

# Investigations of Carbon Sequestration and Storage Using Advanced Geospatial Analysis

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**Abstract:** This research demonstrated quantitative methods of geospatial analysis applicable to carbon sequestration and storage in the conterminous United States. We identified national-scale NEP (net ecosystem production) changes for conversions to and from crop, and land in frequent conversion among forest, wetland, pasture and rangeland. The trend showed an increase in the margins of the Corn Belt states and coincided with land conversion from previous non-cropland to cropland in the United States. This research will not only improve the engineering understanding of carbon dioxide removal options involving the terrestrial biosphere, but will also inform decision-making in the carbon emission impacts. Therefore, it will provide a spatio-temporal reference for analyzing the national-level carbon exchange systems in the United States.

**Key words:** Carbon sequestration, carbon exchange, temporal filter, spatial analysis, zonal statistic.

## 1. Introduction

The United States has seen a substantial increase in the production and consumption of liquid biofuels for transportation applications in recent years. These biofuels, mainly corn ethanol and soybean biodiesel, displace petroleum-based gasoline and diesel fuel in response to public policies including the RFS (Renewable Fuel Standard). U.S. biofuels use more than tripled from  $4.2 \times 10^9$  gallons (Ggal;  $16 \times 10^9$  L) in 2005 to 14.6 Ggal ( $55 \times 10^9$  L) in 2013 [1]. By way of comparison, gasoline and diesel fuel consumption was 176 Ggal ( $666 \times 10^9$  L) in 2013, about 3% lower than it was in 2005 due to the displacement of petroleum fuels by biofuels coupled with net changes in overall fuel demand over the period. The NRC (National Research Council) report [2] concluded that the net climate mitigation effects of the program are ambiguous because of land-use change considerations.

Many of carbon estimation methods, either for GHG (greenhouse gas) inventories or for LCA

(lifecycle analysis), does not count biogenic CO<sub>2</sub> emissions under the assumption that biomass is inherently carbon neutral [3, 4]. This convention is equivalent to assuming that the end-use CO<sub>2</sub> emissions from biofuels or other forms of bioenergy are fully offset by CO<sub>2</sub> uptake during feedstock growth. However, errors arise when this assumption is undertaken for policy purpose in the absence of controls on terrestrial carbon stocks in land-use sectors. Moreover, in order for a biogenic carbon offset to occur, the associated biomass feedstock production must result in additional carbon uptake [5]. Many of established energy policy analysis methods, including those used for the RFS, California's LCFS (Low-Carbon Fuel Standard) and many other fuel-related programs and policies, are unable to evaluate the extent of additional carbon uptake in biofuel feedstocks [6, 7]. Therefore, their results may not reflect the actual changes in CO<sub>2</sub> emissions accompanied by changes in fuel utilization.

By using aggregate crop production data, DeCicco et al. [8] found that additional carbon uptake sufficed to offset only 37% of U.S. biofuel-related biogenic CO<sub>2</sub> emissions for 2005-2013. However, that

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evaluation did not make use of the high-resolution, satellite-based U.S. land use and land cover data that have recently become available. These newer data enable the use of GIS (geographic information system) methods, which promise greater consistency for evaluating terrestrial carbon uptake even in light of diverse and changing land uses. Also, further refinements and more experience will eventually lead to greater accuracy. To estimate net carbon uptake, it is necessary to know in where biofuel feedstocks are grown and any CO<sub>2</sub> emissions from land-cover conversion are occurring.

Many studies have investigated the effects of CO<sub>2</sub> emission associated with land-use change related to biofuel production [9, 10]. Corn is the most common crop planted directly on new land and is the largest contributor for crop-driven direct land-use change [11]. Corn, soybeans and wheat are three major crops in the US and their distribution patterns of croplands are concentrated in the central region and the northwest [12, 13]. These agricultural commodities involve a short-cycle (i.e., annual) of CO<sub>2</sub> exchanges with the atmosphere due to consumption of the commodities for feed and food. This trait accounts for not only carbon uptake during biomass growth but also local (cropland) CO<sub>2</sub> emissions from autotrophic and heterotrophic respiration as well as remote CO<sub>2</sub> emissions. Although LCA (lifecycle analysis) methods have traditionally been used to assess the net CO<sub>2</sub> and other GHG impacts of biofuels, the highly dispersed and market-mediated nature of the associated CO<sub>2</sub> exchanges has resulted in significant ambiguities and debates around the net impact. For this reason, spatially explicit analysis, which evaluates CO<sub>2</sub> exchanges in the specific locations where they occur, provides a way to empirically resolve key questions about net impact [14].

This study focused on measuring NEP (net ecosystem production) impacts associated with U.S. biofuel production between 2012 and 2013. NEP estimation enables us to evaluate the carbon removed

from the land through harvests and provides the net rate of carbon uptake in terrestrial ecosystem. We developed quantitative methods of geospatial analysis to make it able to evaluate the crop rotation from land-cover conversion and estimate the NEP of the cropland in the United States. This paper presents a pioneering application of GIS data and methods to provide a spatially explicit evaluation of the additional carbon uptake associated with U.S. biofuel production. Eventually, this research will provide a spatio-temporal template for analyzing the national-level RFS (Renewable Fuels Standard).

## 2. Data Sets

The ACP (Annual Crop Production) survey data and CDL (Cropland Data Layer) from NASS (National Agricultural Statistics Service) of the USDA (U.S. Department of Agriculture) are the two main agricultural databases available for national-scale analysis of crop production. The ACP database provides an annual statistical sampling of individually planted areas. The data are reported by farmers and compiled by state and federal agriculture agency field staffs, making it a fairly accurate source of information [15]. The CDL is a satellite-based, crop-specific land cover map for the continental United States starting from the year 2008 (Fig. 1). The CDL has a spatial resolution of 56 meters and each pixel is an area of 3,136 square meters (56 meters × 56 meters. i.e. an area of 0.77 acre). The attribute table of CDL contains the number of pixels for every major crop [16].

Because we used the CDL for our final analysis, we reclassified all CDL land-cover categories to be consistent with USDA classifications of land cover. We followed the USDA distinctions, which show how the CDL crop categories are grouped to create the crop specific layers [17]. After reclassifying certain minor crop types as done for previous U.S. cropland aggregation analyses [18, 19], we identified crops comprising of at least 95% of the CDL crop count. We

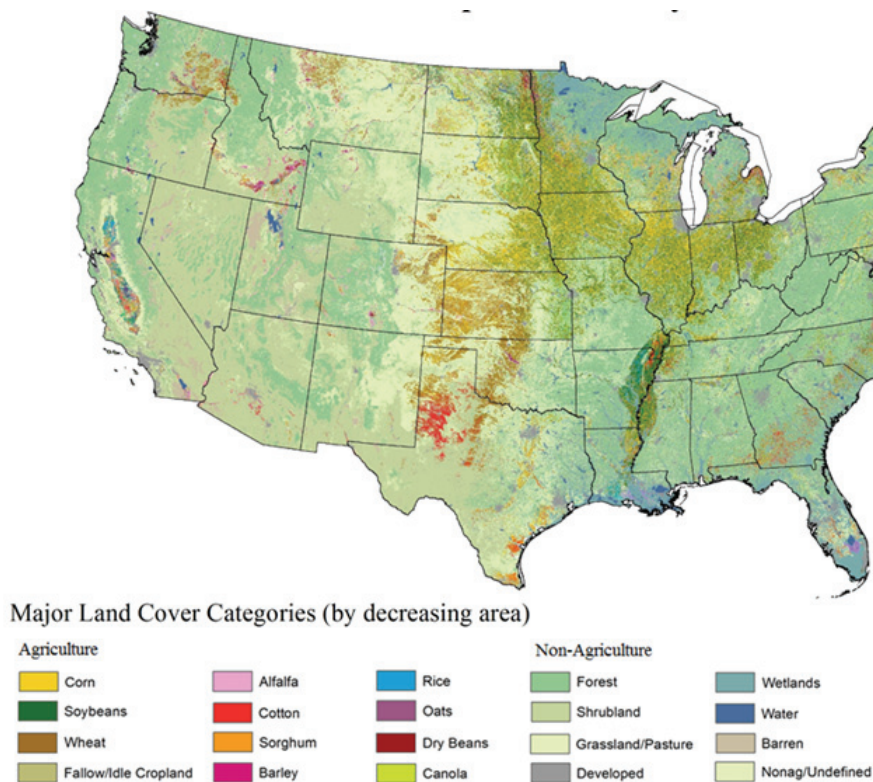


Fig. 1 The CDL map for 2013 in the conterminous United State.

then used the ACP summaries for those dominant crops in order to obtain the data needed to analyze NEP, including crop yields and annual production. The production was computed by multiplying the yield per harvested area from ACP and the planted area from CDL. Since each county has different values for yield per harvested acre, the values were estimated independently for each county.

Estimating carbon flows requires yield information because the dominant disposition of the net carbon removal from the atmosphere over cropland is in the harvest. Yields are obtained from NASS crop production statistics as accessed through an online tool known as Quick Stats. We measured “harvested area” of the major crop types from the CDL and collected “yield per harvested acre” from Quick Stats. Production was computed by multiplying the “yield per harvested area” and the harvested area from both data sources. As each county has a different value for “yield per harvested acre”, the value of each state was estimated independently. In case that Quick Stats did

not contain the value for the “yield per harvested acre” for a specific county, the national average was used.

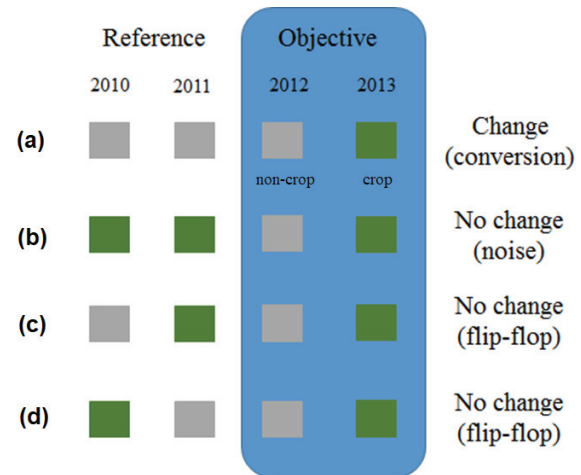
The important term for estimating carbon exchange is NEP, which indicates the net flow of carbon from the atmosphere into the biosphere over a given area of land. NEP can be derived from data on the quantity of biomass harvested and estimates of soil carbon accumulation. As defined as the difference between NPP (net primary production) and  $R_h$  (Heterotrophic Respiration), NEP reflects net rate of carbon uptake in terrestrial ecosystems. For this study, the annual NEP is estimated based on the definition of Lovett et al. [20]. Simply put, for a parcel of land growing a specific crop over a year,  $NEP = NPP - R_h = H + \Delta SOC + Ex + Ox$ , where  $H$  represents the mass of carbon embodied in the harvest;  $\Delta SOC$  is the change in soil organic carbon;  $Ex$  is carbon exported through runoff or wind; and  $Ox$  is carbon oxidized non-biologically, e.g., through fire. On annual cropland, other terms except  $H$  average to zero, and so we assume that  $NEP \approx H$ . The change in NEP was

evaluated over a single year, comparing the NEP on the cropland serving the facility during its first year of operation to the NEP that occurred on the same land in the prior year. If  $\Delta\text{NEP}_t$  is positive, it represents additional carbon uptake that can be credited against biogenic  $\text{CO}_2$  emissions from biofuel combustion and processing.

### 3. Methodology and Results

We utilized CDL maps for 2012 and 2013 to measure land-cover conversion. In order to determine actual cropland expansion with minimal error that is caused by land variation over time, we included 2010 and 2011 maps as a reference as shown in Fig. 2. To identify shift patterns in crop cultivation, we first consolidated the CDL into two broad categories: cropland and non-cropland. We followed the distinctions used by the analyses of cropland and non-cropland in the USDA. These two broad categories not only eliminated the difficulties in distinguishing among different crop types and among different non-crop types, but also improved the accuracy of the data set. Theoretically, cropland expansion between 2012 and 2013 happens at the lands that used to be non-cropland in 2012 and was converted to cropland in 2013. There is a risk of overestimation, if no-reference years are used to rule out flip-flop data over years and data noise. Thus, we listed all possible combinations of land cover conditions in 2010 and 2011, followed by identifying necessary conditions for cropland expansion, from non-crop in 2012 to crop in 2013.

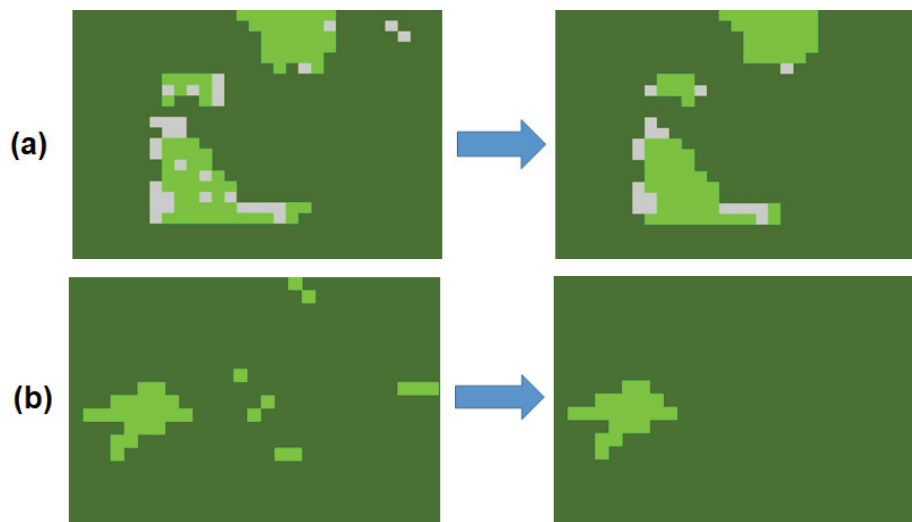
In Fig. 2, cases row (c) and (d) are identified as no change, a flip-flop to be more precise. This is more of a long-term crop rotation condition than an actual cropland conversion, since land-cover change is not unidirectional over time. Case row (b) is identified as no change as well, and this is more likely to be data noise, or even one year rotation with non-crop grassland or pasture. Most importantly, by referencing 2010 and 2011 maps, we can be sure that for cases



**Fig. 2** Temporal filter of land-cover conversion between 2012 and 2013: (a) is classified as stable land-cover change, but (b), (c) and (d) are considered as no change.

row (b), (c) and (d), cropland has expanded into that parcel of land before 2012, and should not be included in the new cropland expansion between 2012 and 2013. The only case that is determined to be land change is case row (a). Across years from 2010 to 2012, it shows an unidirectional change from non-cropland to cropland, and thus is a convincing candidate for cropland expansion.

We applied spatial analyses to refine the data and identify issues including edge effect, resolution change artifacts and misclassification (Fig. 3a). A  $3 \times 3$  majority filter was selected to smooth spatial anomalies and the results were compared to 2012 USDA FSA (Farm Service Agency) ground truth data to aid selection and refinement. Since developed areas typically do not revert to agricultural uses, all conversion from the developed/open class to cropland was considered spurious and removed. Additionally, we applied a minimum mapping unit to consider only areas of at least 20 pixel (~15 acres) in size and that displayed a consistent trend in cultivation (Fig. 3b). Removing small areas of change improves confidence that the remaining identified change is real. By mapping only significant areas of change, we focused on areas congruent with conversion of whole fields. An added benefit of intentionally mapping only whole-field conversion is that our methods are better



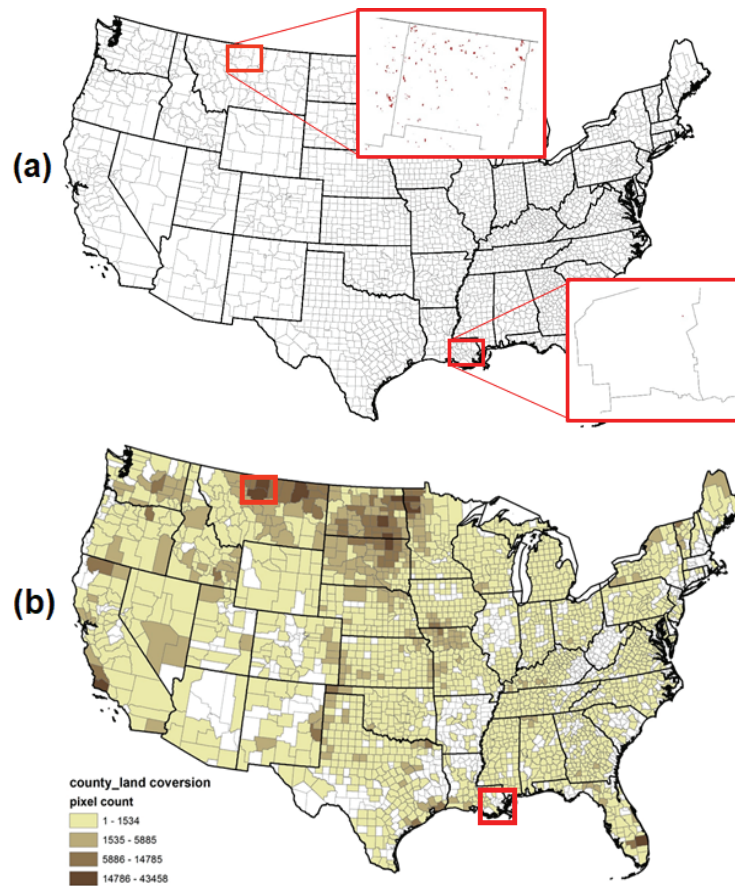
**Fig. 3** Example of spatial analyses in the study area: (a) spatial filter ( $3 \times 3$  major filter was applied to smooth spatial anomalies) and (b) minimum mapping unit (less than  $\sim 15$  acres was removed).

suites for comparison with NASS survey-based data, which are not designed to capture incremental change [21].

We then utilized zonal statistics analysis in GIS to calculate the county-level NEP reflecting land-use patterns in the agricultural and non-agriculture systems across the conterminous United States (Fig. 4). The zonal statistic calculates a value of the pixels containing the land-use type and assigns to each county across the conterminous United States. These values were then matched with crop and county specific “yield per harvest acre” values obtained from Quick Stats 2.0. Using these values, production in metric tons was calculated for each crop, in each county, for each year between 2012 and 2013. The production values for each crop per year were then aggregated and combined to form total production values per county in each year. These values were then put back into ArcGIS and mapped over the United States. Fig. 4b shows the calculated NEP map between 2012 and 2013 using zonal statistics analysis.

Carbon release from cropland expansion varies by the original state of land that is converted to cropland. Fargione et al. [22] evaluated that highest carbon release (“carbon debt”) occurs when grassland was converted to corn field supplying corn ethanol

production. They reported that a  $134 \text{ Mg CO}_2\text{e ha}^{-1}$  (i.e.  $3.65 \times 10^{-5} \text{ Tg C ha}^{-1}$ ) carbon release due to this conversion case. Lark et al. [13] found that 3.0 million hectares (Mha; or 7.3 million acres) of land that had been uncultivated since 2001 were converted to cropland between 2008 and 2012. This increase in grassland would lead to carbon uptake from the atmosphere. USDA [23] mentioned that cropland decreased by 34 million acres from 2002 to 2007, whereas forest and grassland (including pasture and range) increased by 20 million acres and 27 million acres, respectively. There is an increase in cropland and decrease in land attributed to the other major land uses after 2007. Although the decrease in cropland contributes to the increase in grassland, there was limited information which displayed how much of this land change was attributed to specific conversions [24-26]. In this study, the CDL maps were utilized to examine the direct land-use change between 2012 and 2013. We also found that cropland expansion occurred and increased by about 1.65 million acres between 2012 and 2013 [14]. As shown in Fig. 4b, most of the land conversion comes from the Mid-West, in states like North Dakota, South Dakota, Montana, and Iowa. This number comes from an increase in conversion area between 2012 and 2013 throughout the United States.



**Fig. 4** The spatial distribution of land-cover conversion between 2012 and 2013: (a) the calculated NEP map and (b) the calculated NEP map after zonal statistics analysis.

#### 4. Conclusions

We evaluated carbon sequestration and exchange in the conterminous United States using advanced geospatial analysis techniques. Both temporal and spatial analyses were used to further refine the area of land-use changes from 2012 to 2013. A temporal filter was applied to account for areas which undergo multiple changes in class within the study period. This allowed identification of likely crop rotations and 1-year misclassifications and separation from that of a consistent one time conversion to or from cropland. The additional 2-year series of data ensured that we identify and eliminate temporary rotation and data noise, and only counted true land conversion to our best knowledge. We then applied spatial filters to refine the data and identify issues including edge

effect, resolution change artifacts and misclassification. We also applied a minimum mapping unit to consider only areas of at least 20 pixel (~15 acres) in size and that displayed a consistent trend in cultivation. Removing small areas of change improves confidence that the remaining identified change is real. Carbon exchange from cropland expansion varies by the original state of land that is converted to cropland. The trend displays an increase in counties on the margins of the Corn Belt states. We identified carbon exchanges for coupled agricultural, forest and other high-carbon-uptake ecosystems systems, conversions to and from crop, and land in frequent conversion among forest, wetland, pasture and rangeland. Findings from this study will provide important information to support and promote the co-production of science and decision-making.

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