Use of Remote Sensing to Measure Land Use Change from Biofuel Production

by STEFFEN MUELLER AND KEN COPENHAVER

▶ Studies assert that the conversion process of native ecosystems to agriculture for biofuel production may result in carbon releases from native biomass and negatively affect the greenhouse gas profile of biofuels.

Over the last three years, academics and others have frequently recognized that expanded production of biofuels is one means of reducing the U.S. dependence on foreign transportation fuels. However, several studies assert that the crop demand for biofuel production may prompt conversion of native ecosystems to agriculture. This conversion process of ecosystems may, in turn, result in carbon releases from native biomass and negatively affect the greenhouse gas (GHG) profile of biofuels (Righelato and Spracklen 2007; Searchinger et al. 2008).

The California Air Resources Board and the U.S. Environmental Protection Agency (EPA) are currently in the advanced stages of developing rules on how to quantify and include GHG emissions when comparing the environmental impacts of different fuel pathways (California Environmental Protection Agency 2009). The initiating legislation for the rulemaking process are California's Low Carbon Fuel Standard (LCFS) and the federal Renewable Portfolio Standard (RPS), which require the GHG emissions from biofuels to be assessed on a full life cycle basis, including contributions from direct and indirect land use change.

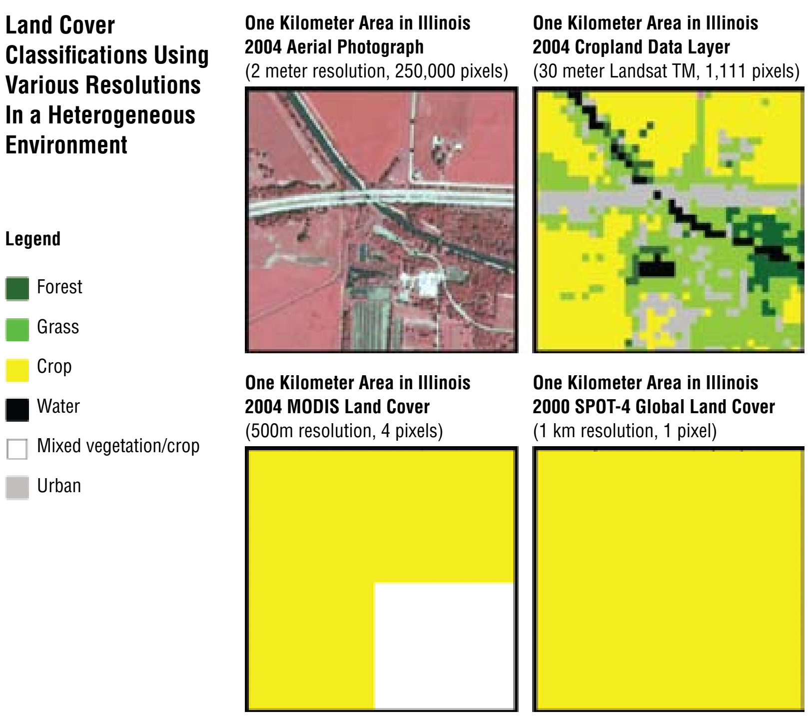


Figure 1 Scene 1 in Illinois: satellite imagery with different resolutions.

GHG emissions from direct land use change are generally considered those associated with the direct supply chain of biorefineries (Plevin and Mueller 2008). For corn ethanol, such emissions include those from land converted to a corn crop to meet the incremental demand of an ethanol plant. Economics-based indirect land use change models take into account market forces that induce land use change on domestic but mostly foreign land that is not part of the direct supply chain (Kim, Kim, and Dale 2008). For example, one proposition of these modeling efforts is that increased ethanol production in the United States leads to more widespread planting of corn, which reduces the area available for soybean production, thereby reducing U.S. soy exports. In turn, other countries such as Brazil will adjust their agricultural land use and ultimately convert native land to meet the soybean shortfall created by U.S. biofuel production.

The quantification of the GHG impact from this process is captured by models in a two-stage process: (1) the adjustments in land surface area converted to crop production in different countries are quantified for various U.S. biofuel production scenarios (for example, the number of new hectares in corn or soybeans in each country), followed by (2) an assessment of what types of ecosystems are being converted to crop production (for example, rainforest to corn or savannah to soybeans). Most datasets used to assess the types of ecosystems conversions under way for biofuel production are based on remotely sensed imagery. However, we are not aware of a sound assessment of the accuracy of remote sensing for land use changes associated with biofuel production. The hypothesis of this study is that the accuracy of these global remotely sensed information products is insufficient for determining land use changes from biofuel production.

The use of remotely sensed imagery for the determination of land cover is well documented. Since the 1970s and the launch of the first Landsat satellite by the U.S. National Aeronautics and Space Administration (NASA), this imagery has been classified with good success into land cover parcels. The type of cover usually indicates the land use. For example, if the land cover is pavement, it is safe to assume the land use would be human development or urban. When compared from year to year, satellite imagery can identify changes in land use. If an area is identified as agriculture one year and human development the next, it may be assumed that the area is one of urban encroachment.

Comparison of Spatial Resolutions for Different Sensors

The recent introduction of remote sensing datasets into the assessment of land use change associated with the possible expansion of agriculture to accommodate biofuel production seems obvious. Remote sensing offers an opportunity to directly image the extent of land use change, but the errors associated with the classification must be taken into account. For example, if 15 percent of forested areas is incorrectly identified in year one and 10 percent is incorrectly identified in year two, the error range totals 25 percent. Another common problem with land use change is the nature of the occurrence itself. Land use change usually occurs in transition areas between two land cover types such as forestry and agriculture. These transition areas are prone to misclassification from a mixed pixel effect. A pixel is the minimum area on the ground for which one value associated with the intensity of light reflected from the earth's surface is being recorded. If the area within a pixel consists of more than one land cover type, it can be misclassified, especially from one year to the next. These errors may seem minor, but when one is assessing land use change on a regional scale over millions of hectares, small percentage errors can indicate large, incorrect changes. The higher the number of pixels recorded by a sensor for a given surface area, the higher is the spatial resolution of the imaging system.

▶ The study presented here hypothesizes that the accuracy of global remotely sensed information products is insufficient for determining land use changes from biofuel production.

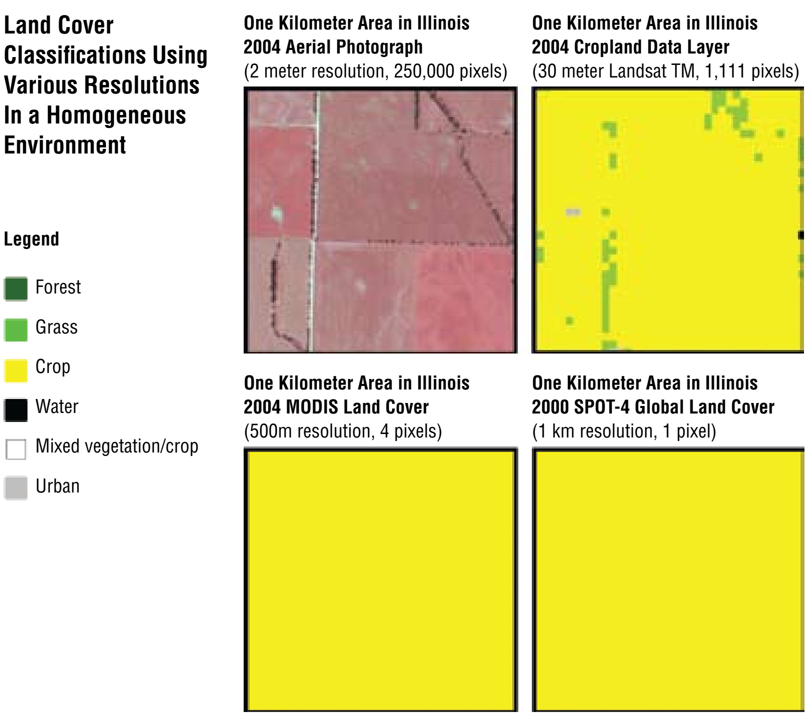


Figure 2 Scene 2 in Illinois: satellite imagery with different resolutions.

Figure 1 shows a 1-kilometer area in Illinois captured with sensors on board different satellites. Depending on the spatial resolution of the sensors on the satellites, the 1-kilometer area is divided into different amounts of pixels. At the top left of Figure 1 is an aerial photograph of the scene showing agricultural land, water, urban buildings, and roadways. Indeed, buildings and roadways make up a significant part of the scene.

At the top right of Figure 1 is the same scene by means of the 30-meter resolution Landsat Thematic Mapper (TM) sensor used by the U.S. Department of Agriculture (USDA) for the NASS Cropland Data Layer from 1999 to 2005. The USDA NASS Cropland Data Layer classification for 2004 using the Landsat TM captures the waterway, grass, forest, and urban areas. Currently, USDA NASS is using the AWiFS sensor for the Cropland Data Layer with a resolution of 56 meters, which is close to that of Landsat (AWiFS also has a shorter revisit time of five days versus seventeen days for TM, which increases accuracy).

In the lower left corner of Figure 1 is the same scene by means of the 2004 Global Landcover Classification's 500-meter resolution from the MODIS sensor. According to the EPA, its modeling efforts for life cycle analyses of the Renewable Portfolio Standard are relying on MODIS satellite data. The figure reveals that the use of MODIS results in significant reductions and that one pixel now combines forest, crop, and urban areas into one "crop" category.

In the lower right corner of Figure 1 is the Illinois scene with a 1-kilometer resolution from the SPOT-VEGETATION sensor, which, for example, is used for the "New IPCC Tier-1 Global Biomass Carbon Map for the Year 2000" (Ruesch and Gibbs 2008). By means of this sensor, the complete scene is further reduced and characterized as cropland. Figure 2 provides a similar demonstration for a more homogeneous land cover scene in Illinois. The MODIS and SPOT sensors combine the mixed land cover in that scene into one cropland category.

For the study described here, we chose the best possible sensors to determine the accuracy of modeling direct and indirect land use while acknowledging the trade-off between resolution and cost (availability). Therefore, direct land use change was modeled using the higher resolution AWiFS sensor, whereas indirect land use change was modeled using MODIS because this sensor produces a global land cover product. The region chosen for direct land use modeling was the corn supply area for an ethanol plant in Illinois; indirect land use change was modeled for Illinois and Brazil.

▶ **Land use change usually occurs in transition areas between two land cover types such as forestry and agriculture.**

▶ **The region chosen for direct land use modeling in this study was the corn supply area for an ethanol plant in Illinois; indirect land use change was modeled for Illinois and Brazil.**

Direct Land Use Change

In a previous study, we assessed land use change in a 40-mile circle surrounding an ethanol plant in Illinois (Mueller and Copenhaver 2008). For this study, we have further analyzed the data because it is representative of the accuracies that can be achieved in direct land use change assessments. The assessment uses the USDA NASS Cropland Data Layers for 2005, 2006, and 2007 (developed by USDA NASS using AWiFS imagery with 56-meter resolution and five-day revisit time for agricultural areas) combined with the 2001 National Land Cover Dataset (NLCD) for nonagricultural classifications, which is currently the most recent version.[1] The overall accuracy of the cropland data for Illinois in 2007 is 97.6 percent (cropland data include only agricultural classes).[2] The error range for land use change between two years, in this case for Illinois, would approximate 2 × (1 – 0.976) = 4.8 percent.

However, the accuracies of the 2001 NLCD are lower and not consistently assessed. The NLCD has not been formally assessed for accuracy on a national basis, but overall accuracy assessments have been estimated at 83.9 percent (Homer et al. 2007). Furthermore, roadways and field fringes introduce further inaccuracies. Therefore, the accuracy assessment of our direct land use parcel employed an additional vetting routine.

The data revealed that 39,841 hectares out of the 601,994 hectares in corn (or 7 percent) during the study year 2007 would have been predicted to change from nonagricultural use to corn. However, in further analysis, we performed additional vetting of the data by applying a routine to the masked area that subtracted a 0.3 hectare buffer along the roadways. Subtracting the roadway buffers resulted in a significant drop in the nonagricultural categories from a total of 39,841 hectares to 1,663 hectares, or 0.27 percent of predicted nonagricultural land use change. We took about fifty test samples with aerial photography to confirm that these parcels were indeed roadway buffers or field fringes around agricultural land (see Figure 3). The characteristics of roadway buffers and fringes are such that very minor changes in vegetation can prompt change in land use classifications. Furthermore, an additional 10,771 hectares that, in the imagery evaluation routine were classified as agricultural to nonagricultural to agricultural conversion (an unlikely scenario) over the three-year period 2005–2007, were categorized separately. Test samples again confirmed that agricultural to nonagricultural to agricultural conversions are misclassified. In fact, the land remained in continuous corn rotations.

We conclude that for direct land use change assessments for biofuel production in which the emphasis is on changes from nonagricultural land to agricultural land the lower accuracy of the NLCD as well as roadways and field fringes may lead to significant overestimations of land use change (39,841 hectares from nonagricultural use to corn versus 1,663 hectares). Therefore, the data require additional vetting for direct land use assessments (Table 1). Because the additional vetting affected primarily (nonagricultural) NLCD classifications, it is clear that the vetting process raised the lower accuracy associated with the NLCD to cropland data levels (in excess of 95 percent).

[1] A new version is expected in 2010. Information on the National Land Cover Dataset is available from the website of the Multi-Resolution Land Characteristics Consortium (MRLC) at http://www.mrlc.gov.

[2] Accuracies for all USDA NASS Cropland Data Layers are available at http://www.nass.usda.gov/research/Cropland/metadata/meta.htm.

This 2.8-hectare area was classified as woodlands in 2006 and corn in 2007, but it appears to have been in agricultural production both years. Trees surrounding the field likely led to the misclassification in 2006.

Figure 3 Field fringe test sample.

Table 1 Unvetted and Vetted AWiFS (NASS USDA) Crop Data

	2007 crop area in 2006	
Land use	**NASS unvetted hectares**	**NASS vetted hectares**
Corn	276,370	275,324
Soybeans	269,417	267,764
Winter wheat	5,848	6,081
Other small grains	299	111
Winter wheat/soybean double cropped	113	45
Alfalfa	2,809	1,238
Other crops	4,537	3,815
Fallow/idle cropland	2,760	651
Grass/pasture/nonagricultural[a]	37,639	1,611
Woodland[a]	1,401	49
Urban/developed[a]	747	2
Water[a]	49	0
Wetlands[a]	4	0
Agric. in 2005 to nonagric. to agric.	0	10,771
Field and roadway fringes	0	34,531
Total analyzed	601,994	601,994

[a] Of the total of these nonagricultural categories, 39,841 of the NASS unvetted hectares were converted to corn and 1,663 of the NASS vetted hectares were converted to corn.

▶ Analyses of land cover predicted for Brazil indicate that there is some potential confusion about the amount of natural vegetation being converted into cropland.

▶ We conclude that the MODIS datasets are fairly inaccurate for predicting land use changes from or to forested areas in Illinois and areas with similar ecosystems.

Indirect Land Use Change

NASA offers a global land cover product that was developed from the agency's MODIS sensors on board the Terra and Aqua satellites. As pointed out earlier, the MODIS remote sensing data have been considered for land use change modeling of biofuels for regulatory purposes. Therefore, the accuracy of land use change predicted with MODIS land cover data was selected for further assessment.[3] The MODIS sensor collects images at 250-meter, 500-meter, and 1-kilometer resolution pixels over the earth's entire surface on a daily basis. The dataset, known as MCD12Q1, is processed at the 500-meter resolution. The global land cover product was developed on an annual basis from 2001 to 2005 by combining cloud-free MODIS images throughout the year and analyzing these multitemporal datasets for land cover based on the reflectance and a detailed network of ground truth information.

The MCD12Q1 actually comes in different land cover classification schemes, including one developed by the University of Maryland and another that breaks agriculture into cereal and broadleaf crops. This analysis used the International Geosphere-Biosphere Programme (IGBP) land cover types, but they were aggregated to facilitate data analysis (see Table 2).

An analysis of land cover predicted for Brazil for 2001 and 2004 by the MCD12Q1 dataset does show a decline in the number of hectares in forest and shrubland and an increase in cropland, but it also shows a considerable increase in savanna and a significant decrease in the mixed/crop class (Table 3). These classifications indicate that there is some potential confusion about the amount of natural vegetation being converted into cropland.

The accuracy associated with these MCD12Q1 land cover classifications should be taken into consideration when determining the relevance of change measured with these datasets. The NASA land cover team gathered ground truth points from various locations throughout the world and then compared those points with the results from the land cover classification. For the current version of the MCD12Q1, version five, there are no published errors; the most recent published errors are for version three (Boston University 2009). Because it is unlikely that version five will have achieved a significant increase in accuracy for the purposes of this analysis, the accuracies associated with version three will be used. Table 4 lists the probabilities, in confidence values, that each pixel will meet the accuracy of the ground truth used to develop the map.[4]

[3] The MODIS dataset can be downloaded at no charge by the general public at ftp://e4ftl01u.ecs.nasa.gov/.

[4] The table is reproduced from http://www-modis.bu.edu/landcover/userguidelc/consistent.htm.

Table 2 Reclassification of IGBP Classes

IGBP classification scheme	Classification scheme used for this analysis
Water	Water
Evergreen needle-leaf forest	Forest
Evergreen broad-leaf forest	Forest
Deciduous needle-leaf forest	Forest
Deciduous broad-leaf forest	Forest
Mixed forest	Forest
Closed shrublands	Shrub
Open shrublands	Shrub
Woody savannas	Savanna
Savannas	Savanna
Grasslands	Grassland
Permanent wetlands	Wetland
Croplands	Crop
Urban and built-up	Urban
Cropland/natural vegetation mosaic	Mixed
Permanent snow and ice	Other
Barren or sparsely vegetated	Other

▶ **The accuracy of remote sensing for land use analyses generally varies by the type of land use and the resolution of the sensor.**

If a class has a confidence value of 70 percent, each location in this class has a 30 percent probability of incorrect classification. Anyone assessing changes in a class from year to year, then, must take this error into account. If the amount of change in the class is less than the amount of potential error, there is a real chance that the change may be incorrect. For example, if a class consists of 1 million hectares in 2001 and 800,000 hectares in 2004 but its accuracy is 70 percent, then that class could be off by up to 300,000 hectares in 2001 and 240,000 hectares in 2004, creating a total error of 540,000 hectares. With the potential error of 540,000 hectares for a 200,000-hectare change, it may be difficult to use this change with a high level of confidence.

For this analysis, the potential error for each class was applied to the 2001 and 2004 MODIS datasets. Specifically, the error was applied to the hectares for each individual class and then combined to ensure accuracy (see Table 5). These errors, when applied to the data, bring into question efforts to calculate change in a number of these classes to or from crop. The combined error range for land use change in forestland, for example, could total 90 million hectares. In Brazil, about 28 million hectares are in crops each year. Figure 4 illustrates the scale of these values. The combined error range for land use change for savanna is even greater—almost seven times as many hectares in question (192 million) as land in crops (28 million). If the error range far exceeds the land use transitions predicted for biofuel production, then these datasets are not suited to support sound analyses in this field. In fact, the Global Landcover Validation report states that the purpose of the MCD12Q1 datasets is to assess global land cover and that they should not be used to assess interannual change (Strahler et al. 2006).

Finally, we analyzed MODIS imagery for Illinois and compared the results with tabular survey data compiled by the U.S. Forest Service and the USDA NASS. Figure 5 shows that MODIS underestimates the surface area of forests by 75 percent, whereas

Table 3 NASA MCD12Q1 Land Cover Classification Dataset, 2001 and 2004

Land cover	2001	2004	Difference
Forest	393,451,000	382,090,000	–11,361,000
Shrub	5,394,000	2,720,000	–2,674,000
Savanna	272,622,000	312,837,000	40,215,000
Grassland	45,449,000	23,965,000	–21,484,000
Wetland	10,450,000	11,296,000	846,000
Crop	27,869,000	28,110,000	241,000
Urban	3,924,000	3,921,000	–3,000
Mixed/crop	85,737,000	79,866,000	–5,871,000
Barren/snow	705,000	225,000	–480,000

Table 4 Global Confidence Values by Land Cover Class

IGBP land cover class		Confidence value (percent)
1.	Evergreen needleleaf	68.3
2.	Evergreen broadleaf	89.3
3.	Deciduous needleleaf	66.7
4.	Deciduous broadleaf	65.9
5.	Mixed forest	65.4
6.	Closed shrubland	60.0
7.	Open shrubland	75.3
8.	Woody savanna	64.0
9.	Savanna	67.8
10.	Grasslands	70.6
11.	Permanent wetlands	52.3
12.	Cropland	76.4
14.	Cropland/natural vegetation	60.7
15.	Snow and ice	87.2
16.	Barren	90.0
17.	Water	n.a.
	Average value, all classes	70.7
	Area-weighted average	78.3

n.a. = not available.

Table 5 Hectares Possibly in Error from MODIS Land Use Change Analysis

Land cover	Hectares possibly in error in 2001	Hectares possibly in error in 2004	Total
Forest	46,910,000	43,070,000	89,980,000
Shrub	1,870,000	980,000	2,850,000
Savanna	89,910,000	102,500,000	192,410,000
Grasslands	13,360,000	7,050,000	20,410,000
Crop	6,580,000	6,630,000	13,210,000

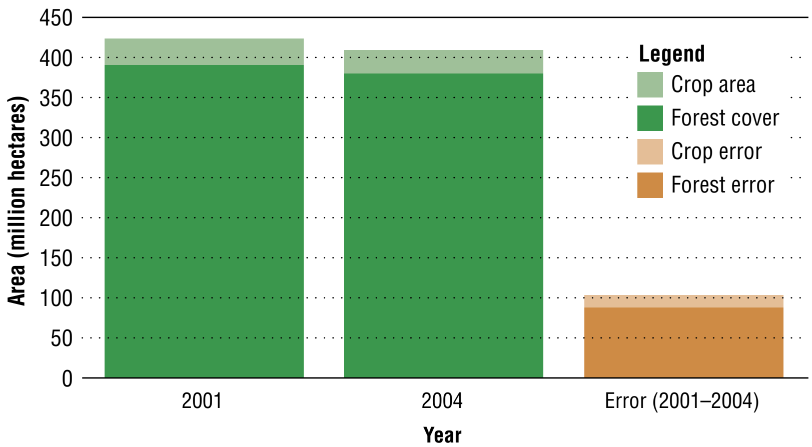
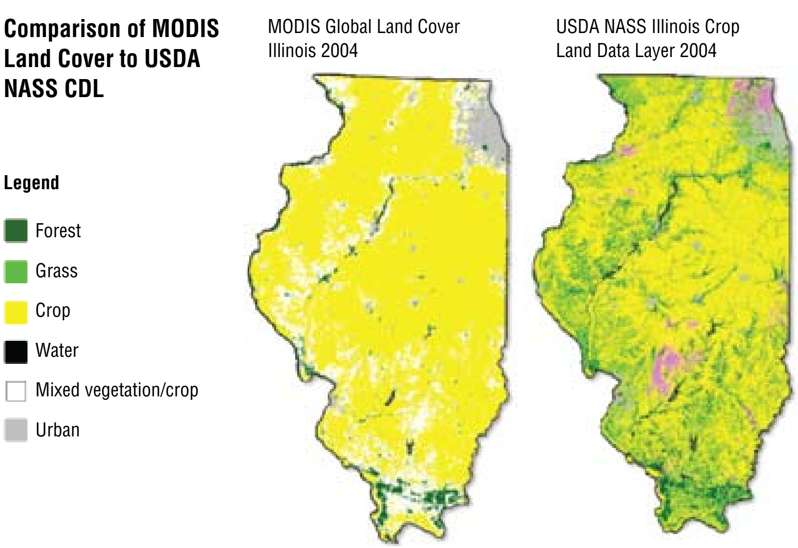


Figure 4 Land use and land use error for Brazil, determined using MODIS.



Class	MODIS Acres for Illinois in 2004	Tabular Data
Forest	1,127,000	4,423,000
Cropland	26,989,000	23,515,000

Figure 5 MODIS imagery for Illinois.

it overestimates the surface area of cropland by 15 percent. We conclude that the MODIS datasets are fairly inaccurate for predicting land use changes from or to forested areas in Illinois and areas with similar ecosystems (such as other Midwestern states).

Conclusions

The accuracy of remote sensing for land use analyses generally varies by the type of land use and the resolution of the sensor. For changes in crop types between two years, for example, Landsat or AWiFS imagery can achieve a combined error range as low as 4.8 percent (Illinois, 2.4 percent error for each year), which is sufficiently accurate in combination with survey data for many types of cropland statistics (including the USDA NASS Cropland Data Layer sets).

For this study, we assessed the accuracy of remote sensing for land use changes—both direct and indirect—expected from biofuel production. For direct land use change assessments for biofuel production in the United States that look at changes from nonagricultural land to agricultural land, the lower accuracy of the current National Land Cover Dataset as well as roadway and field fringes may lead to significant overestimations of land use change. Without additional vetting, we would have predicted land use changes from nonagricultural land to agricultural land of 39,841 hectares (or 7 percent of all hectares in corn in a given area), whereas the vetted data revealed that only 1,663 hectares were probably converted to agricultural land (or 0.27 percent of all hectares in corn in a given area). Because the additional vetting affected primarily (nonagricultural) NLCD classifications, it can be asserted that the vetting process raised the lower accuracy associated with the NLCD to cropland data levels (in excess of 95 percent for land use change assessments).

Looking at indirect land use changes in Brazil, we found that for land use changes such as those that might be associated with biofuel production (forest to cropland), the combined error range between two years was larger than the predicted change. The combined error range for forest land use change, for example, could total 90 million hectares, whereas the total amount of land in crops in Brazil is about 28 million hectares a year. If the potential error far exceeds the predicted change, then using these datasets is tenuous at best.

As for indirect land use change in Illinois, for forest ecosystems MODIS underestimates the surface area by 75 percent. For cropland, MODIS overestimates the surface area by 15 percent. We conclude that the MODIS datasets are fairly inaccurate for predicting land use changes from or to forested areas in Illinois and areas with similar ecosystems (such as other Midwestern states).

In summary, direct land use changes for biofuel production can be assessed using higher resolution imagery from sensors such as Landsat and AWiFS (30 meters and 56 meters, respectively) if the data are further vetted for field and roadway fringes. The accuracy of this process is likely in excess of 95 percent. An assessment of indirect land use changes for biofuel production using imagery from SPOT-VEGETATION or MODIS produces results with high inaccuracies. In fact, the combined error range may exceed the predicted land use change between important ecosystems such as the conversion of tropical rainforest to cropland in Brazil. Regulatory agencies such as the California Air Resources Board and the U.S. Environmental Protection Agency, which are in a rulemaking process to incorporate land use considerations in biofuel production, must consider the limitations of remote sensing for this purpose. We recommend that land cover products based on high resolution AWiFS imagery for transition regions associated with indirect land use change be created.

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