

## Recent grassland losses are concentrated around U.S. ethanol refineries

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## LETTER

# Recent grassland losses are concentrated around U.S. ethanol refineries

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## Abstract

Although the United States has pursued rapid development of corn ethanol as a matter of national biofuel policy, relatively little is known about this policy's widespread impacts on agricultural land conversion surrounding ethanol refineries. This knowledge gap impedes policy makers' ability to identify and mitigate potentially negative environmental impacts of ethanol production. We assessed changes to the landscape during initial implementation of the Renewable Fuel Standard v2 (RFS2) from 2008 to 2012 and found nearly 4.2 million acres of arable non-cropland converted to crops within 100 miles of refinery locations, including 3.6 million acres of converted grassland. Aggregated across all ethanol refineries, the rate of grassland conversion to cropland increased linearly with proximity to a refinery location. Despite this widespread conversion of the landscape, recent cropland expansion could have made only modest contributions to mandated increases in conventional biofuel capacity required by RFS2. Collectively, these findings demonstrate a shortcoming in the existing 'aggregate compliance' method for enforcing land protections in the RFS2 and suggest an alternative monitoring mechanism would be needed to appropriately capture the scale of observed land use changes.

## 1. Introduction

With passage of the Energy Independence and Security Act of 2007 (EISA), the United States embarked on an ambitious program of biofuel development. Prior to EISA, the Energy Policy Act of 2005 set out modest increases for U.S. biofuel production under the Renewable Fuel Standard, from four billion gallons (Bgal) in 2006 to 7.5 Bgal by 2012 [1]. Under EISA, an expansive Renewable Fuel Standard version 2 (RFS2) committed the U.S. to development of a 36 Bgal per year capacity by 2022 [1].

The RFS2 schedule sets annual standards for total renewable fuel volume, to be met by a portfolio of conventional and advanced biofuels, with an initial focus on increasing conventional biofuel production from nine Bgal in 2008 to a 15 Bgal per year level by 2015. Note, the conventional biofuel standard does not

explicitly apply to ethanol refined from corn starch, but instead requires a 20% decrease in lifecycle greenhouse gas emissions compared to gasoline, regardless of feedstock type [2]. However, the market dominance of corn ethanol has meant that the conventional biofuel mandate operates, in practice, as a corn ethanol standard.

As an energy policy, EISA was intended to reduce U.S. dependence on foreign oil. As environmental policy, it was designed to reduce the global warming impact of the transportation sector. However, the immediate greenhouse-gas benefit of biofuels largely disappears if feedstock production promotes counter-acting land use change that releases carbon stocks sequestered within previously untilled soils. The resulting carbon debts may take several decades to reverse [3–5]. Therefore, in order to prevent this unintended consequence of biofuel development,

EISA requires that lands eligible for feedstock production must have been ‘cleared or cultivated’ prior to the law’s enactment in December, 2007 [2].

Tasked with enforcing EISA’s land protection provision, the U.S. Environmental Protection Agency (EPA) initially proposed feedstock recordkeeping and reporting requirements for refineries, but following public comment adopted a fundamentally less restrictive final rule termed ‘aggregate compliance’ [2]. Within this framework, EPA compiled national crop-area statistics from the U.S. Department of Agriculture (USDA) to define a 402 million acre baseline of agricultural land eligible for feedstock production in 2007. If this baseline is exceeded in subsequent years, EPA must implement feedstock recordkeeping and reporting. If a lower, 397-million acre threshold is exceeded, EPA must re-evaluate the aggregate compliance approach [2]. In fact, in 2010—the year aggregate compliance took effect—EPA reported an agricultural land area of 398 million acres, and committed to performing the required methodological assessment in the coming year [6]. However, we find no public record of those findings.

Based on USDA crop and land cover statistics, EPA subsequently reported that U.S. cropland area fell to 392 million acres in 2011 [7] and 384 million acres in 2012 [8]. By contrast, a number of independent studies found substantial conversion of non-cropland to crop production using moderate resolution (30–56 m), satellite-based land cover data [9–12] during a period when conventional ethanol output doubled under RFS2. This apparent contradiction suggests that aggregate compliance may not be an effective enforcement mechanism if it cannot detect land use conversion potentially stimulated by the biofuels industry at the spatial scales where change is occurring and relevant.

Using a recently developed data set from Lark *et al* [12] we provide a comprehensive assessment of land cover/land use change (LCLUC) surrounding ethanol refineries as RFS2 was initially implemented from 2008–2012. Given limited production of advanced biofuels during this period, our focus was solely on conventional corn ethanol (hereafter, we use ‘ethanol’ to mean conventional ethanol refined from corn starch). First, we evaluated land-use impacts of RFS2 in aggregate, analogous to EPA’s aggregate compliance framework, but targeted within 100 mile neighborhoods surrounding all actively producing refineries. Next, we assessed spatially explicit rates of change, emphasizing the ethanol industries’ geography and proximity to underutilized feedstock potential in the Midwest and Great Plains, primarily on grasslands—including both native prairie and introduced grassland types. Finally, we considered policy implications of our results.

Under EISA reporting requirements, the EPA must submit triennial reports to the U.S. Congress summarizing the environmental impacts of biofuels. In its initial report in 2011, the agency identified the

expansion of corn cultivation onto lands enrolled in the Conservation Reserve Program (CRP) or used as pasture (both essentially grassland conversions) as the most important source of negative environmental impacts potentially arising from ethanol development [13]. Whether feedstock demand would be met through cropland expansion or by intensification of corn production on existing cropland was identified as a key uncertainty [13]. However, a second triennial report was not submitted in 2014. Following investigation of this omission, EPA’s Inspector General recently concluded: ‘Not having required reporting and studies impedes the EPA’s ability to identify, consider, mitigate and make policy makers aware of any adverse impacts of renewable fuels’ [14]. The present study aims to help address this gap.

## 2. Methods

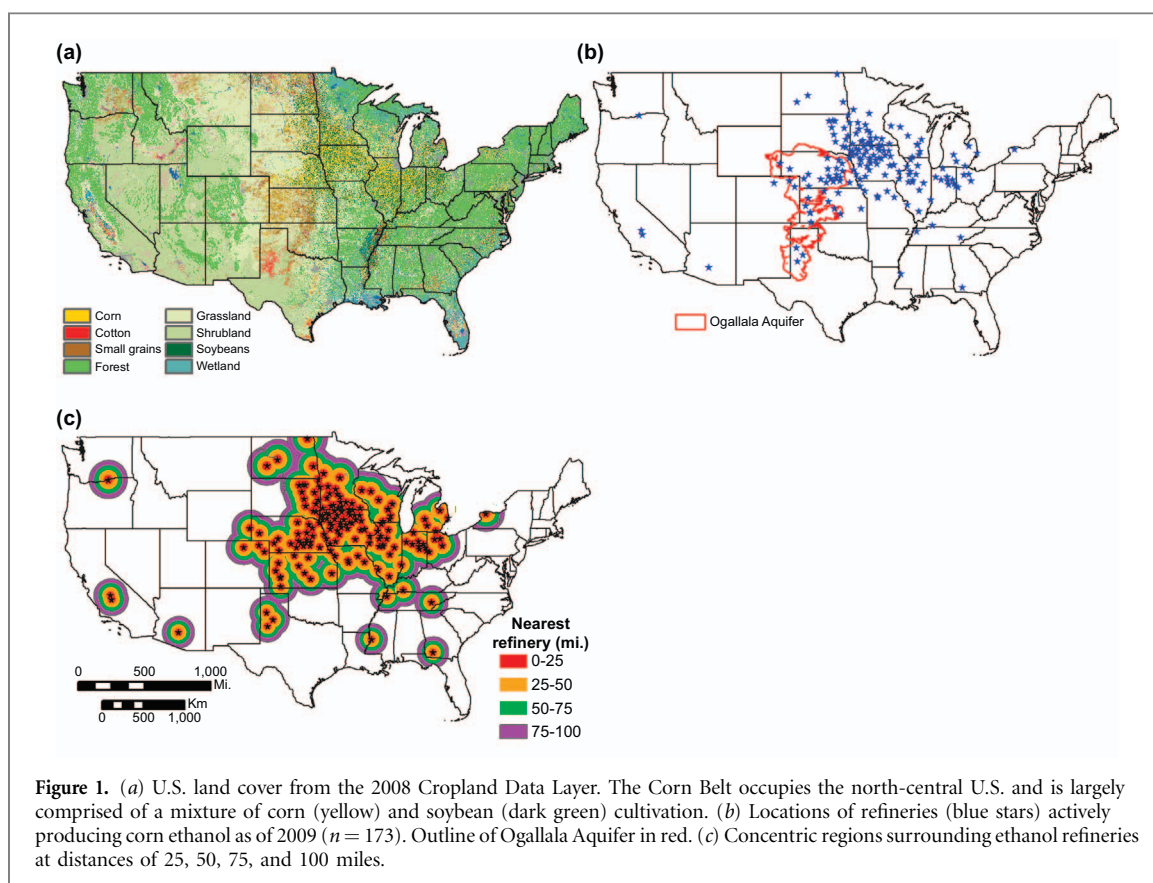
### 2.1. Refinery locations and feedstock draw areas

Locations of all active ethanol refineries as of 2009 ( $n = 173$ ), using corn as a sole feedstock, were obtained from the National Biorefineries Database [15]. The U.S. ethanol industry is largely centered in the Midwest Corn Belt (figures 1(a) and (b)). A second grouping of refineries spans the Ogallala Aquifer (figure 1(b)), which is a critical source of irrigation water from Nebraska to Texas facing unsustainable groundwater withdrawals [16]. Remaining plants are widely dispersed (figure 1(b)). Relative to this distribution, the majority of U.S. corn production occurs within 50 miles of an ethanol refinery. For example, 49% of the 2008 corn crop (by area) was located less than 25 miles from a refinery, 28% at 25–50 miles, 9% at 50–75 miles, and 3% at 75–100 miles (figure 1). Less than 12% of the 2008 corn crop was grown more than 100 miles from a refinery.

Most ethanol refineries have limited on-site storage capacity. In order to maintain feedstock supplies year-round, they typically pay a five to 20 cent per bushel premium over corn prices offered by local grain elevators [17]. Transportation costs generally dictate that a corn producer must be within a 50 mile radius of an ethanol refinery to benefit from this premium [18, 19]. Hence, we defined the basic feedstock draw area for the ethanol industry as a 50 mile radius surrounding all refineries (figure 1(c)). Significant price effects have also been observed as far as 100 miles from refineries [17], therefore we defined a maximum national draw area at a 100 mile radius (figure 1(c)).

### 2.2. Change detection

Agricultural LCLUC surrounding refineries was analyzed from a data set previously assembled by Lark *et al* [12]. Using the USDA Cropland Data Layer [20] from 2008–2012, they identified generalized



crop and non-crop categories at 56 m resolution. The generalized crop class included row crops (corn, soybeans, sorghum, cotton, potatoes, peanuts, sugar beets, etc.), small grains (wheat, barley, oats, rice, millet, rye), oilseeds (canola, sunflower, safflower), pulses (dried peas, edible beans, lentils, chickpeas), legume hay (alfalfa, clover) and various fruits and vegetables [12]. The non-crop category encompassed forest, shrubland, wetland, open water, native prairie, improved grassland (pasture, hay), and developed land [12]. The resulting five-year image time series of binary classifications was then used to identify four categories of change/no-change over that interval: (1) Non-cropland converted to cropland; (2) Cropland reverted to non-cropland; (3) Stable cropland; and (4) Stable non-cropland. See Lark *et al* [12] for details.

### 2.3. Accuracy assessment

Preliminary pixel-level accuracy assessment showed a 98% overall accuracy of the Lark *et al* [12] data set (table S1 available at [stacks.iop.org/ERL/12/044001/mmedia](http://stacks.iop.org/ERL/12/044001/mmedia)). The conversion of non-cropland to cropland was mapped correctly over 70% of the time. Critically, for purposes of this study, conversion was identified with a very small positive bias, 3%, indicating that the Lark *et al* [12] data set accurately predicted the true area converted to cropland, nationwide. However, cropland reversion to non-cropland was over-predicted with a large positive bias, 125% (table S1), introducing the likelihood of under-

predicting net cropland change (conversion minus reversion).

### 2.4. Bias correction

A 125% bias implies that gross reversion in the Lark *et al* [12] data set was 2.25 times greater than actual reversion, nationwide. Assuming this bias was relatively uniform spatially, we corrected for it by dividing the area of cropland reversion, at a given spatial scale, by 2.25 (multiplication by 0.44). Next, the remaining area (.56 of the uncorrected total) was re-assigned to the stable cropland category. Figure S1 shows the effect of uniformly de-biasing cropland reversion at 3.5 mile resolution, first plotting original reversion rates as quintiles (figure S1(a)) and then mapping bias-corrected reversion rates using the same legend (figure S1(b)). Note the resultant shift toward values less than 2.4%, and generally less than 0.8% (figure S1(b)).

Next, we compared net cropland change (conversion minus reversion) using uncorrected vs. de-biased reversion totals, also at a 3.5 mile scale, nationally (figure S2). In some cases, bias correction reversed the sign of net cropland change, i.e. from net cropland losses to net gains. More generally, it tended to neutralize the magnitude of those losses. For example, net cropland losses in northern and eastern North Dakota based on original reversion totals (figure S2 (a)) were largely neutralized by bias correction (figure S2(b)). A comparable effect was found in the southern

half of the Ogallala Aquifer (figure S2). However, these types of reversals were comparatively rare. Most importantly, de-biasing did not fundamentally alter the overall pattern of net cropland increases surrounding ethanol refineries (figure S2).

Aggregate effects of uniform bias correction within neighborhoods surrounding ethanol refineries are summarized in figure S3. While aggregate reversion rates were substantially reduced, as expected (figure S3 (c)), the effect of bias correction on net conversion rates was less pronounced; in general, reducing rates by a half percentage point relative to uncorrected net conversion rates (figure S3(d)).

## 2.5. Source lands

As a basic measure of land suitability, the Natural Resources Conservation Service (NRCS) Land Capability Classification (LCC) system [21] was used. LCC data were extracted from the NRCS Soil Survey Geographic database (SSURGO) [21]. In order to maintain a degree of uniformity across the U.S. agricultural landscape, LCLUC analyses were confined to those lands classified as 'arable' (LCC classes I-IV). Previously identified change areas from Lark *et al* [12] were overlain on the arable lands layer, with intersections between the two retained for further analysis. This overlay eliminated 12% of the cropland expansion identified in the original Lark *et al* [12] data that occurred on land defined as non-arable by the NRCS.

The types of potentially-arable land cover undergoing conversion to cropland were identified by overlaying the 2006 National Land Cover Database (NLCD) [22] on change areas. From the 2006 NLCD, four generalized classes were assembled: grassland, forest, shrubland, and wetland. The generalized grassland class merged two NLCD classes: grassland/herbaceous and pasture/hay. Notably, the NLCD does not distinguish undisturbed grassland (native prairie) *ineligible* for feedstock production under EISA from *eligible* grassland types including introduced grass pasture, introduced grass hay, and idle cropland planted to grasses under the Conservation Reserve Program (CRP). In addition, the NLCD pasture/hay class represents a combination of grass pasture, grass hay, and leguminous hay, predominantly alfalfa [22]. However, alfalfa is identified as a distinct crop type by the Cropland Data Layer, and Lark *et al* [12] included alfalfa in their generalized cropland class. Given that alfalfa was not a component of non-crop to crop conversion events, we assumed that alfalfa land cover embedded within the NLCD was eliminated by the overlay operation with change areas, the end result being a generalized class composed of a combination of grass-dominated cover types.

In terms of land available for additional crop production, our 100 mile national draw region encompassed nearly 223 million acres of arable non-cropland in 2008 (table S2). In addition, 8.7 million

acres of feedstock-eligible CRP land left the program from 2009–2012 [12].

With respect to grassland likely ineligible for feedstock production, the U.S. Geological Survey's Gap Analysis Program (GAP) indicates nearly 30 million acres of short-, mixed-, and tall-grass prairie in North- and South Dakota, combined, as of 2001 [23]. Note that 100° W longitude represents an approximate climatological limit for non-irrigated corn production in the Dakotas. East of the 100th Meridian, the 2001 GAP product shows 1.7- and 4.4 million acres of tall- and mixed grass prairie, respectively [23]. In Kansas, temperate grassland covers more than a third of the state, with grassland stature (type) declining along an aridity gradient from east to west [23]. By comparison, native prairie covers less than 1.5% of Iowa and Missouri, combined [23].

## 2.6. Aggregate analysis

Aggregate LCLUC as a function of distance from ethanol refineries was analyzed within 25 mile concentric increments surrounding refineries (figure 1(c)). Within each increment, non-cropland conversion and cropland reversion were summed and rates of change were normalized relative to the area of arable non-cropland or cropland, respectively, present in 2008. For the four generalized land cover classes, conversion to cropland was summed over each increment and normalized relative to the potentially arable area in each class in 2008. Initial crops following conversion were determined from the Cropland Data Layer for the year individual conversion events occurred. Rates of net cropland change were calculated by subtracting gross reversion from gross conversion, normalized by cropland area in 2008. Net change in grassland, forest, shrubland, and forest categories was based on non-crop land cover types identified by the CDL in the year cropland reversion occurred.

## 2.7. Spatially explicit analysis

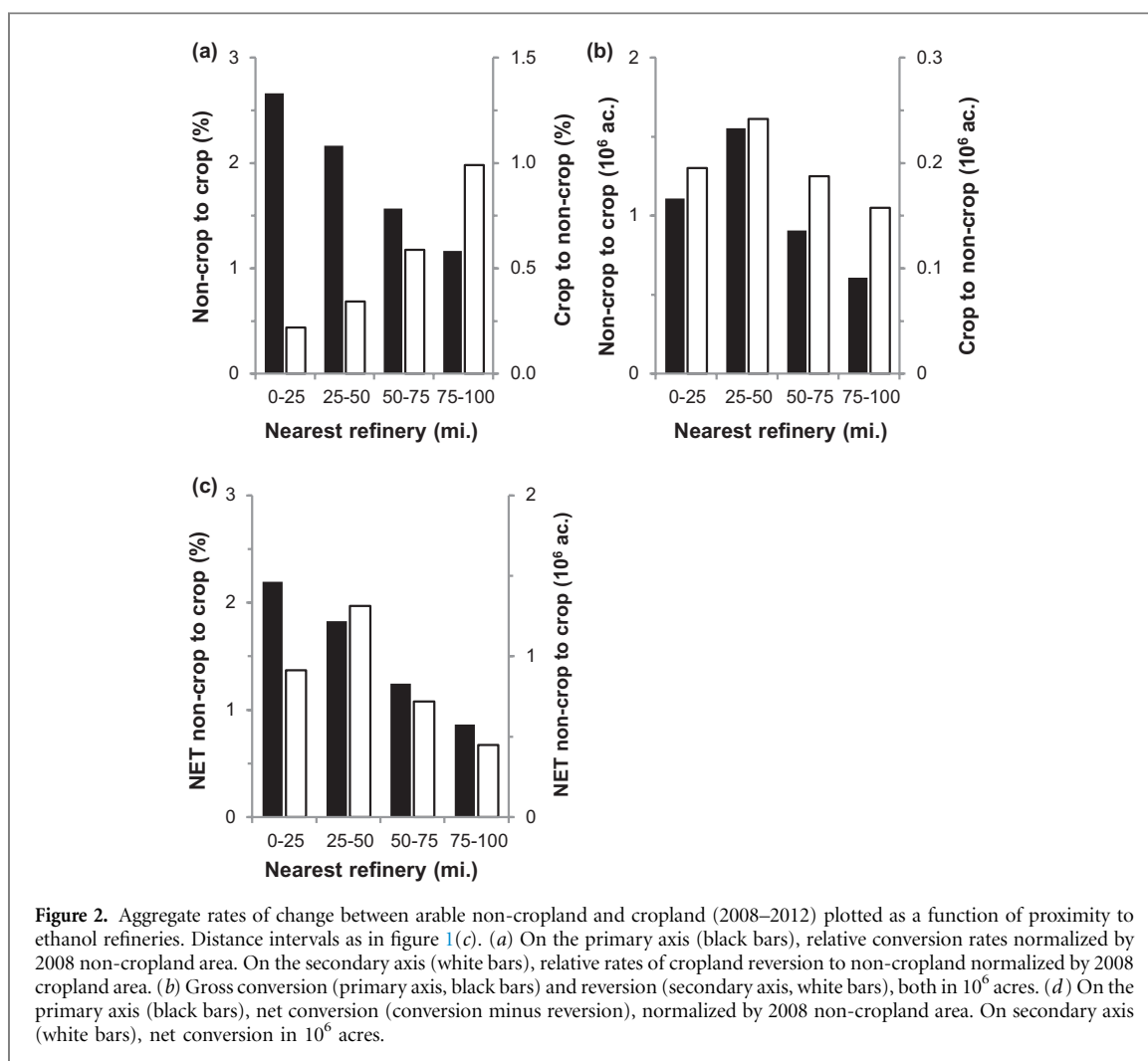
LCLUC rates were calculated similarly at a spatial resolution of 3.5 mile grid cells for arable land across the entire U.S. Intermediate between farm- and county scales, we found that 3.5-mile grid cells captured important sub-county variability while smoothing farm-scale noise. Recently, Motamed *et al* [24] also used gridded CDL data to assess LCLUC across the ethanol sector over a comparable time period (2006–2010). They found aggregating the CDL at 6.2 mile resolution enabled identification of annual changes in crop selection at sub-county scales [24].

# 3. Results

## 3.1. Aggregate change

Aggregated across the U.S. ethanol sector, the four-year conversion rate of arable non-cropland to cropland was highest within 25 miles of refineries





**Figure 2.** Aggregate rates of change between arable non-cropland and cropland (2008–2012) plotted as a function of proximity to ethanol refineries. Distance intervals as in figure 1(c). (a) On the primary axis (black bars), relative conversion rates normalized by 2008 non-cropland area. On the secondary axis (white bars), relative rates of cropland reversion to non-cropland normalized by 2008 cropland area. (b) Gross conversion (primary axis, black bars) and reversion (secondary axis, white bars), both in  $10^6$  acres. (d) On the primary axis (black bars), net conversion (conversion minus reversion), normalized by 2008 non-cropland area. On secondary axis (white bars), net conversion in  $10^6$  acres.

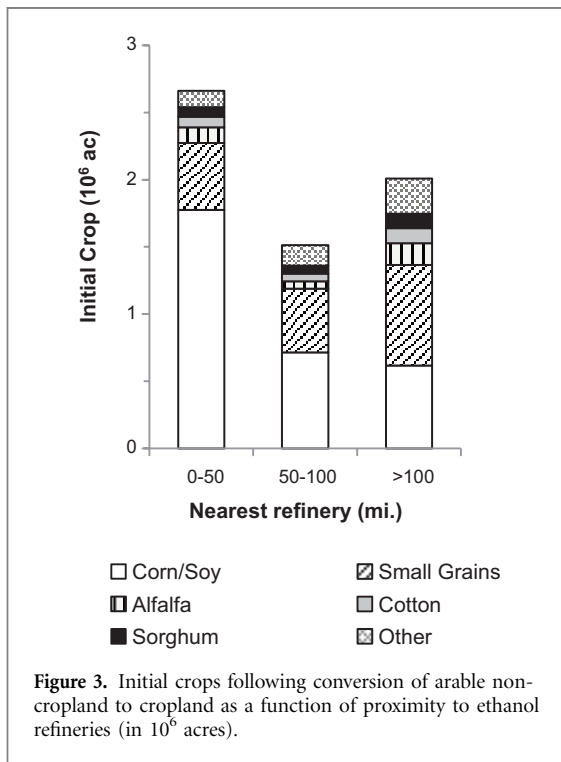
(2.7%) and declined linearly to 1.2% at 75–100 mi. (figure 2(a)). To test the statistical significance of the observed proximity effect, we compared it with a null model assuming a fixed conversion rate within 100 miles of refineries (spatially-invariant, random conversion of arable land at the overall 0–100 mile rate, 1.9%). By the Cochran-Armitage test for linear trends across ordered categories [25, 26] the aggregate effect of refinery locations was highly significant ( $\chi^2_{(3)} = 444\,994$ ,  $p \ll 0.01$ ). Outside our 100-mile draw region, the conversion rate fell to 0.55%. At the state level, gross conversion was concentrated (in order) in Kansas, South Dakota, North Dakota, Missouri, and Iowa (table S2).

In the opposite direction, the reversion of cropland to non-cropland increased significantly ( $\chi^2_{(3)} = 305\,886$ ,  $p \ll 0.01$ ) as a function of distance from refineries (figure 2(a)). Corresponding net conversion rates were generally a half percentage point smaller than gross conversion rates (figures 2(a) and (c)). More than 100 miles from refineries, the reversion rate increased to 1.3%.

In total, we found nearly 2.7 million acres of arable non-cropland converted to cropland within a 50 mile radius of refineries, our minimum national draw area (note that change totals should be treated

as slightly conservative given that analysis was restricted to arable lands; see Methods). Initial crops post conversion included mainly corn and soybeans (figure 3). At distances of 50–100 miles from refineries, an additional 1.5 million acres of cropland expansion were found. However, more than 50% of newly-converted land at this distance was planted to crops other than corn or soybeans, mostly small grains. Outside 100-mile neighborhoods, the fraction of new land planted to corn or soybeans dropped below 20% (figure 3). These declines may reflect an indirect LCLUC effect where increased corn/soy production at closer proximity to refineries drove conversion at greater distances to meet demand for displaced crops. Alternatively, it may signal that the ethanol industry is operating close to climatic limits for corn cultivation, namely on the northern and western edges of the Corn Belt, beyond which small grains are better adapted to more arid climates and/or shorter growing seasons.

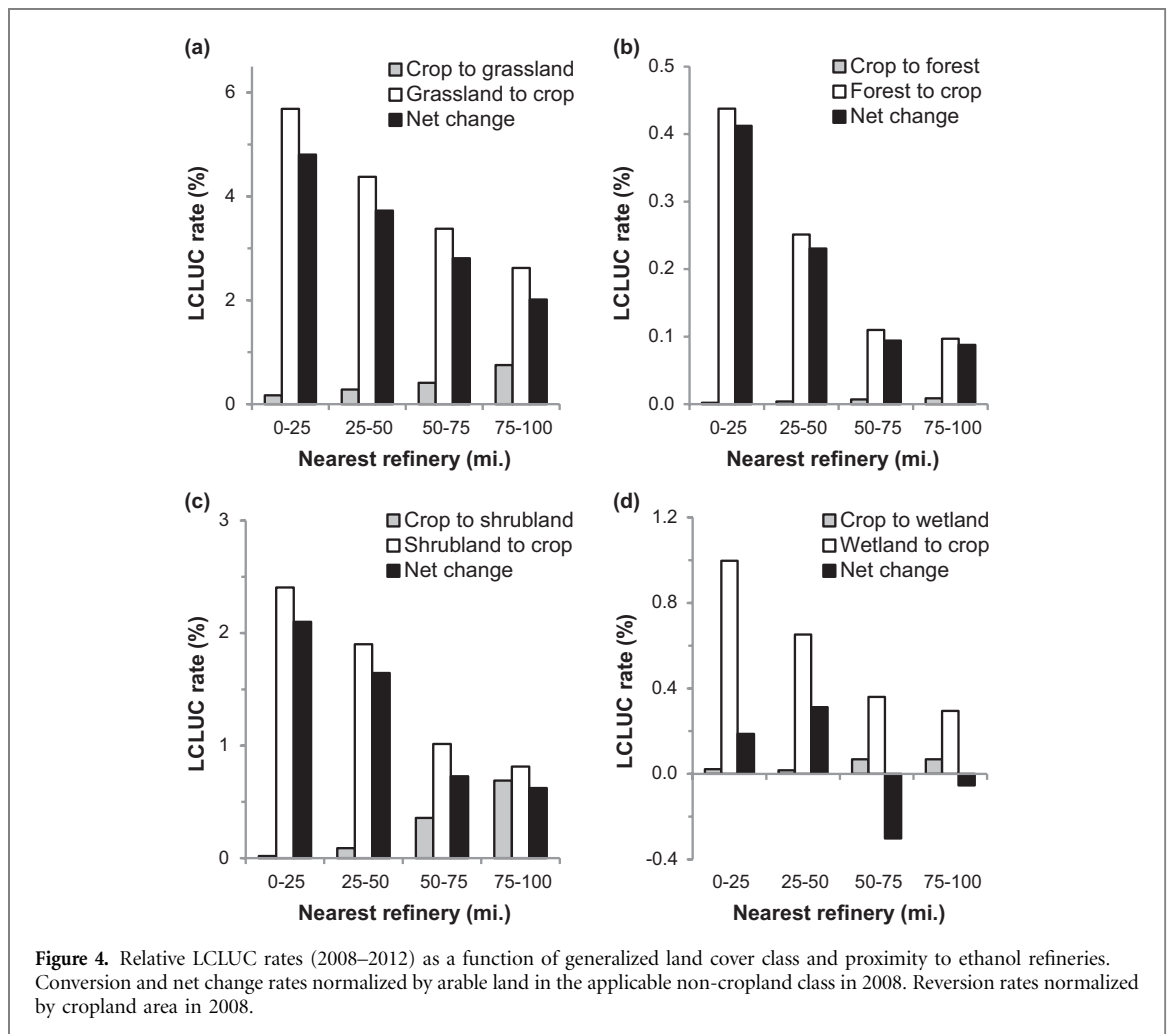
Land-use transitions involving grassland dominated observed change (figures 4 and 5). Within 25 miles of ethanol refineries, 5.7% of arable grassland was converted to cropland (figure 4(a)). Aggregate grassland conversion rates declined significantly as a function of distance from refineries ( $\chi^2_{(3)} = 164\,604$ ,

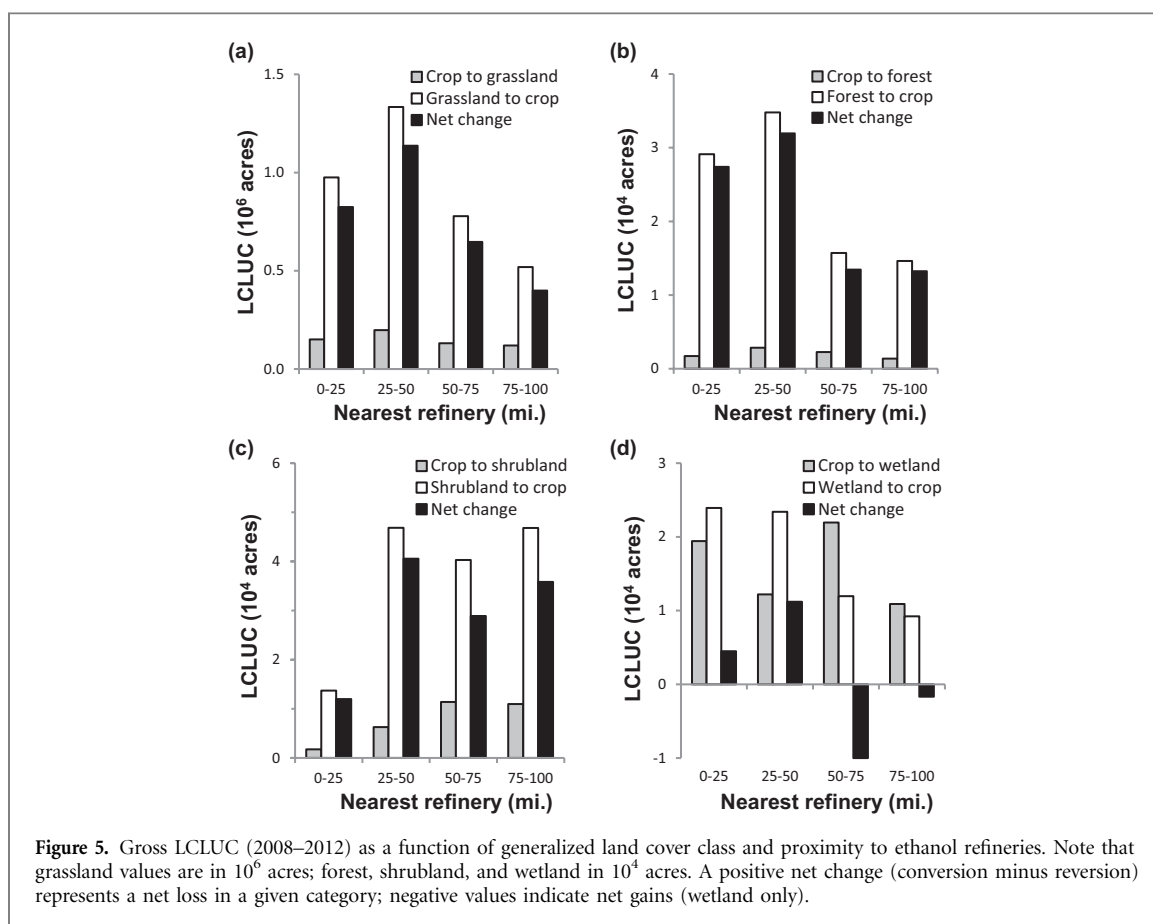


$p << 0.01$ ) while reversion rates increased significantly ( $\chi^2_{(3)} = 211\,678$ ,  $p << 0.01$ ). Net grassland conversion rates tended to be 0.25 percentage points smaller than corresponding gross conversion rates (figure 4(a)).

Within the 100-mile national draw area, 0.9 million acres of arable grassland was converted to cropland in the Dakotas, followed by Missouri, Kansas, and Iowa (table S4). These five states also experienced the largest net losses of grassland (table S6). Cropland reversion to grassland occurred mostly in Great Plains states other than South Dakota (table S6). Among major ethanol-producing states, only South Dakota experienced substantial grassland conversion (135 000 acres) outside 100 mile neighborhoods (table S5).

Forest, shrubland, and wetland conversion rates also declined with increasing distance from refineries (figures 4(b–d)). Gross cropland reversion to forest and shrubland was minimal (figures 5(b–c)), as would be expected over such a short time interval, and may largely reflect classification errors. At 50–100 miles from refineries, a small (< 12 000 acres) net increase in wetland occurred (figure 5(d)).





### 3.2. Potential ethanol production from cropland expansion

From LCLUC totals, we estimated the potential contribution of cropland expansion toward meeting the 4.2 Bgal per year increase in ethanol blending mandated by RFS2 from 2008–2012. U.S. farmers frequently grow corn and soybeans in rotation as a means to control insect pests and plant pathogens. Therefore, we assumed 50% of land converted to corn or soybeans would be available for feedstock production in subsequent years; i.e. 887 000 acres within 50 miles of refineries, plus another 358 000 acres at 50–100 miles distance. Given a ten-year (2005–2014) average U.S. corn yield of 151.7 bushels per acre [27] and a conversion efficiency of 2.76 gallons per bushel for first-generation corn ethanol [28], observed cropland expansion within 50 miles of refineries could generate on the order of 0.37 Bgal of ethanol per year. Increasing the national draw area to 100 miles raises potential ethanol capacity to 0.53 Bgal per year, 12.4% of the conventional biofuel mandate.

Others have found that the intensity of corn production increased under RFS2 as farmers supplanted traditional corn/soy rotation with continuous-corn production [29, 30]. As an upper bound on potential ethanol capacity generated from recent conversion, suppose that all land initially planted to corn or soybeans represents the pool of new cropland available for feedstock production. Assuming the entire pool is dedicated to continuous-corn production, the

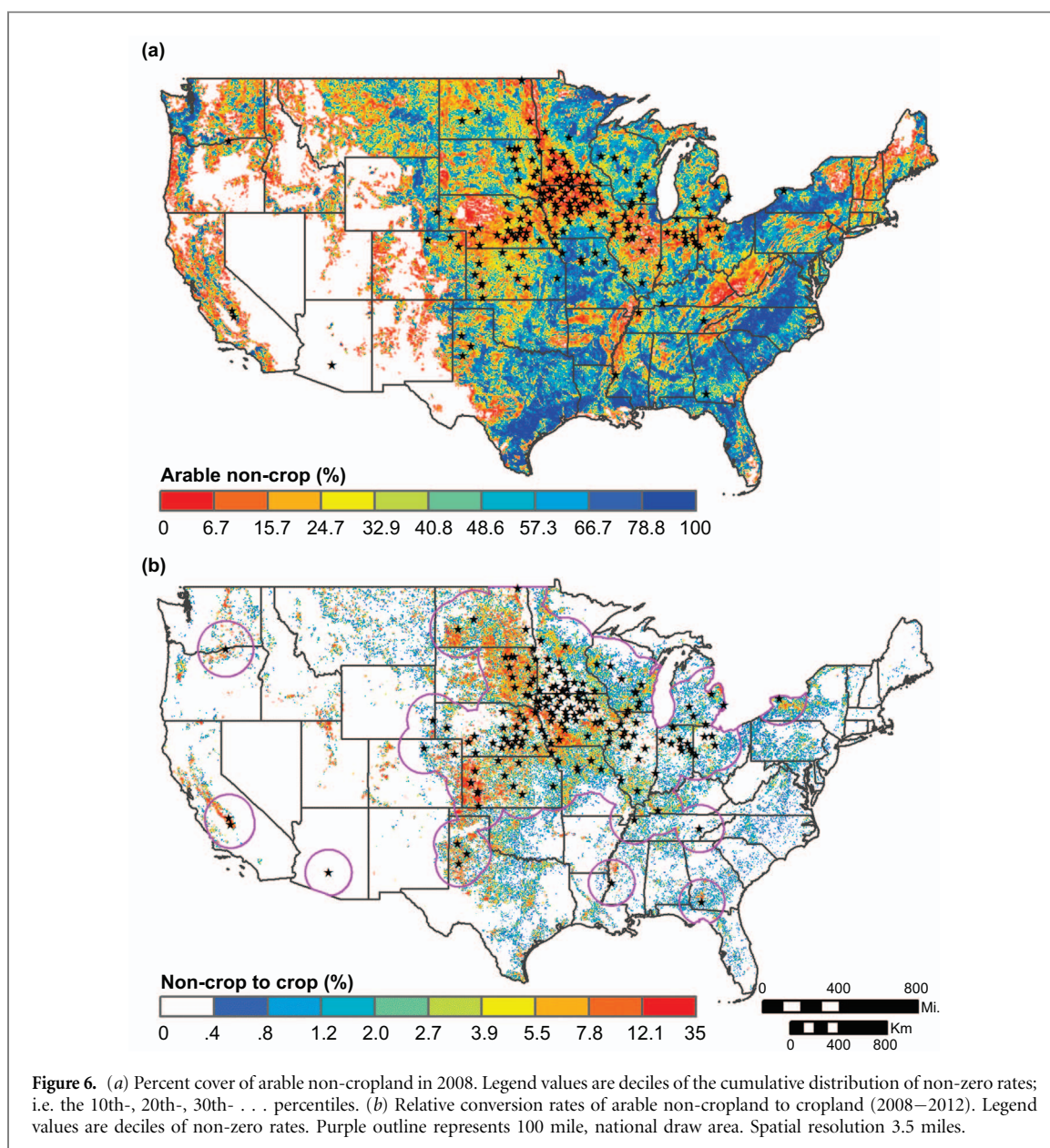
maximum contribution to ethanol production would be double the estimates for corn/soy rotation from above. Thus, we estimate that direct LCLUC from 2008–2012 could contribute, at most, less than 25% of the mandated increases in conventional biofuel capacity over that period.

### 3.3. Spatially explicit change

Within 3.5 mile grid cells, normalized rates of change were calculated by dividing the area converted (2008–2012) by the arable non-cropland area available in 2008 (figure 6(a)). Conversion of non-cropland to cropland surrounding ethanol refineries generally reflected this availability (figure 6(b)). For example, within the industry's core production areas in Iowa, Minnesota, Illinois, and Indiana, where arable non-cropland is rare (figure 6(a)), relative conversion rates were generally low (figure 6(b)). Outside core production areas, both the availability of arable non-cropland surrounding refineries, and its rate of conversion, tended to increase (figure 6). Importantly, the spatial pattern in figure 6(b) shows that aggregate results (figures 2–5) were largely determined by change around the ethanol industry's periphery. This can be seen in state-level totals from Iowa where aggregate conversion rates *increased* moving away from core refineries (table S2).

In the Dakotas, where an estimated 25% of the pre-settlement extent of mixed grass prairie remains unplowed [31], four-year conversion rates commonly





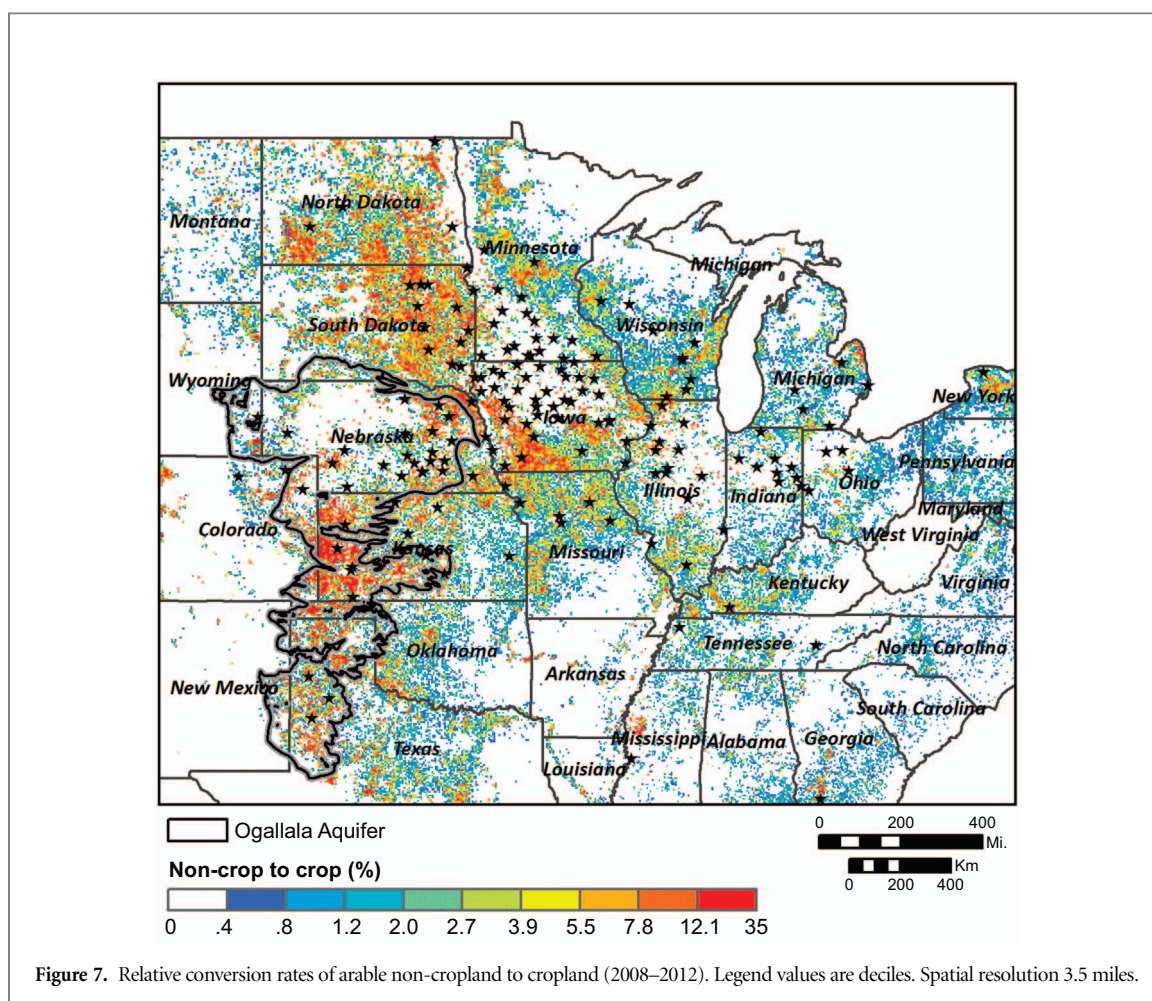
exceeded 7.8% across what was the largest expanse of cropland expansion found (figure 7). From there, elevated conversion rates extended into northeast Nebraska and southern Iowa. Slightly lower rates on the Corn Belt's southern margin coincided with a line of refineries from Missouri to Kentucky. Similarly, cropland expansion paralleled refineries across the Corn Belt's northern margin in Minnesota and Wisconsin and between the two core production regions in Iowa/Minnesota and Illinois/Indiana.

Along the Ogallala Aquifer, elevated conversion rates in western Kansas, Oklahoma and Texas coincided with areas experiencing groundwater depletion rates ranging from 5%–20% per decade [16]. In western Kansas, where remnant shortgrass prairie is concentrated [23], conversion rates generally exceeded 12.1%, the most intense hotspot of change found (figure 7). Outside the Ogallala Aquifer and Corn Belt regions, cropland expansion surrounding isolated ethanol refineries was relatively

localized, with the exception of western New York (figure 6(b)).

Rates of cropland reversion to non-cropland were consistently low surrounding ethanol refineries, generally less than 0.6% (figure 8(a)). Conversely, net cropland change rates, upwards of 9.4%, accentuated expansion around the margins of the Corn Belt (figure 8(b)). Along the Ogallala Aquifer, net increases occurred at slightly lower rates (2%–9.4%) and mainly in the region's southern half (figure 8(b)).

Not surprisingly, the spatial pattern of grassland conversion rates (figure 9(a)) closely resembled that for all non-cropland (figure 8(b)). Surrounding ethanol refineries, rates of cropland reversion to grassland were uniformly low, with a patchy distribution of higher values elsewhere (figure 9(b)). In turn, net grassland loss rates were highest around the margins of the Corn Belt, namely in the Dakotas, and in the Southern Great Plains (figure 9(c)). Elevated net loss rates covering much of western



New York were unexpected (figure 9(c)). In some areas where relative conversion rates were high (figure 9(a)), rates of net grassland loss were comparatively low to neutral, e.g. in western Iowa (figure 9(c)). Given limited availability of unutilized arable land in western Iowa (figure 6(a)), low reversion rates across landscapes with high cropland cover were apparently sufficient to offset grassland losses. A similar phenomenon was found in northwest Minnesota and along parts of the Corn Belt's northern margin. Within core ethanol producing areas, net grassland change was generally neutral to positive (figure 9(c)), further emphasizing the contrast between core and peripheral refineries.

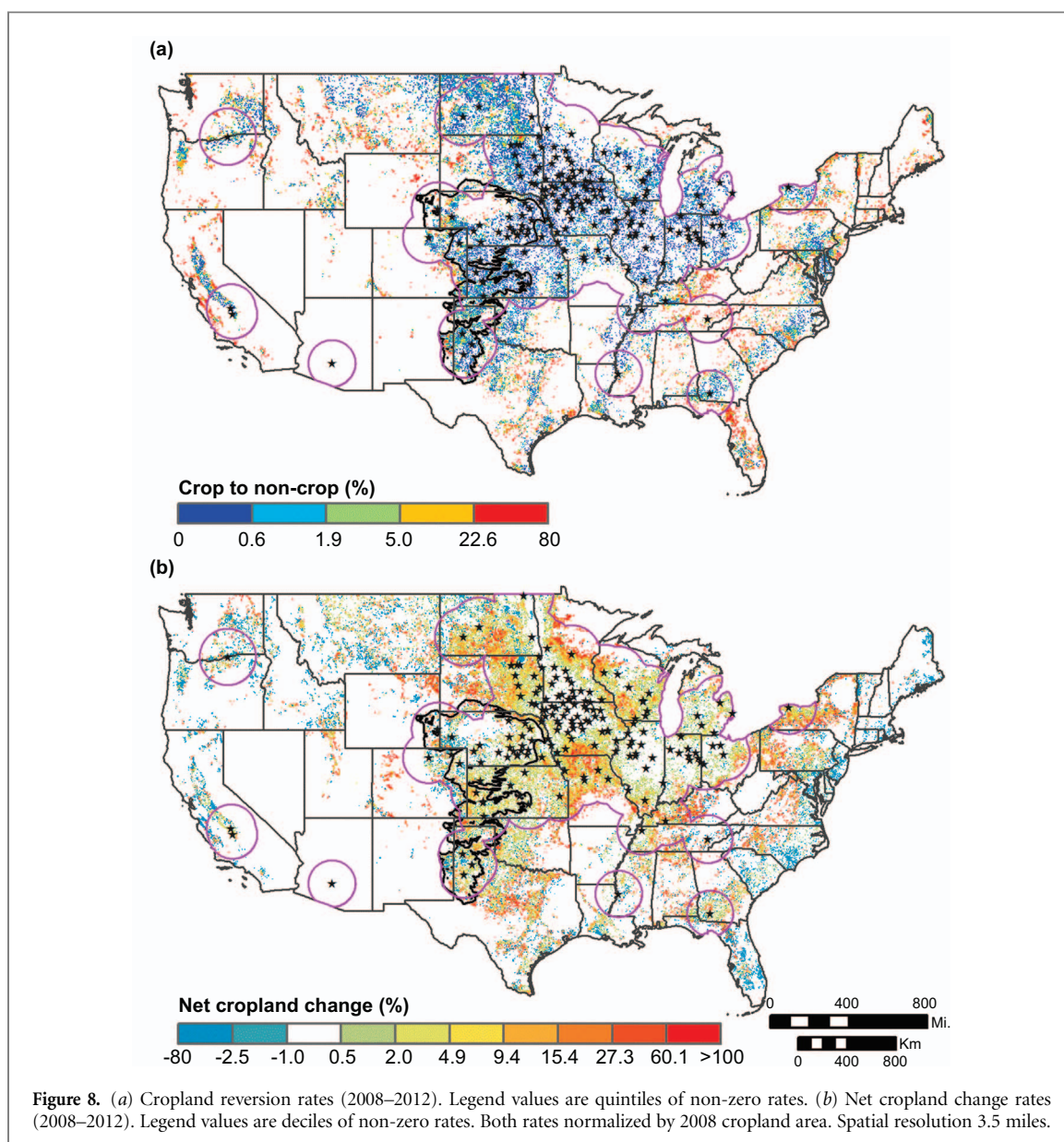
Spatially explicit forest, shrubland, and wetland conversion rates revealed important regional difference in sources of new cropland other than grassland (figure 10). Expansion along the Corn Belt's northern margin, and in western New York, involved all three classes. While forest conversion occurred broadly in the eastern half of the U.S., including along the Corn Belt's southern margin, relative conversion rates were low (figure 10(a)). As a result, gross forest loss within 100 miles of refineries was relatively modest (94 000 acres) with less than half that amount (43 000 acres) occurring beyond 100 miles. Note, forest with no prior history of cultivation is ineligible for feedstock production under EISA; this may explain, in part, its limited conversion. Isolated, higher rates of

forest conversion in the Central Plains (figure 10(a)) likely involved the clearing of shelterbelts; trees planted to control erosion or shelter farmsteads from prevailing winds. Shrubland conversion occurred largely in southwest North Dakota and the Texas- and Oklahoma Panhandles (figure 10(b)). In southern Iowa and northern Missouri, mixed conversion of grassland, shrubland, and forest (figures 9 and 10) likely reflected the clearing of oak savannah or similar mixed landscapes. Very high rates of wetland conversion (>16.5%) were found in the Prairie Pothole Region of eastern South Dakota and parts of North Dakota (figure 10(c)).

#### 4. Discussion

Our study represents the second comprehensive assessment of land-use impacts across the ethanol industry. The first, by Motamed *et al* [24], analyzed the effect of feedstock demand from a slightly different perspective—that of increases in corn acreage and total cultivated area rather than specific land-use transitions. We interpreted countervailing trends in aggregate rates of conversion vs. reversion (figure 2(a)) as evidence that farmers closer to refineries had a greater incentive, as a group, to increase and maintain land in crop production. However, we did not consider potential effects of other explanatory variables. After



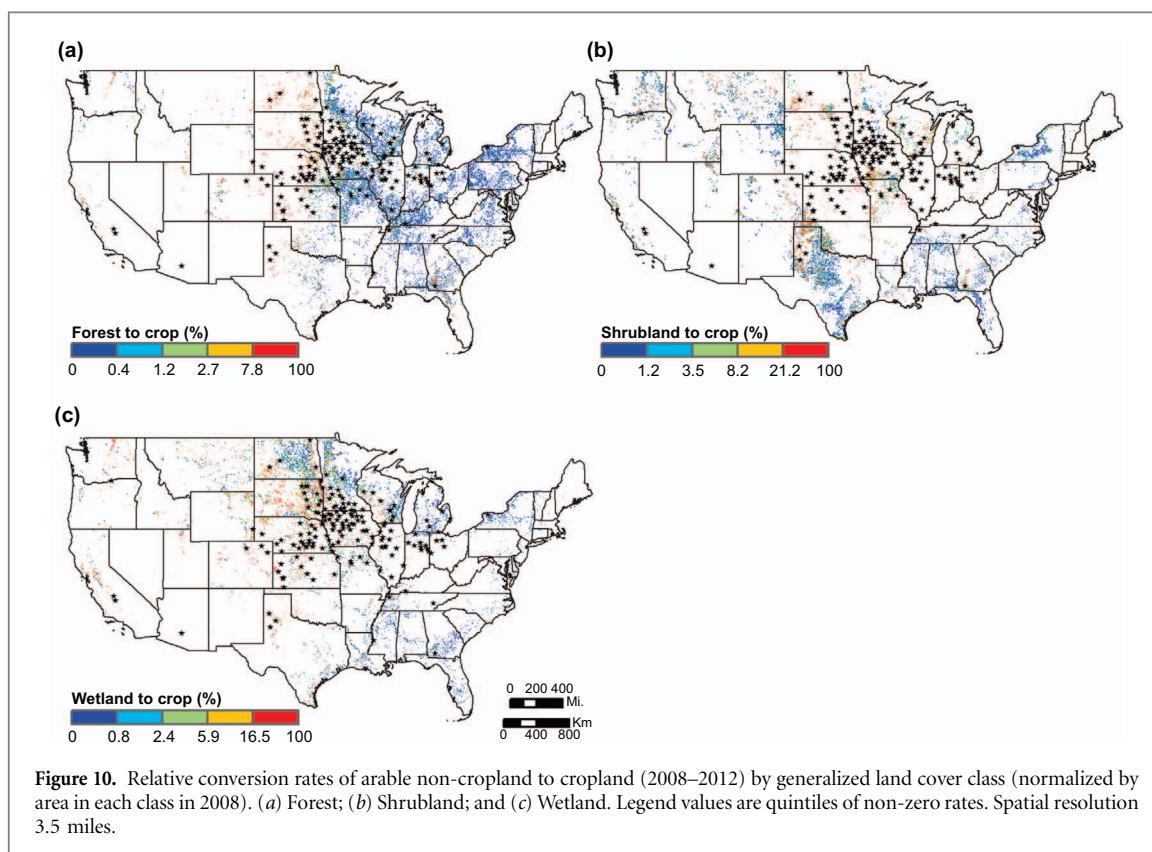
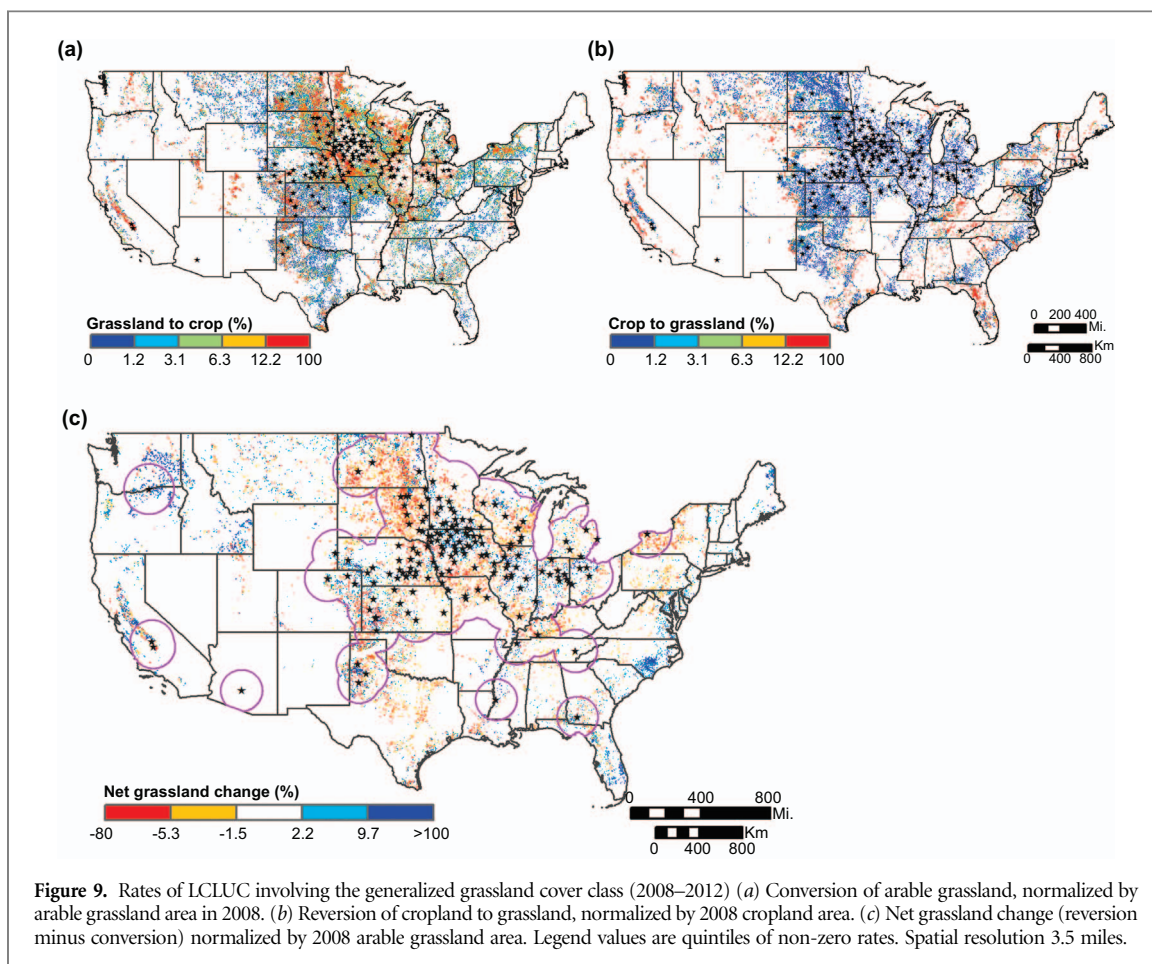


controlling for climate, soils, and terrain factors expected to influence land use decisions, Motamed *et al* [24] found that the positive effect of neighborhood refinery capacity on corn acreage increases remained statistically robust. This stimulative effect was strongest in areas where corn acreage and cultivated area were low to begin—also around the margins of the Corn Belt. However, they did not consider the types of non-cropland brought into production. In combination, our results and those of Motamed *et al* [24] provide corroborating evidence that accelerated ethanol development under RFS2 was an important driver of recent grassland losses.

At the same time, potential ethanol capacity attributable to cropland expansion was modest. This industry-wide result was consistent with state-level findings from Kansas, over a comparable time period (2007–2009) [30]. There, corn intensification surrounding ethanol refineries, due to crop switching and an increase in continuous-corn production, was five-times greater, by area, than expansion of corn onto

new cropland [30]. With respect to uncertainties surrounding feedstock sourcing, as acknowledged in EPA's first triennial report [13], our results are consistent with an argument that U.S. ethanol development has been achieved more so by corn intensification—including crop switching, yield improvements, and continuous-corn production—than by corn extensification [32].

However, implementation of RFS2 was accompanied by substantial changes in U.S. corn utilization that also likely played an important role in meeting the conventional biofuel mandate. For example, as the percentage of harvested corn dedicated to ethanol increased from 25% in 2008, to 43% by 2012, average annual corn prices rose from \$4 to \$7 per bushel [33]. High prices stimulated corn production, internationally, reducing U.S. competitiveness in global markets. Consequently, the export share of U.S. output declined by 50% between 2008 and 2012 [33]. Over the same period, rising prices contributed to a 20% reduction in corn used for animal feed, offset in large



part by substitution of ethanol by-products (distillers' grains) [33].

#### 4.1. Indirect land-use change

Nearly one-third of all non-cropland conversion, nationwide, occurred outside our 100-mile national draw area (table S3, figure 6(b)), concentrated in Oklahoma, Texas, Montana and South Dakota (table S3). These Great Plains states are characterized by extensive livestock- and small-grain production (figure 1(a)) as well as an abundance of potentially arable land (figure 6(a)). There, Lark *et al* [12] found a preponderance of grassland conversion to winter wheat from 2008–2012, with additional conversion to alfalfa and barley in eastern Montana, and to oats in central Texas. This broader LCLUC may have simply been a general reaction to high commodity prices. From 2008–2012, prices of wheat, barley, and oats increased in tandem with corn due to cross-price effects and other market interactions [33]. Alternately, specific transitions to wheat, barley, oats, and alfalfa in areas where cattle ranching is a dominant land use may represent an adaptation to high corn prices where distillers' grains are not a viable alternative.

Such an indirect land-use change effect of ethanol production has not been considered by others, but anecdotal evidence suggests its' potential. For example, grazing cattle on winter wheat prior to feedlot finishing is a common practice in the southern Great Plains [34]. When the spread between wheat and corn prices falls to a ratio near 1.25:1, substitution of wheat for corn in feedlot cattle rations becomes economical, as occurred in 2011 when rising corn prices outpaced wheat [35]. In the northern Great Plains (Montana and North Dakota) barley is a common livestock feed valued for its flexibility; it can be grazed, hayed, or harvested for grain [36]. However, barley is planted in spring, as opposed to winter wheat planted in autumn. Recently, the Montana Agricultural Experiment Station released a winter wheat cultivar bred expressly for feeding cattle during the early-season period before barley becomes sufficiently mature [37].

Outside the Great Plains, we found extensive conversion of non-cropland in the eastern U.S. (figure 6(b)), primarily to corn and soybeans [12]. Although relative conversion rates were uniformly low across the region (figure 6(b)), they were associated with relatively high rates of net cropland change in a number of areas (figure 8(b)). In the Southeast, where the U.S. poultry industry is concentrated, cropland expansion from North Carolina to Mississippi (figure 6(b)) coincided with the largest concentration of grain-consuming animal units (GCAUs)—a standardized measure of animal feed requirements across a range of species—outside the Mid-West [38]. Given vertical integration of the industry, poultry processors typically operate feed-processing facilities, as well. Perhaps, in response to high input costs, poultry processors increased their sourcing of feed grains,

locally, with farmers benefiting from a lower corn/soy basis, or entering into direct contracts with feed mills, and bringing new land into cultivation, accordingly. In the Mid-Atlantic region, cropland expansion from Virginia to New York (figure 8(b)) coincided with intermediate concentrations of GCAUs [38].

International, indirect land use-change (ILUC) effects of U.S. ethanol production have been controversial and extensively studied [39]. Comparatively limited attention to domestic ILUC effects has focused on the substitution of distillers' grains in confined animal feeding operations [40, 41]. Interestingly, we observed approximately ten-times less forest conversion to cropland (figure 5(b)) than projected by these models [40, 41], but two-times more grassland conversion (tables S4, S5). In sum, our results suggest, at least anecdotally, that further attention should be given to potential ILUC associated with spatially diffuse adaptations to higher feed costs beyond the substitution of ethanol by-products.

#### 4.2. Aggregate compliance

By focusing on 100 mile neighborhoods surrounding refinery locations, we found evidence of a significant land-use response to RFS2. Grassland conversion occurred largely in South Dakota, North Dakota, and Kansas, states where unplowed native prairie is extensive [23, 31]. However, given limitations of available satellite-based land cover data, we were unable to separate the conversion of native prairie ineligible for feedstock production from conversion of eligible grassland types (introduced pasture, hay, and CRP lands). Nonetheless, we note that EPA's aggregate compliance approach is based, in essence, on *indirect* evidence of *potential* feedstock sourcing from ineligible land. Under this standard of evidence, we contend, our results show that aggregate compliance, as implemented at a national scale, is not responsive to LCLUC relevant to EISA's land protection provision occurring at finer spatial scales.

EPA findings of no significant impact under RFS2 followed from an 18 million acre decline in U.S. cropland area reported from 2007–2012, based on USDA data [8]. In 2012, the USDA Agricultural Census found a comparable 16.7 million acre drop in total cropland from the preceding census in 2007 [42]. However, closer inspection of the 2012 Agricultural Census shows this net loss was largely explained by a 23 million acre decrease in 'cropland pasture' offset, in part, by a 9.3 million acre *increase* in planted cropland (harvested cropland + failed cropland) [42].

Cropland pasture represents the pasture phase of longer-term crop rotations, and is treated as a component of total cropland area by USDA. Therefore, land-use transitions between cropland pasture and cropland (in either direction) have no net impact on total cropland area reported by USDA. In our analysis, cropland pasture returning to



cultivation was captured by transitions between arable grassland and cropland (figure 9), encompassing 5.2 million acres of grassland conversion to cropland (tables S4, S5), 1.2 million acres of cropland reversion to grassland, and a net loss of 4.0 million acres of arable grassland, nationally (tables S6, S7). If lands classified as non-arable are included, grassland conversion from 2008–2012 totaled 5.7 million acres, of which Lark *et al* [12] estimated 75% had been cultivated at least once in the preceding 20 yr.

Clearly, the magnitude of land-use transitions between grassland and cropland that we found, albeit over one less year, fell well short of the level of activity involving cropland pasture as reported in the 2012 Agricultural Census. Notably, the preceding 2007 Agricultural Census found a similarly large, 25 million acre reduction in cropland pasture from 2002–2007, accompanied by a 28 million acre decline in total cropland [43]. However, according to the USDA Economic Research Service (ERS), both results from the 2007 census were largely explained by a methodological change in which land identified as cropland pasture in 2002 was re-classified as ‘permanent pasture and range’ in 2007 [44]. Permanent pasture and range is not considered a component of total cropland by USDA. Consequently, the 28 million acre decline in total cropland reported by the 2007 Agricultural Census was largely an artifact of a change in land-use interpretation rather than actual land-use change, ERS concluded [44].

In the description of methods employed by the 2012 Agricultural Census, we find no mention of potential complications related to estimating the area of cropland pasture from land owner surveys [42]. From our reading of the 2012 Census, reconciling our results with USDA figures would require an unexpected level of cropland-pasture conversion to non-agricultural land uses, substantial re-classification to permanent pasture and range, or some combination thereof. Given the apparent absence of an EPA re-assessment of aggregate compliance in 2010, it is clearly important to resolve these discrepancies.

In order to reduce the risk of feedstock sourcing from ineligible grasslands, we suggest revisiting EPA’s original proposal requiring ethanol refineries to conduct feedstock recordkeeping and reporting. Nonetheless, as we show, these risks are likely not evenly distributed across the ethanol industry. Feedstock certification and monitoring may be unjustified within core ethanol producing regions where relative conversion rates were minimal but more appropriate in the Dakotas and western Kansas where conversion risks are higher (figure 9). For example, a refinery under construction in Onida, South Dakota [45] will expand ethanol production (and thus feedstock demand) nearly 100 miles west in the state, with a potential feedstock draw area dominated by grassland (figure 11).

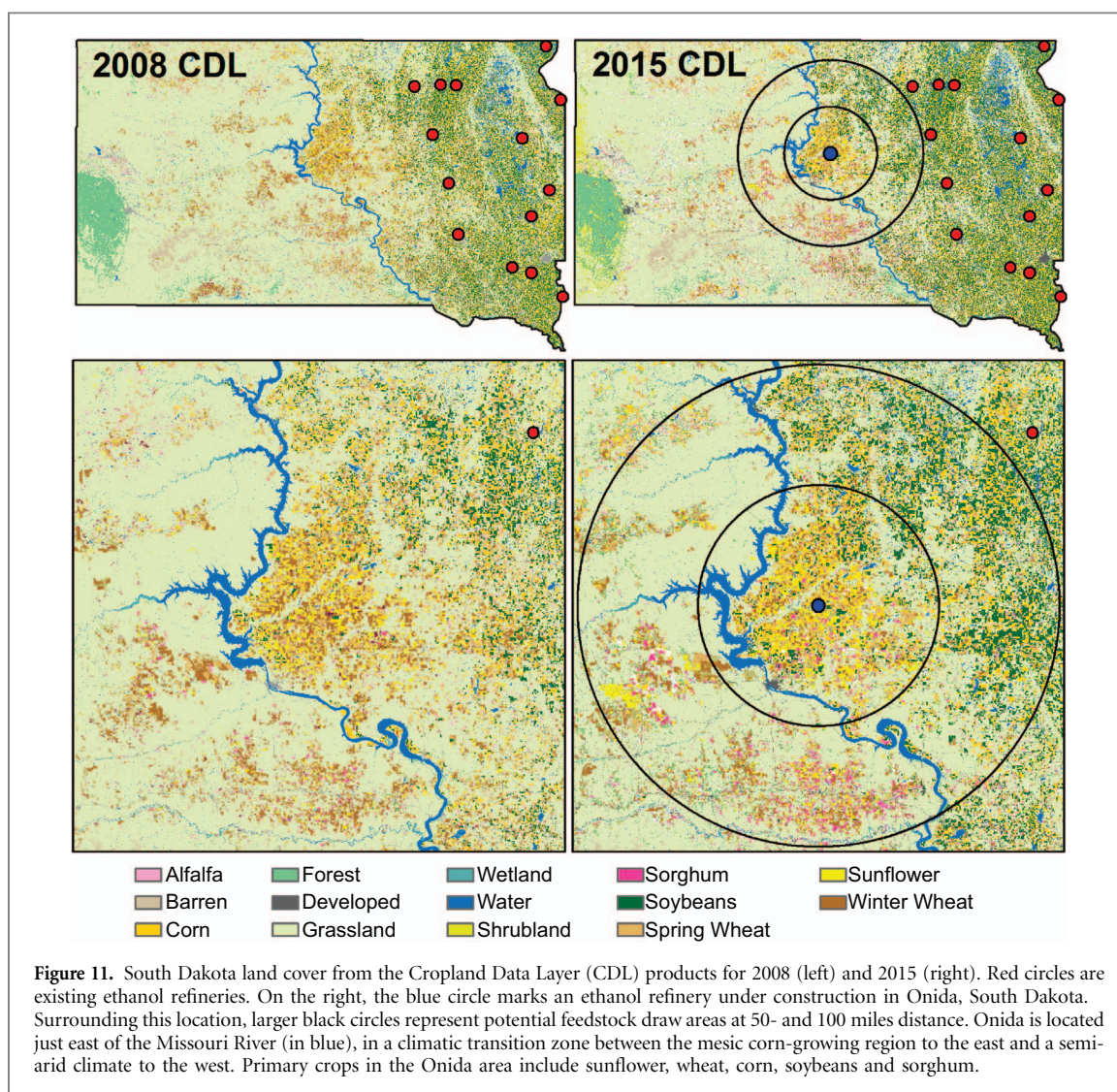
### 4.3. Broader impacts on the extensive margin

In agricultural economics, the ‘extensive margin of cropland use’ refers to agricultural lands that tend to move in and out of cultivation depending on economic factors. Beyond normal market forces, land use on the extensive margin is also responsive to national policies supporting cultivation vs. conservation, e.g. RFS2 vs. CRP. From 1982–1997, widespread deintensification of U.S. agriculture, mainly in the Southern Plains and around the margins of the Corn Belt, resulted in more than 72 million acres of cultivated land reverting to pasture, hay, and CRP, with net cropland losses totaling nearly 50 million acres [46]. From 1998–2007, deintensification slowed in the Corn Belt as cropland reversion to non-cultivated uses was balanced by nearly equal amounts of pasture, hay, and CRP returning to cultivation [47].

Our analysis from 2008–2012 showed an abrupt reversal of this equilibrium on the Corn Belt’s extensive margin, less so along the Ogallala Aquifer (figure 8(b)). Much of this reversal was likely land formerly enrolled in CRP. For example, from 2010–2013 nearly 0.9 million acres of CRP grassland was converted to cropland in the upper Mid-West [48]. Where conservation-oriented federal policy once supported land-use de-intensification, biofuel policy appears to be driving re-intensification.

Studies projecting outcomes of various bioenergy scenarios typically assign feedstock production to marginal lands [49–53]. From these projections, broader impacts of RFS2 can be inferred. For example, the observed conversion of a mixture of land cover types around the Corn Belt’s periphery (figure 9 and 10) represents a reduction in landscape heterogeneity. Under a corn-intensive biofuel scenario, comparable landscape homogenization reduced projected bird species diversity regionally [49], with the highest levels of risk corresponding with elevated conversion rates around the margins of the Corn Belt (figures 8(b)). Increased soil erosion and fertilizer runoff have been documented in corn-intensive scenarios [50, 51], particularly in southern Iowa and northern Missouri [51] where we found rapid cropland expansion (figure 8(b)). In fact, this region was formerly extensively cropped, but previously reverted to pasture and perennial hay due to soil and terrain limitations [54].

Lastly, with respect to forward looking climate-change mitigation, grassland conversion to produce corn feedstock incurs the opportunity costs of not waiting to realize the net carbon advantages of second generation cellulosic biofuels [52, 53], development of which has lagged beyond EISA’s original goals [55]. These costs may be much larger than perhaps anticipated by policy makers. For example, Ahlering *et al* [5] estimate that conversion of just 10% of unprotected grasslands in the Dakotas (520 000 acres) could incur social



costs approaching \$430 million due to emissions from converted soils and foregone carbon sequestration.

## 5. Conclusions

Our study highlights the land use change that occurred during the initial build-out of conventional biofuel capacity following passage of the Energy Independence and Security Act of 2007, and shows the majority of new croplands capable of producing feedstocks came from grasslands at the fringe of the Corn Belt within close proximity of refineries. More recently, as conventional biofuel production approached the 15 Bgal per year cap, U.S. gasoline consumption actually declined [55]. Concerns regarding the transportation sector's ability to absorb a higher biofuel mandate, the so-called 'blend wall', led the EPA to revise downward the conventional biofuel standards for 2014–2016 [55]. However, actual ethanol production substantially exceeded those revisions, contributing to foreign ethanol exports totaling more than 0.8 Bgal in both 2014 and 2015 [56].

EPA has since increased the conventional biofuel standard to 15 Bgal for 2017 [57]. If ethanol exports continue to grow, actual production at 16 Bgal per year appears feasible. Given that peripheral refineries are well-positioned to utilize an under-developed feedstock potential on Mid-West grasslands (figures 6 and 11), annual ethanol production at this level—beyond that originally envisioned by EISA—might reasonably be expected to drive additional grassland conversion.

While recent adjustments to the RFS2 schedule have centered on ethanol demand, the EPA is statutorily empowered to also consider environmental impacts of biofuel production as a basis for revision, but has not done so to date [14]. As the EPA's Inspector General recently concluded, the absence of required studies and reporting has impeded the agency's ability to make such mid-course adjustments [14]. Our study helps quantify and characterize the extent of ethanol feedstock-related land use change around refineries, offering new insights into the scale of landscape transformation and the potential for associated environmental impacts.

The conventional phase of U.S. biofuel development has now reached maturity. This achievement of a



15 Bgal per year capacity coincided with widespread perturbation of U.S. agricultural landscapes [10, 12] and global agricultural markets [58]. Absent an effective monitoring program, this initial effort to mitigate global warming by an ambitious intervention in energy delivery systems has been plagued by fundamental uncertainties surrounding policy outcomes [39] and perhaps, avoidable scientific and public controversy [59]. As U.S. biofuel development moves into its advanced, cellulosic phase—an even more ambitious intervention in ecosystem functioning—our hope is that significant, up-front investments are made in comprehensive monitoring and related assessment and validation of the underlying scientific foundation (biological, physical, and socio-economic) on which successful climate-change mitigation should be based.

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