquids that protect land with high biodiversity and carbon stocks. In particular, primary forests and wooded land and areas with rare or threatened ecosystems or species are protected. There should be no LUC after 2008 for areas that are specified in the legislation. GRAS relies on interpretation of satellite images for visualization as well as on-site visits. The GRAS on line tool that helps clients monitor LUC uses over 60 biodiversity databases to flag hotspots. A number of satellite products are also used including radar sensors. Furthermore, on individual sites, vegetation indices are helpful indicators of LUC or non-conforming activities such as replanting of palm plantations. To identify grassland conversion, GRAS uses a vegetative index and high-resolution satellite imagery in combination (Figure 10). The ISCC and other bodies are considering how to develop certification processes to address the next generation of the European Union's Renewable Energy Directive which came into effect on December 24, 2018. This directive puts a cap on food/feed based biofuels and requires high indirect LUC risk biofuels to be phased out prior to 2030. Potential routes to producing low indirect LUC risk biofuels include developing crops on abandoned or severely degraded land and leveraging improved agricultural practices and machinery on existing agricultural land. Methods to verify these and other standards remain under development but remote sensing methods could be used to identify abandoned land and verify the land use history. Overall, the sustainable certification model is a different approach to incorporating LUC into biofuel regulation that has been adopted to this point in the U.S. and, as Canada is looking to follow the EU example, it will be interesting to follow developments in both locations.

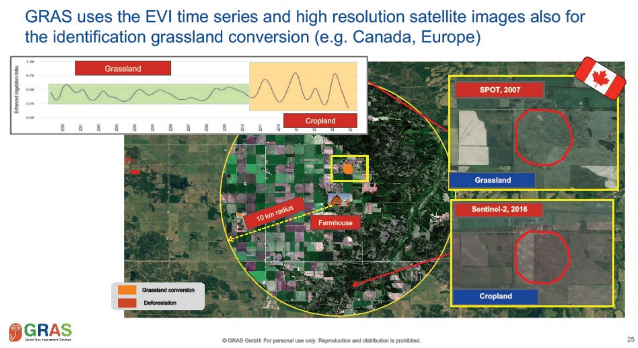


Figure 10. To identify grassland conversion, GRAS uses a vegetative index and high-resolution satellite imagery in combination

Taken together, the presentations at the workshop reflected the wealth of data sources that can be used in a consolidated approach to evaluating LUC and advantages and challenges to their application. Following these presentations, workshop participants gathered in groups to discuss, based on these presentations and their own experience, the critical questions in LUC research and research gaps that must be filled to address these questions.

4. Critical Questions in Land Use Change Research

In the first breakout session, participants addressed three posed questions.

4.1 How can we isolate biofuels production as a cause of land use change among other drivers of land use change (CRP release, commodity investments, urban or conservation land uses)?

This question remains quite difficult to address and participants did not have a definitive answer. Several indicators and factors were mentioned as playing a role in identifying LUC drivers. First, the role of co-products was highlighted as important as well as observing commodity prices. Second, it was noted that differentiating previous land use is critical to help define the quality of land prior to shifts in land use or land cover. The importance of consistent definitions was emphasized. International factors and policies play a role but are very hard to observe at or tie to local-level LUC. Local-level drivers are much more easily tied to local LUC. At what point are we overstretching the abilities of analysis to give us meaningful answers if we attempt to assess causality at a large scale? Yet, there remains a critical need to understand the influence of policies at a large scale. Additionally, the importance of adopting new data sources and methods to interpret them over time was raised although these evolutions will result in changes in reported results that must be explained. Overall, participants discussed managing the complex conversation of LUC while maintaining public trust given the intricacies of these analyses. Clear communication with stakeholders is critical.

4.2 To what degree do we need to know land quality and management before and after LUC?

Attendees raised several aspects of land quality and management that would be helpful to understand or have insight into about land undergoing LUC but that remain difficult to characterize:

- Tillage practices: A compendium of data on tillage practices would be helpful. The Conservation Technology Information Center data is noted as helpful but not entirely recent. Furthermore, tillage practices must be part of International Sustainability and Carbon Certification (ISCC) and Roundtable on Sustainable Biomaterials (RSB) certification processes. Are there other state or university resources that could shed spatially-specific light on this?
- Best practice information for farmer certification using existing tools and modification of tools to improve certification methods
- Inputs to agricultural systems including fertilizers, lime, and pesticides.
- Soil testing data, which is sometimes shared by testing labs in aggregate form. NCR-13 is a Regional Research committee that summarizes soil tests and testing data and, fertilizer sales data and may be a data source.
- Growing efforts to document land use for certifications and compliance protocols will expand interest in survey data of these types in general.

Certainly land quality and pre- and post-LUC land management changes are a key driver of the effects of LUC on greenhouse gas emissions and water quality and using data to evaluate these influences remains an open research area.

4.3 Additional questions, points and key takeaways

It was noted that some LUC can be favorable, that is, results in increased carbon storage and ecosystem services such as reducing agricultural runoff. How can LUC analyses pinpoint where these beneficial LUC are occurring and inform policy and incentives to encourage this type of LUC?

Furthermore, in the European Union, documentation on the part of farmers has a finite time horizon, but the land use and land management information in that documentation has long-term value. How can data sources such as these be (perhaps selectively to capture only what could be considered "important") preserved and how widely can they be shared given confidentiality concerns?

Notably, commodity prices influence the agriculture industry significantly. The current state of the industry also influences agricultural research funding and, perhaps, collection of data that informs evaluation of LUC. Both LUC and the data that inform it are therefore driven in part by commodity prices.

This session highlighted the need for sharpening machine-learning based processing tools applied to the various data sources as a prerequisite for analyzing and interpreting the various sources of data which are notably rich. In particular, NASS data has been expanding and improving and should be a key resource in evaluating LUC. Importantly, big picture trends, rather than minute details of LUC should perhaps be the focus because it is these types of changes that can inform policy decisions. At the same time, local landscapes drive critical local impacts that LUC influences such as biodiversity and water quality and these indeed drive the potential global influences on climate of an expanding bioeconomy. Importantly, many drivers influence LUC and where possible, multiple drivers should be considered comprehensively although LUC attribution is another full field of research that is very young. Critically, evaluating LUC itself using multiple data sources remains in need of further methodology development in multiple areas including machine learning-based and data fusion techniques – without reliable, transparent, and accurate LUC assessment, assigning the causes of LUC holds little meaning.

5. Research Gaps in Land Use Change Analysis

In the second breakout session, participants addressed four posed questions.

5.1 What additions to the USDA Surveys may be helpful to better assess land use change?

Overall, the point was made that LUC analyses can tell us based on remote sensing and aerial imagery interpretation what farmers are doing within a confidence interval, but not how they are doing it. The need for additional data on tillage practices including perhaps more frequent Agricultural Resource Management Surveys (ARMS) and additional questions on existing surveys was highlighted multiple times. ARMS surveys address long-term tillage, but tillage is not addressed on an annual basis. Furthermore, definitions of tillage practices would be helpful.

In addition to more information on tillage, additional information on fertilization by fertilizer type and amount applied would be useful.

It was noted that FSA data includes personally identifiable information that limits its availability for detailed analyses. If there were a method to obscure or aggregate the data, this could be useful, but there could be unintended consequences.

In general, roadblocks to adding or changing surveys include lack of clarity for farmers if wording is complicated and adding questions has a cost to USDA or the surveying agency that must be considered.

5.2 What new remote sensing tools (e.g. Sentinel satellite) to assess LUC going forward will most likely improve LUC assessments?

Several new data sources on the horizon were discussed. Moisture data from NASA are now being leveraged in incorporated into USDA's Crop Explorer website. Furthermore, the potential to use drones through crowd sourcing to farmers to collect high-resolution imagery was an interesting proposal that may run up against confidentiality concerns discussed above if attempted at a large scale. On the other hand, if a citizen science approach were taken to drone imaging as a field validation tool to complement the field-survey based validation the application of drones to evaluating LUC could be more feasible.

The ability to be certified by NASS to work with data on a finer-scale than county-level is helpful but must be weighed against maintaining farmer trust. In general, sharing survey data at the latitude-longitude level is not possible because these data are highly protected. Even if a subset of farmers were willing to share data, this would not help with understanding detailed LUC at a national level.

Regarding the CDL, several possible advancements were noted as being particularly helpful including having a finer-level accuracy assessment, making cautions around data usage more clear, and more clarity in the error range. Furthermore, a clearer disclaimer of areas or pixels possibly containing multiple classes such as at field edges could be helpful.

The Sentinel satellite also holds promise for potentially delivering a multi-temporal vegetation index. Applications of Sentinel data to NASS analyses is intriguing but potentially not feasible because data quality may not be sufficient.

Having NAIP imagery collected with more frequency and continuing techniques to pair it with LiDAR for additional insights was noted as having significant utility.

Finally, Google Earth Engine was noted as a data source worthy of more exploration.[13]

5.3 Given what we've learned about LUC from the tools we are discussing today, would we be in a better position to model the impact of a biofuels policy today than we were 10 years ago? Could we do it better today? If yes, why? If no, why?

Although it was difficult for participants to answer this question, there was hope that as Canada develops its CFS it will leverage the lessons learned from LUC analyses in the U.S. and the European Union. Some data from the University of Wisconsin was provided to economic modelers who develop the Global Trade Analysis Project (GTAP) model at Purdue which may be used for validation of that general equilibrium economic model which has been used in national and state-level renewable fuels policy in the U.S.

5.6 Would there be value in establishing a repository for ground truthed data sets (cover crops, biodiversity parcels, grasslands, etc.)?

Overall, participants saw value in establishing a data repository for ground truthed data sets with various options discussed for collecting such data through citizen science or research projects.

5.7 Additional questions, points and key takeaways

The hunger for more data among workshop participants was evident. Questions remain around how to build community such that funding opportunities can be collectively pursued to collect, store, and share these data and how the research community can continue to work with federal and state agencies to improve how the data they collect is used and interpreted. Tools such as machine learning applied to both remote sensing data and aerial imagery are still at the early stages of development and application and remain a rich area for research. Furthermore, it remains an open question of how to use improved understanding of LUC from evaluation of these data sources with these emerging tools to inform economic modeling and, eventually, policy and incentives for beneficial LUC and land management.

Some additional questions were raised including the following:

- What advances in machine learning can we apply and develop for LUC assessments (e.g. interpretation of visual imagery)?
- What other tools stand out as promising for future LUC assessments?

6 Conclusions and next steps

This workshop assembled experts in the evaluation of LUC with survey data, remote sensing data, and areal imagery and fostered discussion of challenges with existing data sources, which new data sources are on the horizon, and which new data sources would be most valuable. Furthermore, methodology of applying these data sets was explored and research questions surrounding methodology development were also discussed.

It is clear that federal agencies need to understand LUC to develop policies and identify routes to increasing environmental quality and health while enabling the critical goods and services agriculture provides. Importantly, it was recognized that LUC can be beneficial with desirable outcomes such as reducing runoff and increasing carbon stocks.

Furthermore, the United States has a rich data environment for application to questions of LUC but new data sources on the horizon including new, higher-resolution satellites equipped with new sensors (e.g., moisture) will continue to enable new and better estimates of LUC and corresponding environmental effects, notably through data fusion approaches. Furthermore, to speed analysis and make use of data sets that are increasing in size and number, the development of machine-learning-based techniques to evaluate LUC is essential. In efforts to use new and existing data sources, uncertainty quantification remains a critical need to enable results interpretation and any subsequent policy development. A clear interest among workshop attendees is assigning causation to LUC which will be strengthened by robust and defensible methods to quantify LUC with associated uncertainty.

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