

Conterminous United States land cover change patterns 2001–2016 from the 2016 National Land Cover Database

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ABSTRACT

The 2016 National Land Cover Database (NLCD) product suite (available on www.mrlc.gov), includes Landsat-based, 30 m resolution products over the conterminous (CONUS) United States (U.S.) for land cover, urban imperviousness, and tree, shrub, herbaceous and bare ground fractional percentages. The release of NLCD 2016 provides important new information on land change patterns across CONUS from 2001 to 2016. For land cover, seven epochs were concurrently generated for years 2001, 2004, 2006, 2008, 2011, 2013, and 2016. Products reveal that land cover change is significant across most land cover classes and time periods. The land cover product was validated using existing reference data from the legacy NLCD 2011 accuracy assessment, applied to the 2011 epoch of the NLCD 2016 product line. The legacy and new NLCD 2011 overall accuracies were 82% and 83%, respectively, (standard error (SE) was 0.5%), demonstrating a small but significant increase in overall accuracy. Between 2001 and 2016, the CONUS landscape experienced significant change, with almost 8% of the landscape having experienced a land cover change at least once during this period. Nearly 50% of that change involves forest, driven by change agents of harvest, fire, disease and pests that resulted in an overall forest decline, including increasing fragmentation and loss of interior forest. Agricultural change represented 15.9% of the change, with total agricultural spatial extent showing only a slight increase of 4778 km², however there was a substantial decline (7.94%) in pasture/hay during this time, transitioning mostly to cultivated crop. Water and wetland change comprised 15.2% of change and represent highly dynamic land cover classes from epoch to epoch, heavily influenced by precipitation. Grass and shrub change comprise 14.5% of the total change, with most change resulting from fire. Developed change was the most persistent and permanent land change increase adding almost 29,000 km² over 15 years (5.6% of total CONUS change), with southern states exhibiting expansion much faster than most of the northern states. Temporal rates of developed change increased in 2001–2006 at twice the rate of 2011–2016, reflecting a slowdown in CONUS economic activity. Future NLCD plans include increasing monitoring frequency, reducing latency time between satellite imaging and product delivery, improving accuracy and expanding the variety of products available in an integrated database.

1. Introduction

Change in land use and land cover type alters biophysical surface characteristics and can lead to major consequences including

intensification of climate change, land degradation, and changes to biological diversity and ecosystem services (Foley et al., 2005, Pielke, 2005, Rindfuss et al., 2004, Zeleke and Hurni, 2001). The pervasiveness of land cover change globally, predominantly for human use, creates

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concerns about the sustainability and outcomes of current land use trends (Foley et al., 2011, 2005). This concern led to the emergence of land change science (Turner et al., 2007; Rindfuss et al., 2004) and its maturation into land system science (MeyFroidt et al., 2018; Verburg et al., 2013). Land system science views land cover and its change as the medium upon which nature and society interact, and seek to understand the interactions through interdisciplinary assessment, monitoring, modeling, and theory (MeyFroidt et al., 2018). Hence, land cover databases that quantify and monitor land systems provide critical data.

However, databases that support large area land system science monitoring are relatively rare. There are numerous initiatives to map land cover globally and regionally, but mapping is not always monitoring. Further, change detection is not monitoring unless it is developed into land cover data for more than two points in time. The complexity of developing a land change monitoring system able to support land system science for large areas (stable funding over long periods, considerable computing and storage capabilities, database management, research to support continued production and product development) perhaps explains why these land cover monitoring programs that cover large areas are rare. For example, Grekousis et al. (2015) reviewed about 35 large-area land cover mapping efforts of which only eight provide data suitable for reporting trends (Table 1). Of the 8 projects that provide trends (≥ 3 different dates), five are based on coarse resolution satellite data such as Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Very High Resolution Radiometer (AVHRR), and MEdium Resolution Imaging Spectrometer (MERIS). The three remaining land cover monitoring programs are based on Landsat and Operational Land Imager (OLI) at their native resolutions of 30 m \times 30 m pixels (0.09 ha/pixel). Hansen et al. (2013) only provide information on forest trends, with only two offering full land cover class monitoring. The Chinese land cover monitoring project uses primarily visual interpretation to identify land cover classes and changes from one epoch to the next (i.e., 2010–2015) (Zhang et al., 2014). The National Land Cover Database (NLCD) uses digital change detection methods to identify land cover, impervious cover, forest canopy cover, and changes and trends for the United States (U.S.).

NLCD has been providing nationwide data on land cover and land cover change in the U.S. at the native 30 m spatial resolution of Landsat since 2001 with NLCD 2001, NLCD 2006, and NLCD 2011 (Homer et al., 2015; Fry et al., 2011; Homer et al., 2007). The recently released NLCD 2016 database, is the culmination of NLCD product evolution, offering improved cyclical updating of U.S. land cover and associated changes (Yang et al., 2018). NLCD products have become a cornerstone in U.S. land cover applications and are widely used in such areas as climate modeling, hydrology, land management, environmental planning, urban development, wildlife habitat, ecosystem assessment, education, environmental planning, risk and disease analysis and telecommunications (Jones et al., 2017; Byrd et al., 2015; Terando et al., 2014; Vargo et al., 2013; Cooter et al., 2012; Kalyanapu et al., 2010; Claborn et al., 2008).

Table 1
Large-area land cover mapping efforts suitable for reporting trends (see Grekousis et al., 2015).

Product	Study area	Spatial resolution	Satellite	Product dates	Method	Reference ¹
ESA-CCI	Globe	300 m	MERIS, AVHRR, PROBA-V	Annual ('92-'15)	Digital	ESA (2017)
CORINE	Europe	100 m	Landsat	'90, '00, '06, '12	Visual	Büttner (2014)
LCTS	Canada	1000 m	AVHRR	Annual ('85-'05)	Digital	Latifovic (2005)
LCTS	Canada	250 m	MODIS	Annual (2001–2011)	Digital	Pouliot (2014)
DLCD (V2.1)	Australia	250 m	MODIS	Biannual ('01-'15)	Digital	Lymburner (2011)
NLUD-C	China	30 m	Landsat	5 yrs ('90-'15)	Visual	Zhang (2014)
NLCD	USA, incl. Alaska	30 m	Landsat	2–3 yrs (2001–2016)	Digital	Homer (2004)
Forest	Globe	30 m	Landsat	Annual ('00 – '12)	Digital	Hansen (2012)

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The demand for longer temporal duration, more frequent, more accurate and consistent land cover classifications and corresponding change information continues to further drive the development of land system science monitoring. Improved data availability, computer technology innovation, and advanced science development have facilitated this trend (Hansen and Loveland, 2012). NLCD 2016 has capitalized on these innovations with new product development, while still retaining the accuracy of previous delivered products that required substantially more human intervention. These efficiency gains have lowered cost and decreased product generation times, important for maintaining a viable monitoring product into the future. The latest NLCD product release greatly advances CONUS large-area land cover and land change monitoring through an updated suite of land cover and land cover change products (Yang et al., 2018). This database is the most comprehensive and accurate product release in NLCD history, providing new opportunities to examine CONUS land cover change patterns over the last 15 years. NLCD 2016 provides a suite of products that include:

1. 15 years of categorical land cover and land cover for 7 epochs (2001, 2004, 2006, 2008, 2011, 2013, 2016);
2. 15 years of fractional impervious cover and impervious cover change and impervious cover for 4 epochs (2001, 2006, 2011, 2016);
3. 5 years of fractional tree canopy cover and change for 2011 and 2016;
4. One year (2016) fractional cover for shrub, sagebrush, big sagebrush, herbaceous, annual herbaceous, litter, and barren for the western U.S.

The main objectives of this paper are: (1) to provide an overview of the NLCD 2016 product suite; (2) focus on the NLCD 2016 land cover product results; (3) report on the NLCD 2016 land cover accuracy; (4) analyze NLCD 2016 land cover change rates both spatially and thematically over the last 15 years; and (5) analyze land cover change patterns by land cover theme. Although this paper remains focused on the analysis of the NLCD land cover product, other related NLCD database products integral to the development of the land cover product are also described. The NLCD 2016 database provides a complete 15-year record of spatially explicit change data for CONUS. The major patterns of CONUS land cover change described in this article are intended to provide summaries of change (i.e., area estimates) that are consistent with the spatially explicit patterns observable in the NLCD map products. Beyond this analysis, this database provides a wealth of opportunity for future assessments of land cover change at regional and local levels.

2. Methods

NLCD 2016 provides a suite of national products including land cover and land cover change, fractional forest canopy percentage, fractional developed impervious percentage, and fractional shrub and

grass products. This paper focuses on the 7-epoch NLCD 2016 land cover product, including a synopsis of production methods and the process for integrating the other fractional products from the NLCD 2016 database into the land cover product (see Yang et al., 2018 for detailed descriptions). We also describe the approach for assessing land cover accuracy, and the protocol for evaluating the CONUS 15-year land change results, including trends, patterns and specific thematic outcomes.

2.1. Product development

2.1.1. Land cover

a. Data sources

We produced land cover by Landsat Worldwide Reference System path/row geographies. Relevant Landsat 5, 7, and 8 images were obtained from the U.S Geological Survey (USGS) Landsat archive and processed to an Albers projection with Top of Atmosphere (TOA) reflectance. One leaf-on image was selected for each target year (2001, 2004, 2006, 2008, 2011, 2013, and 2016) and one leaf-off image was selected for only 2016. We used six bands (Blue, Green, Red, Near-infrared, Short-wave Infrared (SWIR) 1, SWIR 2) for all the Landsat images. If some selected base images had clouds or anomalies (e.g., fire smoke), additional images were chosen and later used to fill cloud/shadow areas in the base image using the method developed by Jin et al. (2013a).

We compiled and created ancillary data from different sources. The ancillary data included NLCD legacy data 2001, 2006, and 2011, U.S Department of Agriculture (USDA) Cropland Data Layer (CDL) and Cultivated Crop Layer derivatives, Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO) hydric soil, National Wetland Inventory (NWI), Monitoring Trends in Burn Severity (MTBS) fire date and severity, Digital Elevation Models (DEM) and derivatives such as slope and aspect, LANDFIRE Vegetation Change Tracker and Existing Vegetation Type (<https://www.landfire.gov/>), and some in-house specifically designed ancillary data layers such as the Wetland Potential Index (WPI), fire recovery zone strata, wetland zone strata, and sagebrush-dominated region (Yang et al., 2018).

b. Land cover generation

NLCD 2016 land cover product generation is fundamentally very different and much more comprehensive than the methods developed for NLCD 2011 and NLCD 2006 (Jin et al., 2019). The methods for generating previous NLCD products (e.g., 2011, 2006) only focused on detecting and classifying the change areas between that epoch and the previous release of NLCD (Jin et al., 2013b; Xian and Homer, 2010), with very few systematic postprocessing procedures. In contrast, NLCD 2016 created seven epochs of land cover within a uniformly consistent process using four “pillars” of mapping that (1) evaluates spectral signatures, (2) incorporates spectral succession and trajectory patterns over time, (3) defines and incorporates the spectral patch shape to provide context analysis and (4) integrates ancillary data. The entire NLCD 2001–2016 land cover product line was regenerated and integrated to ensure harmony across all the epochs.

Training data were derived for each land cover type for each epoch year using integrated information from the Landsat image of the target year, two spectral indices including Normalized Burn Ratio (NBR) and Normalized Difference Water Index (NDWI), multiple spectral change products from two-date and multi-date change detections and spectral trajectory analysis. The process relied on the original 2001 classification and the integrated information described above to identify spectrally stable land cover pixels for each land cover class. If a pixel for each land cover class stayed within a given spectral mean threshold identified for that class, across the entire timeframe, these pixels were

assumed unchanged and comprised training data across the 15-year timeframe. Alternatively, changed areas were trained separately for each year with this given set of unchanged pixels which supplied a decision tree classification for each epoch. Results from this classification were combined with pixels that were spectrally stable and unchanged from the original 2001 classification to complete each epoch product. Training data were also additionally refined using image objects derived from the same Landsat image date to ensure that pixel-based training data were representative of the larger land cover patch they resided in (Jin et al., 2019), Yang et al., 2018).

Decision tree classifications were performed with these training data using four primary independent variables that represented the temporal, spectral, spatial, and terrain dimensions. These included (a) 1986–target year disturbance year dataset at 2–3-year intervals, (b) Landsat image of the year, (c) compactness of Landsat image segmentation polygons, and (d) DEM and derivatives of slope and aspect. This classification was then further integrated with ancillary data and object-based information to produce the initial land cover map for each epoch. For further details, see Jin et al., (2019).

c. Land cover post-processing

The initial land cover map derived from the decision tree classification process (above) required additional postprocessing before being completed. This postprocessing focused on integrating the spatial coherence (patch uniformity) of land cover labels for each epoch, the temporal consistency of land cover labels over time, and the logic of the land cover change trajectory. The process utilized information from spectral and spatial data, temporal change trajectory, expert knowledge, and ancillary data to refine the initial land cover and change labels through sets of rules. The postprocessing was conducted for each land cover type in succession, with higher confidence land cover labels taking precedence over lower confidence land cover labels. Confidence orders were decided based on mapping confidence in accuracy and are: (1) water, (2) wetlands, (3) forest and forest transition classes, (4) permanent snow and ice, (5) agricultural lands, and (6) persistent shrubland and herbaceous (Jin et al., 2019).

Final refinement emphasized the overall quality and compatibility of land cover labeling of all pixels across the seven epochs from 2001 to 2016. This was done in three primary steps after postprocessing. The first step analyzed all seven epochs as a succession of two-date paired change results in order to identify gross differences that were likely errors. The second step analyzed all seven epochs as a complete succession trajectory by creating spatial-temporal objects across all years to check for reasonable temporal change trajectories, and to ensure that relevant pixels remained consistent within an object. The third step corrected regional issues identified during review with specific models (e.g., vineyards in California misclassified as grassland or forest).

2.1.2. Fractional products required for NLCD land cover

a. Imperviousness product generation and crosswalk to four developed classes

Fractional impervious surface was used to define NLCD's four urban classes. This product was generated using high-resolution training data and Landsat spectral data in regression tree analysis. For NLCD 2016, several improvements were incorporated through all four dates of impervious surface, including removing inaccurate roads from previous generations, including newer, more spatially accurate road layers from Navteq, NavStreets (www.navmart.com), and incorporating areas of energy development with classified Landsat imagery over regions identified from FracTracker, an organization that provides geospatial data on oil and gas wells (www.fractracker.org). Additionally, all four epochs of imperviousness were visually assessed for omission and commission errors and corrected by hand editing if necessary.

Fractional imperviousness products were converted to categorical NLCD-developed land cover classes by thresholding the impervious surface percentage as (< 20% for developed open space, 20–49% for developed low intensity, 50–79% for developed medium intensity, and 80–100% for developed high intensity (Xian and Homer, 2010). For dates in-between impervious surface and development mapping epochs (2004, 2008, 2013) the same developed class information as the previous primary epoch was used. Although new change information on oil pads for 2004, 2008, and 2013 was captured using the National energy oil pad data and seven epochs of the Multi-Index Integrated Change Analysis (MIICA) spectral disturbance detections (Jin et al., 2013b), this information was rolled into the following primary year.

b. Rangeland products generation and cross-walk to shrub, grass and barren classes

We quantified 9 rangeland components, including percent shrub, sagebrush, big sagebrush, herbaceous, annual herbaceous, litter, and bare ground cover, along with sagebrush and shrub heights, at 30 m resolution using regression trees (see Rigge et al., 2020 for a complete description). This process was completed by independently mapping regions defined primarily from ecoregion boundaries, using extensive ground measurements for model training and validation. Ground measurements were strategically collected and expressed with regression trees as 9 rangeland components on high-resolution satellite imagery tasked for this purpose (sensors used included WorldView-2, WorldView-3, QuickBird and Pleiades) across the mapping region. These high-resolution footprints subsequently provided the training to scale up component predictions on Landsat 8 imagery to provide landscape-scale data (Rigge et al., 2020, Xian et al., 2015, Xian et al., 2013). Since only 5–6 mapping regions could be logically completed every year due to intensive field collection requirements, completing these products for the West required 5 years of mapping from 2013 to 2017.

Fractional rangeland products were then converted into three categorical NLCD land cover classes (barren, grass and shrub). This cross-walking process is described in Rigge et al. (2017). Essentially, shrubland components used in the cross-walking process included shrub cover, bare ground cover, herbaceous cover, and litter cover. Shrub height and litter cover were also used to help refine the cross-walk decision process. For each of the three NLCD classes, separate thresholds of the rangeland fractional component products were combined with ecosystem indicator layers to produce the categorical class. Because in some cases the fractional components were mapped in 2014 and 2015, cross-walked land cover classes were then updated to circa 2016 on fire burns that occurred between 2014 and 2016 using fire boundaries, change detection, and Landsat data from 2016. Once a 2016 product was available, historical product estimates also needed to be produced for earlier epochs (rangeland products were only available for the 2016 epoch). Given that fire is the main driver of change in these shrub and grass ecosystems, and good quality ancillary data of fire occurrence were available, we focused our efforts on capturing fire change and modeling fire recovery trajectories. This was done using expert knowledge, fire perimeter, fire severity and other ancillary data to identify areas to map grass, shrub and barren class label changes to 2001 where historical fires had occurred (Yang et al., 2018, Rigge et al., 2017).

2.2. Land cover product accuracy assessment

Accuracy assessment is standard practice for the NLCD project (Stehman et al., 2008). Accuracy assessments usually take 1–2 years to complete and cannot be initiated until product release. Since the reference data for NLCD 2016 are not yet available, existing validation data from the NLCD 2011 accuracy assessment provided an opportunity to validate the 2011 epoch of the NLCD 2016 product. We applied the

reference data collected for the NLCD 2011 accuracy assessment to the new version of the 2011 data that accompanies the NLCD 2016 product suite. Hereafter, we refer to the 2011 land cover in the NLCD 2011 product suite as version 1 and the 2011 land cover in the NLCD 2016 product suite as version 2. The specific objective of the accuracy assessment (Stehman et al., 2008) reported herein was to determine if the new mapping methods for NLCD 2016 led to higher product accuracy. Accuracy assessment of NLCD 2011 version 1 is described thoroughly in Wickham et al. (2017, pp. 329–331). Briefly, the NLCD 2011 version 1 accuracy assessment implemented a stratified random design, collecting a total of 8000 sample pixels distributed throughout CONUS. Reference class labels were collected by a team of individuals using high-resolution aerial imagery. Consistency in reference label assignment was supported by a prior training effort, and web-enabled conference calls during the reference data collection phase. Each of the members of the reference data collection team had several years of experience in image interpretation and mapping.

Reference data collected for NLCD 2011 version 1 were compared to map labels from NLCD 2011 version 2 to determine agreement. User's accuracy (UA), producer's accuracy (PA) (100 – omission error), and overall accuracy (OA) served as the measures of agreement. These agreement measures and associated standard errors were estimated from the stratified sample data using the formulas documented in Wickham et al. (2017). For this analysis, accuracies were based on agreement defined as a match between the map label and either the primary or alternate reference label (see Wickham et al. (2017)). UA, PA, and OA for NLCD 2011 version 2 were then compared to the same measures for NLCD 2011 version 1 (Wickham et al., 2017). We conservatively assigned significance to the differences between version 1 and version 2 for UA, PA, and OA by comparing the respective values to the standard errors (SE). Consistent with the interpretation of side-by-side notched boxplots, the absolute value of version 2 minus version 1 UA, PA, and, OA differences had to be at least 2 times greater than the SE to be considered significant. We used the greater of the 2 SEs (version 1 or version 2) to determine significance.

2.3. Land cover change evaluation

The most critical part of land cover monitoring is measuring and understanding change patterns and trends. For the 2001–2016 land cover change results, we analyzed change trends for CONUS including change rate and change frequency, as well as temporal and spatial change patterns by land cover theme.

For CONUS, the total 2001–2016 change rate was calculated in three ways. (1). A simple percentage of total change across time for all classes was calculated by dividing the entire spatial footprint of change across all years by the total area. (2). The change rate and location by land cover class theme was developed from the NLCD land cover change index. This index was developed to provide a simple and comprehensive way to understand change across all 7 dates of land cover, by summarizing change into 11 change classes. These classes were put into a hierarchical order to help communicate thematic change impact, and the order included water, developed, wetland (emergent herbaceous wetland, woody wetland), agriculture (cultivated crop, pasture hay), rangeland grass and shrub, and forest (with two additional forest regeneration classes). This priority order dictates the change category a change pixel is assigned across the 7 epochs. For example, a change pixel was assigned to the water change index if it converted “from or to water” across the 7 epochs, regardless of when the change occurred or other land cover changes that occurred. Assignment of a change pixel to an index then proceeded according to the hierarchy, such that pixels assigned to the agriculture change index included “from or to agriculture” but not “from or to water” (as these pixels were already assigned to the water index), and so on down the hierarchy. Change theme classes are typically organized at the Anderson 1 (Anderson et al., 1976) level of the legend, with two

Table 2

Land cover extent (km^2) by class across seven epochs from 2001 to 2016. Urban class extents in 2004, 2008, and 2013 are the same as their preceding epochs because impervious cover (the source of urban class delineation) was not available for 2004, 2008, and 2013.

NLCD Class	2001	2004	2006	2008	2011	2013	2016	MEAN	% of 2016 CONUS	Net Change, 2001–2016
Open Water	424,962	423,241	422,740	424,108	429,541	424,784	423,670	424,721	5.26	−241
Perennial Ice/Snow	514	514	514	514	514	514	514	514	0.01	0
Developed-Open Space	225,435	225,435	229,307	229,307	231,433	231,433	232,276	229,232	2.84	+6841
Developed-Low Intensity	112,228	112,228	115,421	115,421	117,685	117,685	119,756	115,775	1.43	+7528
Developed - Medium Intensity	45,991	45,991	50,794	50,794	53,952	53,952	56,283	51,108	0.63	+10,292
Developed - High Intensity	16,296	16,296	18,039	18,039	19,419	19,419	20,260	18,252	0.23	+3964
Barren Land	81,820	82,497	81,416	82,026	81,394	82,332	82,897	82,054	1.02	+1077
Deciduous Forest	780,529	773,016	764,851	761,746	757,369	759,065	756,813	764,770	9.46	−23,716
Conifer Forest	963,379	947,830	937,814	930,183	929,753	931,326	923,780	937,724	11.61	−39,599
Mixed Forest	293,390	292,688	291,654	290,842	290,813	292,996	293,167	292,221	3.62	−223
Shrub/Scrub	1,755,623	1,764,682	1,758,856	1,766,856	1,752,378	1,756,432	1,760,135	1,759,280	21.77	+3657
Grassland Herbaceous	1,092,991	1,115,338	1,129,833	1,131,729	1,140,488	1,125,422	1,118,412	1,122,030	13.89	+25,421
Pasture/Hay	551,345	538,968	530,906	526,023	517,094	514,650	507,568	526,651	6.52	−43,777
Cultivated Crops	1,264,559	1,268,928	1,275,151	1,281,122	1,290,360	1,299,517	1,313,114	1,284,679	15.90	+48,555
Woody Wetlands	351,624	346,382	345,984	348,753	349,268	353,214	352,719	349,706	4.33	+1095
Herbaceous Wetlands	119,391	126,044	126,799	122,614	118,616	117,337	118,714	121,359	1.50	−677

exceptions; wetland within change which quantifies change between emergent herbaceous wetland and woody wetland and agriculture within change quantifying change between cultivated crop and pasture/hay. For the same land cover type, level 1 within change had the higher priority than cross level 1 change. Calculations of change pixels from each class were summed and divided by the total CONUS number of pixels and the total changed to derive the change percentages. (3) CONUS change frequencies were calculated by analyzing each 30 m cell across the seven epochs of land cover. Any land cover change between epochs is counted as one time of change. These were summarized into a map of change frequencies, with 6 being the highest change frequency possible.

Land cover theme change was also analyzed to provide more specific change information, to demonstrate key land change results, and to examine patterns of land cover change. Analyzed land cover themes include forest, water, wetland, agricultural, shrub, herbaceous, and barren and are specified below.

Forest change – We calculated forest areal coverages and change extents for 2001–2016 from the three forest classes (deciduous, evergreen and mixed). However, one additional class (woody wet) was used to analyze forest fragmentation change. NLCD has been used extensively for forest change and fragmentation analyses within the Montréal Process (MPLO, 2015) and for U.S Forest Service (USFS) international reporting of forest fragmentation (Robertson et al., 2011). We updated fragmentation results with the new NLCD 2016 data. Following an earlier example (Riitters et al., 2012), the “proximate causes” of the land cover fragmentation were summarized for rural forest land use by combining NLCD information about forest/non-forest edges with field plot data from the USFS Forest Inventory and Analysis (FIA) program (O'Connell et al., 2017). We used the forest area density (FAD) fragmentation indicator (Riitters et al., 2002, Riitters and Wickham 2012) which identifies, for each pixel of NLCD forest (classes 41, 42, 43, 90), the proportion of a surrounding neighborhood that is also forest. Each forest pixel is then classified as dominant ($FAD \geq 0.6$), interior ($FAD \geq 0.9$), or core ($FAD = 1.0$). The classification is cumulative such that core forest is also interior and dominant forest, and interior forest is also dominant forest. The classification is performed separately for each of five neighborhood sizes (4, 15, 66, 590, and 5314 ha) to ensure a wide range of patch size is analyzed, and for each analysis year (Riitters et al., 2012).

Water and wetland change – Water and wetlands are often closely connected, hence we analyzed both water and wetland extents and their changes within different drainage basins. The USGS Watershed Boundary Dataset (WBD) is a comprehensive aggregated collection of hydrologic unit data which defines the perimeters of drainage areas (hydrologic units), formed by the terrain and other landscape

characteristics, at a 1:24,000 scale in the U.S. (<https://www.usgs.gov/core-science-systems/ngp/national-hydrography/>). We used WBD 2-digital Hydrologic Units at the HU2 hierarchical scale for 18 different watersheds across CONUS. NLCD 2016 datasets were then summarized for water extent, wetland extent, and their changes in each mapping years. We then focused on the connection between annual precipitation and water or wetland extent in every drainage basin using correlation analysis. Precipitation data were obtained from Daymet (<https://daymet.ornl.gov/>). Total amounts of annual precipitation were calculated in these basins in each mapping epoch. A simple correlation between precipitation and water or wetland extent was calculated for the period from 2001 to 2016.

Agricultural change – We calculated areal coverages of cultivated crop and pasture/hay. We also analyzed the cropland change from 2001 to 2016 by grouping the data into four “from and to” change classes including: crop or pasture/hay to non-cropland, non-crop pasture/hay to crop//pasture/hay, pasture/hay to cropland, and cropland to pasture/hay.

Shrub, herbaceous, and barren change – Analysis for shrub, herbaceous, and barren class change was completed by examining spatial extent and abundance patterns across CONUS. These numbers were directly calculated from the CONUS raster files for each mapping period.

3. Results and discussion

3.1. Land cover change and distribution

A total of 435 Landsat path rows were analyzed across the conterminous U.S. to produce 7 epochs of land cover with 16 thematic classes between 2001 and 2016. Nominal leaf-on base image acquisition dates for the seven periods were similar, with 2001 being August 5, 2001, 2004 being August 13, 2004, 2006 being July 6, 2006, 2008 being July 8, 2008, 2011 being July 17, 2011, 2013 being July 28, 2013 and 2016 being August 28, 2016. Shrub/scrub is the most abundant class with an average of 1,759,280 km^2 or 21.8% of CONUS and Perennial Ice/Snow the rarest with only 514 km^2 or 0.01% of CONUS (Table 2). Nine of 16 classes have gains across these 15 years (Developed-Open Space, Developed-Low Intensity, Developed-Medium Intensity, Developed-High Intensity, Barren Land, Shrub/Scrub, Grassland Herbaceous, Cultivated Crops and Woody Wetlands), six classes have losses (Open Water, Deciduous Forest, Conifer Forest, Mixed Forest, Pasture/Hay, Herbaceous Wetlands) and one class is unchanged (Perennial Ice/Snow). Cultivated crops has the highest positive gain rate, and Pasture/Hay the highest negative loss rate (Table 2, Fig. 1).

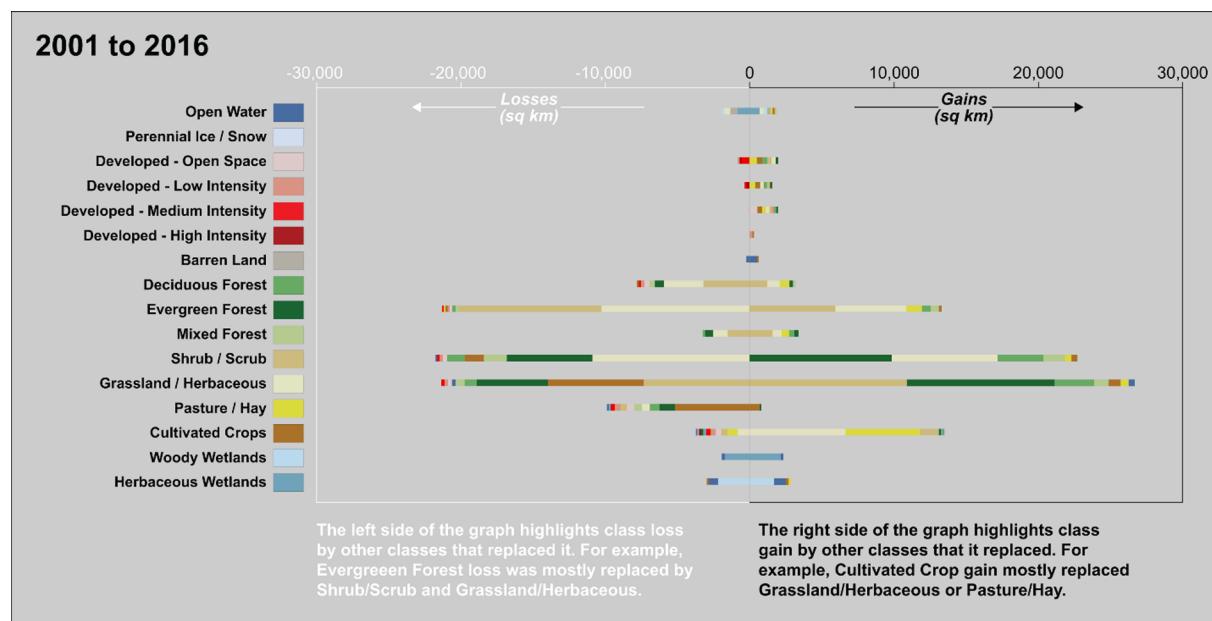


Fig. 1. The overall loss and gain for each CONUS land cover class for 2001–2016. The loss and gain magnitude for each class is displayed, along with the corresponding classes that replaced it or were replaced by it.

Table 3

NLCD land cover change between 2001 and 2016 by 30 m pixel.

Change class of 2001–2016	Pixels_Count	Percentage_CONUS	Percentage_Change
no-change	8,292,496,313	92.37	
water change	49,101,916	0.55	7.16
developed change	38,147,823	0.42	5.57
wetland within change	44,636,128	0.50	6.51
herbaceous wetland change	10,327,191	0.12	1.51
woody wetland change	30,529	0.00	0.00
agriculture within change	28,868,230	0.32	4.21
cultivated crop change	56,883,557	0.6–3	8.30
pasture/hay change	22,999,008	0.26	3.36
rangeland grass and shrub change	99,578,673	1.11	14.53
barren change	1,247,763	0.01	0.18
forest-theme change	333,546,917	3.72	48.67
Total	8,977,864,048	100.00	100.00

Nearly 8% (~646,400 km²) of CONUS, an area slightly larger than France, experienced land cover change at least once during 2001–2016 (Table 3, Fig. 2). Nearly 50% of the change involved forest, the majority of which occurred in the Pacific Northwest and southeastern U.S. where commercial forestry is common. Agriculture-related changes totaled 15.87% from combining the agriculture within change, cultivated crop change and pasture/hay change. Grass and shrub change comprise 14.53% of the total, with this change occurring predominantly in rangeland areas and resulting from fire. Wetland-related changes comprise 8.02% of the total change amount and water-related change comprise 7.16% but impacts only 0.55% of the CONUS area and is likely the most ephemeral change. Urban-developed change comprises 5.57% of the total change and represents the most permanent and persistent change. Fig. 2 shows the spatial footprint of NLCD land cover change types from 2001 to 2016. Change is not distributed evenly across CONUS but has regional patterns. Southeastern and western CONUS have the most intensive forest-theme change, central CONUS has mostly water, agriculture and wetland changes, and western-central CONUS has more prevalent grass, shrub change and water change (Fig. 2).

During the 15-year time span, the frequency of change for each pixel across the seven land cover epochs also varies from one to six times (Fig. 3, Table 4). During the 15 years, 53.3% of the changed area

across CONUS only changed one time, 30.6% of the changed area changed twice and 16.1% of the changed area experienced three or more changes. By change class, developed change had the highest one time change rate at 80.86% and water the lowest at 22.24% (Table 4). Alternatively, wetland-related change had the highest two-time change rate at 53.44%, with agriculture-change, the lowest at 15.28%. Of the 16.13% of CONUS change area that changed three or more times, water had the highest frequency of this change at 40.33% of all water change, and rangeland shrub and grass the lowest at 0.7% (Fig. 3, Table 4). Change frequency is further explained in Jin et al., (2019).

3.2. Land cover accuracy assessment

We applied the reference data collected for the NLCD 2011 accuracy assessment to the new version of the 2011 data that accompanies the NLCD 2016 product suite. The new classification methods developed for NLCD 2016 produced a quantifiable improvement in classification accuracy, with a small but significant increase in overall accuracy (Table 5). Version 1 and 2 overall accuracies were 82.0% and 83.0%, respectively, and the SE was 0.5%. The small increase in overall accuracy was attributable to a more significant increase in the eastern U.S. accuracy, whereas the western U.S. did not yield a statistically

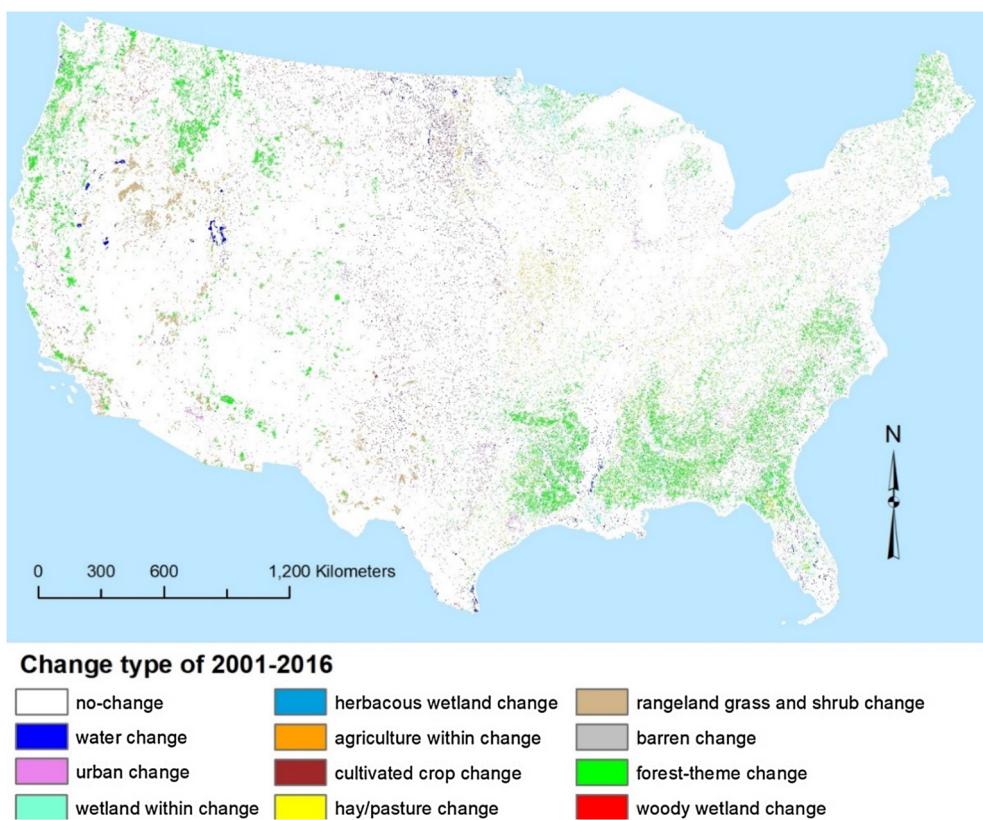


Fig. 2. Spatial distribution of NLCD land cover change types by 30 m pixel from 2001 to 2016.

significant improvement. The modest gain in overall accuracy realized in version 2 was attributable to statistically significant gains in user's accuracy for deciduous forest (41), cropland (82), shrubland (52) and grassland (71) in the eastern U.S. The static (between versions 1 and 2) overall accuracy in the western U.S. is likely attributable to a mix of statistically significant increases and decreases in class-specific user's accuracy. Setting aside changes in the snow & ice class (12) because of

its rarity, statistically significant increases in the user's accuracies for pasture (81) and cropland were offset by statically significant declines in open developed (21) and shrubland. There were no statistically significant declines in class-specific user's accuracies in the eastern U.S. Differences in class-specific producer's accuracies were more variable nationally and regionally even though there were more statistically significant increases than statistically significant decreases. At the

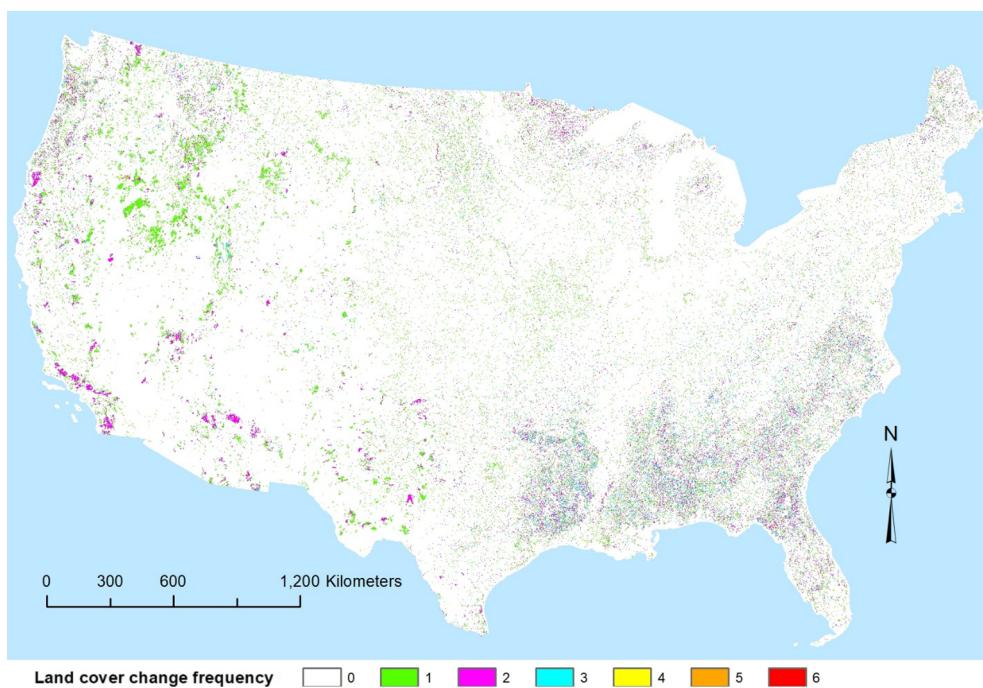


Fig. 3. The frequency of land cover change by each 30 m pixel across 7 epochs from 2001 to 2016.

Table 4

Individual 30 m pixel land cover class change frequency across 7-epochs from 2001 to 2016.

Change class	Land cover change frequency						Total	
	1		2		> = 3			
	Pixels	Percent	Pixels	Percent	Pixels	Percent	Pixels	Percent
Water	10,920,900	22.24	18,378,900	37.43	19,802,159	40.33	49,101,959	100.00
Developed	30,845,300	80.86	5,984,220	15.69	1,318,346	3.46	38,147,866	100.00
Wetland	21,262,044	38.66	29,391,189	53.44	4,340,597	7.89	54,993,830	100.00
Agriculture	80,115,990	73.67	16,613,275	15.28	12,021,578	11.05	108,750,843	100.00
Grass/Shrub	75,788,900	76.11	23,085,500	23.18	704,272	0.71	99,578,672	100.00
Barren	550,840	44.15	375,358	30.08	321,565	25.77	1,247,763	100.00
Forest	145,517,000	43.63	115,930,000	34.76	72,099,463	21.62	333,546,463	100.00
Total	365,000,975	53.26	209,758,444	30.61	110,607,998	16.14	685,367,396	100.00

national level, there were statistically significant increases in producer's accuracies for open developed, evergreen forest (42), mixed forest (43), pasture, cropland, woody wetland (90) and emergent wetland (95) and statistically significant declines for barren (31) and shrubland. At the regional level, there were fewer statistically significant changes and a more equal mix of statistically significant increases and decreases. Overall these results suggest the NLCD 2016 land cover product is at least as accurate as NLCD 2011, and likely even more accurate for some classes. However, more conclusive results will need to wait for the completion of the formal NLCD 2016 accuracy.

A formal, statistically rigorous accuracy assessment of NLCD 2016 land cover and land cover change is underway. Accuracy for many of the loss and gain strata were reported for NLCD 2011 (Wickham et al., 2017). In that assessment, user's accuracies for urban gain, forest loss, and forest gain were 79% ($\pm 2\%$), 82% ($\pm 2\%$), and 74% ($\pm 3\%$), respectively. User's accuracy for the remaining loss and gain classes (water, shrubland, grassland, and agriculture) were between 54% and 65%. Producer's accuracies were much lower. Wickham et al. (2018) found a positive relationship between density of the change classes (e.g., forest loss) in the immediate 3- \times -3 pixel neighborhood for

Table 5

National and regional 2011 land cover classification accuracies for version 1 (V1) and version 2 (V2) of the NLCD 2011 land cover product. Cell entries are user's accuracy (UA) and producer's accuracy (PA) and their associated (standard errors) expressed as percent of area. Agreement is defined as a match between the map label and either the primary or alternate reference label (see Wickham et al., 2017). The column Δ is V2 – V1 with statistically significant changes shown in bold type. Overall accuracy (OA) is reported at the bottom of the UA panel.

UA	National			East			West			
	Class	V1	V2	Δ	V1	V2	Δ	V1	V2	Δ
UA	11	92 (2)	95 (2)	2	89 (3)	94 (3)	5	86 (2)	95 (2)	9
	12	36 (10)	88 (12)	52	–	–	–	36 (10)	88 (12)	52
	21	57 (3)	57 (4)	0	55 (4)	60 (5)	5	61 (4)	52 (6)	–9
	22	69 (3)	75 (3)	6	70 (4)	75 (4)	5	67 (4)	73 (6)	6
	23	79 (3)	76 (4)	–3	76 (4)	75 (4)	–1	84 (3)	77 (7)	–7
	24	83 (3)	84 (3)	1	81 (4)	82 (4)	1	87 (4)	87 (4)	0
	31	60 (4)	59 (6)	–1	43 (7)	29 (9)	–14	62 (4)	63 (7)	1
	41	84 (4)	89 (1)	5	87 (2)	92 (1)	5	68 (4)	70 (5)	2
	42	88 (4)	89 (1)	1	*4 (2)	85 (2)	1	89 (1)	90 (2)	1
	43	59 (3)	57 (3)	–2	64 (2)	60 (3)	–4	33 (6)	31 (6)	–2
	52	88 (1)	86 (1)	–2	28 (3)	43 (5)	15	93 (1)	88 (1)	–5
	71	81 (1)	82 (2)	1	39 (3)	49 (5)	10	85 (2)	84 (2)	–1
	81	72 (2)	75 (2)	3	75 (3)	75 (2)	0	65 (4)	72 (5)	7
	82	88 (1)	93 (1)	5	86 (2)	92 (1)	6	89 (2)	94 (1)	5
	90	70 (3)	69 (3)	–1	74 (3)	74 (3)	0	37 (5)	40 (9)	3
	95	60 (4)	57 (4)	–3	61 (5)	56 (6)	–5	58 (5)	58 (5)	0
OA		82 (0.5)	83 (1)	1	76 (0.8)	79 (0.8)	3	86 (0.7)	85 (0.7)	–1
PA										
Class	V1	V2	Δ	V1	V2	Δ	V1	V2	Δ	
11	84 (3)	86 (3)	2	87 (4)	90 (4)	3	81 (6)	81 (6)	0	
12	100 (0)	100 (0)	0	–	–	–	100 (0)	100 (0)	0	
21	30 (3)	57 (3)	27	54 (1)	52 (4)	–2	71 (5)	67 (6)	–4	
22	56 (4)	59 (4)	3	59 (1)	56 (4)	–3	50 (5)	65 (7)	15	
23	65 (5)	64 (5)	–1	61 (6)	59 (6)	–2	73 (6)	72 (9)	–1	
24	52 (5)	71 (7)	–1	75 (7)	74 (7)	–1	67 (10)	67 (14)	0	
31	81 (6)	64 (7)	–17	60 (14)	42 (12)	–18	83 (8)	67 (8)	–16	
41	81 (1)	78 (2)	–3	82 (1)	79 (2)	–3	70 (5)	73 (5)	3	
42	79 (1)	81 (1)	2	62 (2)	68 (2)	6	89 (2)	89 (2)	0	
43	65 (4)	80 (3)	15	65 (4)	80 (3)	15	63 (8)	79 (10)	16	
52	89 (91)	87 (1)	–2	48 (5)	42 (5)	–6	90 (1)	89 (1)	–1	
71	87 (1)	85 (2)	2	65 (6)	70 (6)	5	88 (2)	86 (2)	–2	
81	68 (2)	73 (2)	5	79 (3)	88 (2)	9	48 (3)	42 (4)	–6	
82	88 (1)	94 (1)	6	86 (2)	93 (1)	7	90 (2)	94 (1)	4	
90	86 (2)	90 (92)	4	87 (3)	92 (2)	5	72 (8)	78 (8)	–2	
95	71 (4)	80 (4)	9	76 (6)	82 (5)	6	63 (7)	76 (7)	13	

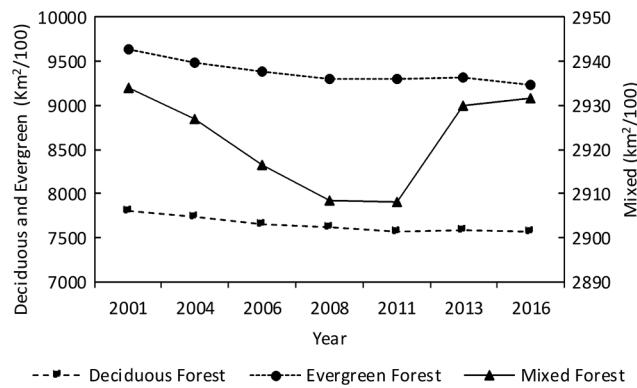


Fig. 4. Total extent in km^2 divided by 100, of three NLCD forest classes (Deciduous, Evergreen and Mixed) across CONUS for 2001–2016. Note the different y-axis numbers for mixed forest.

omission error but not for commission error, suggesting there was a moderate association between the spatial configuration of land cover change and the likelihood of accurately identifying change.

3.3. Land cover change analysis

3.3.1. Forests

Overall, forest theme change was the most frequently changing class consisting of 48.67% of total CONUS change across the 15-year period (Table 3). Forest extent declined across the 15 years, with a total loss of 63,538 km^2 (an area the size of West Virginia) at an average annual rate loss of 4236 km^2 (Fig. 4). The bulk of this change is because of forest harvest and regrowth which is especially prevalent in the southeast, the northwest and northeast parts of CONUS (Fig. 2), with much of the rest coming from stand-replacing forest fires primarily in the West (Cohen et al., 2016).

The spatial extents of the three forest classes are different (Fig. 4). The extent of deciduous forest varies from 780,529 km^2 to 756,813 km^2 between 2001 and 2016. Evergreen and mixed forests had 963,379 km^2 to 923,780 km^2 and 293,390 km^2 to 293,167 km^2 during the same period. During the mapping period, the total extents of deciduous, evergreen forest and mixed forest declined about 23,716 km^2 or

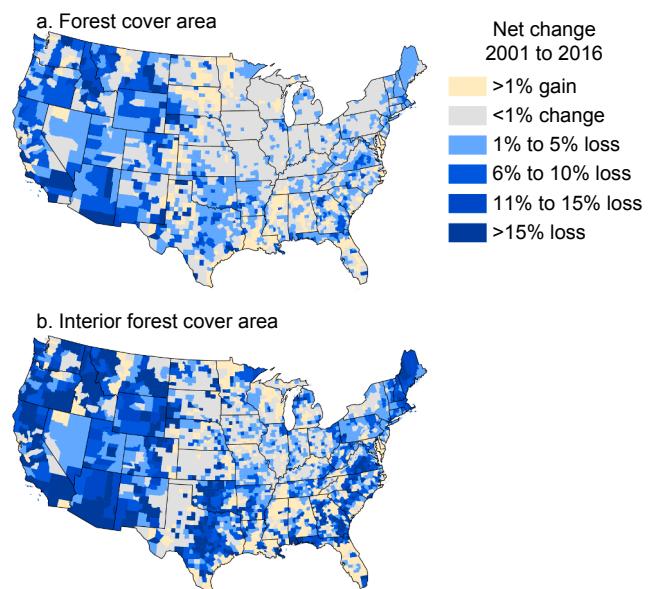


Fig. 6. (a) Net change in total forest in a county from 2001 to 2016, expressed as a percentage of the total forest in 2001. (b) Comparable net change in interior forest (66 ha neighborhood).

Table 6

Status and change of forest cover from 2001 to 2016, by East and West (11 Western states) regions.

	All forest			Interior forest (66 ha neighborhood)			Change ratios ^a	
	2001	Net change		2001	Net change			
	Mha	Mha	%	Mha	Mha	%	ha/ha	%/%
East	164.0	-1.9	-1.1%	59.5	-2.8	-4.6%	1.5	4.1
West	74.8	-4.4	-5.9%	32.3	-5.0	-15.4%	1.1	2.6
CONUS	238.8	-6.3	-2.6%	91.8	-7.7	-8.4%	1.2	3.2

^a Net change of interior forest area divided by net change of all forest.

^b Regions do not sum to CONUS due to rounding.

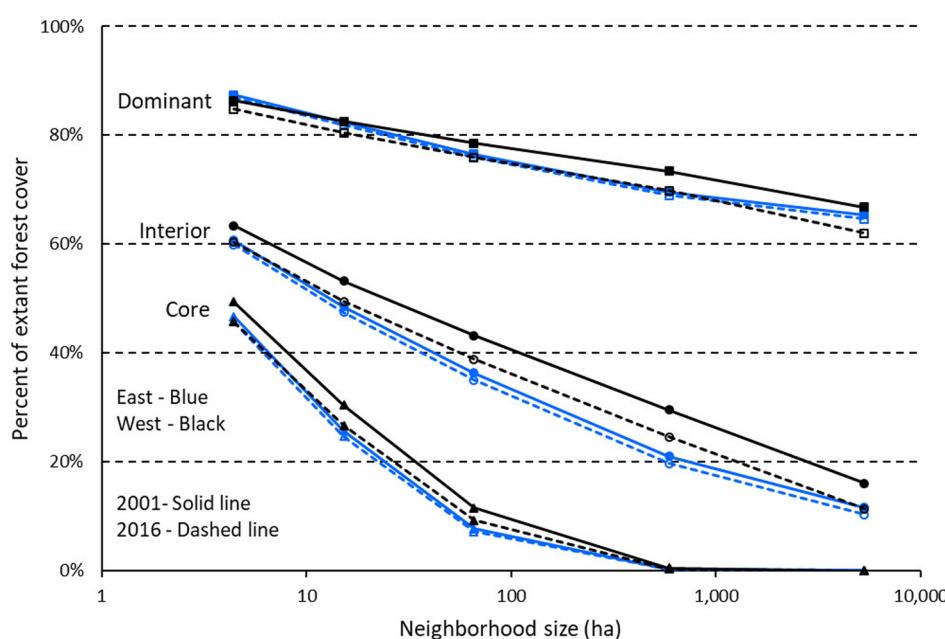


Fig. 5. The status and change of dominant, interior, and core forest cover from 2001 to 2016 in relation to neighborhood size, by region.

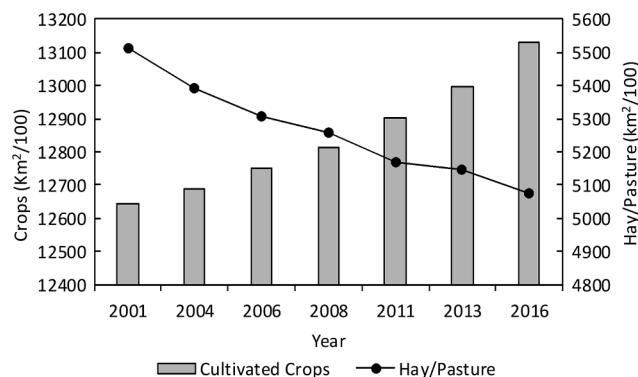


Fig. 7. Pasture/Hay and Cultivated Crop trends across 15 years, in km^2 divided by 100.

-3.04% , $39,599 \text{ km}^2$ or -4.11% , and 223 km^2 or -0.08% , respectively. The total forest extent declined about $63,537 \text{ km}^2$ or -3.12% . These patterns mirror the U.S. wood industry trends which are based primarily on soft-wood (evergreen) species such as Southern pines-led by loblolly pine- and Douglas fir in the Pacific Northwest. Overall, during the study period, about 70% of the U.S. wood production was from softwoods and 30% from hardwoods (deciduous forest), with domestic production peaking in 2005 and declining drastically with the recent deep economic recession (2009 the low point) and rebounding by 2016 but still considerably lower than the 2005 high (Howard and Jones, 2016). The U.S. Forest Service's "South" was the leading production region, followed by the "West" and then the "North" (Howard and Jones, 2016).

When examining forest change from a fragmentation perspective, results indicate a net increase of fragmentation from 2001 until 2016 for three examined fragmentation classes, with fragmentation characteristically increasing by neighborhood size (Fig. 5). The net percent change of interior forest (66 ha neighborhood) was typically larger than the net percent change of all forest area (Fig. 6). In both absolute and relative terms, the losses of total and interior forest were higher in the West (11 Western states) (Table 6), but the East exhibited larger change ratios indicating that the patterns of forest change (gains and losses) were more fragmented there (Wickham et al., 2007).

3.3.2. Agriculture

The total 2016 CONUS extent of pasture/hay was $507,568 \text{ km}^2$ and cultivated crops was $1,313,114 \text{ km}^2$ for a total cropland extent of $1,820,682 \text{ km}^2$ (Table 2). In 2001 the total cropland extent was $1,815,904 \text{ km}^2$ representing a modest 4778 km^2 expansion over 15 years. More notable during this time was the loss of $43,477 \text{ km}^2$ of pasture/hay (7.94%), while cultivated crop gained $48,555 \text{ km}^2$ largely at the expense of pasture/hay (Fig. 1). However, during the 15-year period, both pasture/hay and cultivated crops exhibited consistent change trends during each mapping epoch (Fig. 7). Likely reasons for pasture/hay loss include both normal crop cycling and more permanent conversion. However, more permanent extent change is located in parts of the northern and eastern Great Plains where overall land used for hay has decreased when compared to the 1980s and 1990s (Auch et al., 2018) and the eastern U.S where "pasture" land, often consists of tame grass species that can easily be converted to cropland. This conversion was the second leading source of new cropland in a humid-to-semi-arid transition state such as South Dakota in the second half of the 2001–2016 era (Wimberly et al., 2017) (Fig. 8).

3.3.3. Water and wetlands

Water extent varies across time depending on different weather, climate, and land use conditions. Likewise, wetlands also have similar extent fluctuations from these change drivers. According to our results, the total surface water extent in CONUS was $424,962 \text{ km}^2$ in 2001 and $423,670 \text{ km}^2$ in 2016 (Table 2), producing a change rate of -0.30% between 2001 and 2016. Both woody and herbaceous wetlands also had different spatial extents and change rates. The spatial extents of woody wetland were $351,624 \text{ km}^2$ and $352,719 \text{ km}^2$ in 2001 and 2016 respectively (Table 2), or a 0.31% increase. Herbaceous wetland had extents of $119,391 \text{ km}^2$ and $118,714 \text{ km}^2$ in 2001 and 2016, respectively (Table 2), or -0.57% change. The total wetland extent, therefore, increased about 417 km^2 or 0.09% .

Fig. 10 illustrates proportions of wetland extent to the drainage basin area in 2001 (A), 2016 (B), and the change rate between 2001 and 2016 (C). Similar to the spatial distributions of water ratio to the drainage basin extent, the wetland extent distribution pattern is smaller in the west and larger in the east. For example, the ratios in the Lower Colorado Region were 0.43 and 0.44 in 2001 and 2016 respectively. The ratios in the South Atlantic-Gulf Region were respectively 20.82 and 20.72 during these same two periods. The spatial distribution of

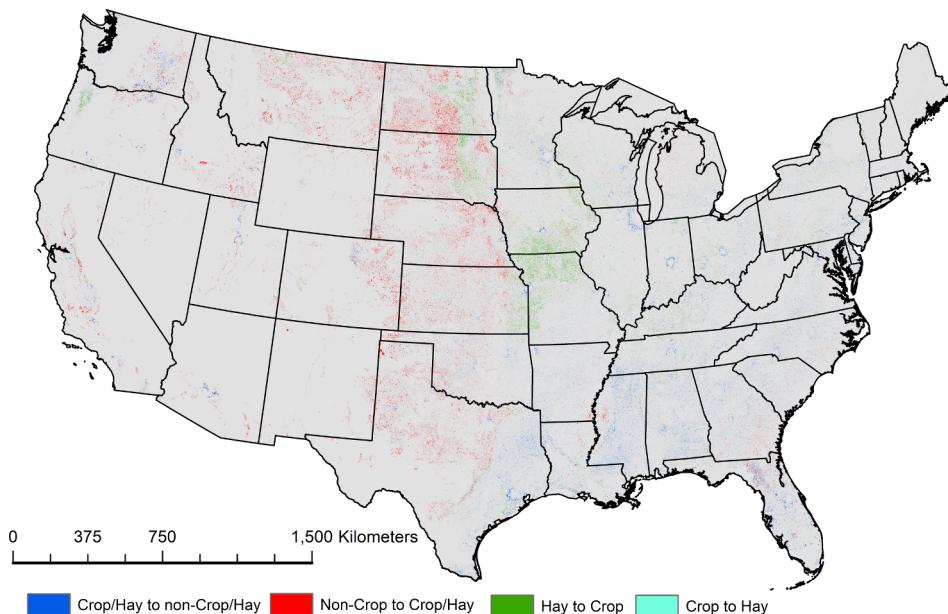


Fig. 8. Cropland extent change between agricultural classes of pasture/hay and cultivated crop from 2001 to 2016.

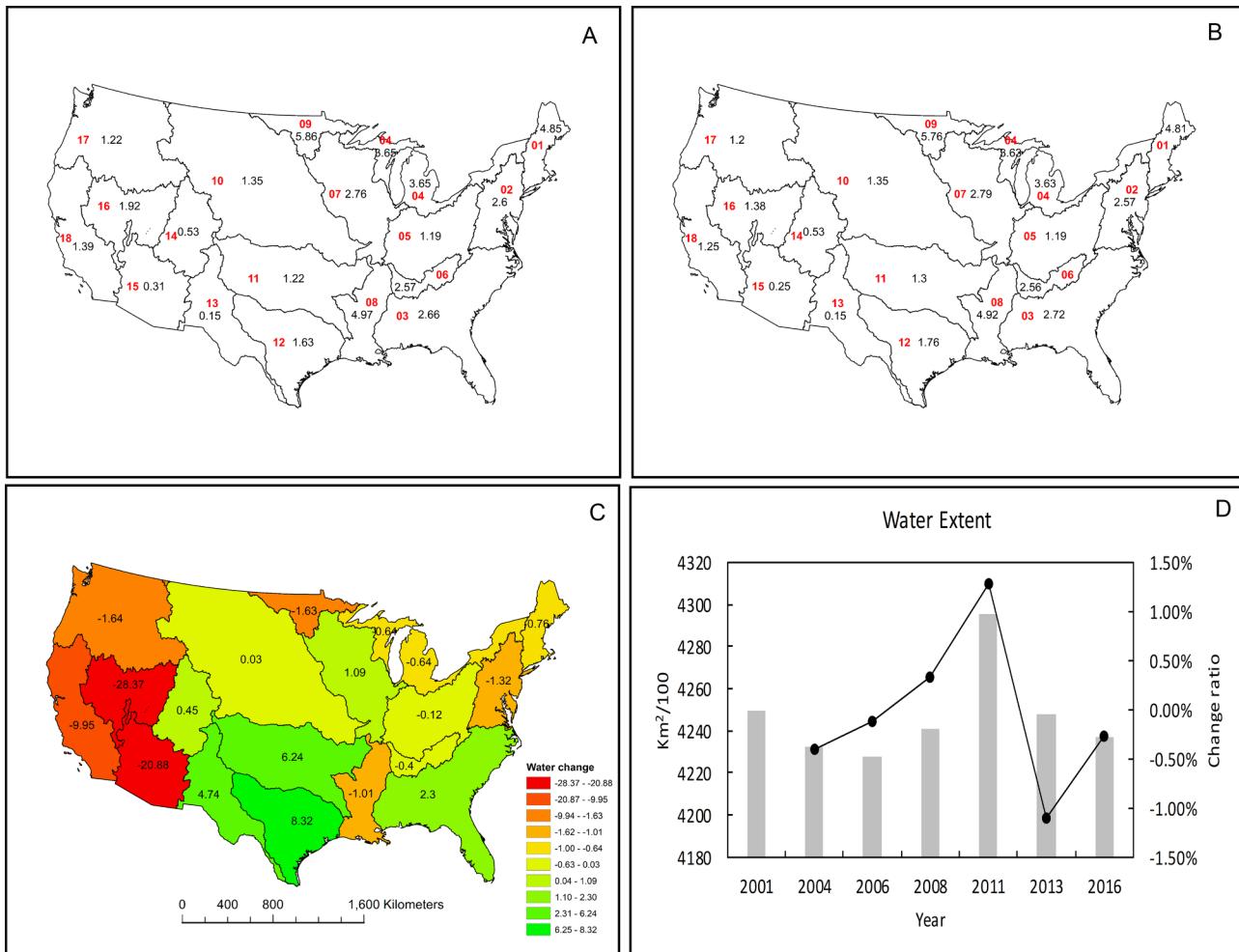


Fig. 9. shows proportions of water extent to the drainage basin area in 2001 (A), 2016 (B), and changes between 2001 and 2016 (C). Generally, most of the western basins had relatively lower water to drainage basin ratios than those in the east. For example, in the lower Colorado region, the water to drainage basin ratios were 0.31 and 0.25 in 2001 and 2016 respectively. However, in the South Atlantic-Gulf Region, the ratios were respectively 2.66 and 2.72 in the same two periods. The change of ratio between 2001 and 2016 shows a substantial decline in these western regions due to drought and an increasing trend in most of the southern regions. **Fig. 9(D)** represents the total water extent change and the change rate between any two mapping periods in CONUS. Specifically, the water extent was the largest in 2011 and the smallest in 2006.

wetland change by drainage basin ratio between 2001 and 2016 was opposite from the water change pattern, and revealed substantial increases in the western basins and decreases in most southern and eastern basins. For example, the decrease of the wetland extent in the South Atlantic-Gulf Region (**Fig. 10C**) was associated with the increase in the water extent in the same region (**Fig. 9C**). The variations of the total wetland extent across CONUS (**Fig. 10 D**) also shows a connection between wetland and water extents. For example, in 2011, the water extent had the highest level in the nation or 1.00% increase from the previous period. The wetland extent in the same year exhibited the lowest spatial coverage with a substantial decline (−0.80%) from the previous period.

Water and wetland variations can be influenced by many factors such as weather and climate conditions, land use intensity, and other external disturbances. For additional analysis we focused on the correlation between annual precipitation and water or wetland extent in every drainage basin. Precipitation data were obtained from Daymet (<https://daymet.ornl.gov/>), and total amounts of annual precipitation were calculated in these basins in each mapping epoch. A simple correlation between precipitation and water or wetland extent was calculated for the period of 2001 to 2016. **Fig. 11** shows correlations of precipitation-water (**Fig. 11A**) and precipitation-wetland (**Fig. 11B**). Most of basins had positive correlations between precipitation and

water extent. The correlations in both Ohio and Texas-Gulf Regions were at $p < 0.10$ and $p < 0.05$ significance levels, respectively. However, in the Souris Red Rainy, Upper Colorado, Lower Colorado, Lower Mississippi, and Great Basin Regions, correlations were negative. For these basins, water levels are heavily influenced by upstream water input and without many lakes to hold precipitated water, extents might not directly correlate to the amount of rainfall in the basins as directly as the correlations between precipitation and Water or Wetland extents in the Ohio and Texas-Gulf Regions.

The wetland variations show negative correlations with annual precipitation for most regions. The correlation of annual precipitation in the New England Region was at the $p < 0.05$ significance level. Annual precipitation correlations in the Ohio, Texas-Gulf, Tennessee, and Great Lakes Regions were at the $p < 0.10$ significance levels. Similar to the correlation between water extent and precipitation, annual precipitation and wetland correlations in the Souris Red Rainy, Lower Colorado, Lower Mississippi, and Great Basin regions were negative but not significant. The negative correlation between wetland extent and annual precipitation suggests that precipitation can reduce wetland extent due to the increase in water extent along riparian areas. The regions where wetland extent had positive correlations with annual precipitation were the same regions where water extent was negatively correlated with precipitation. One exception was in the Upper Colorado

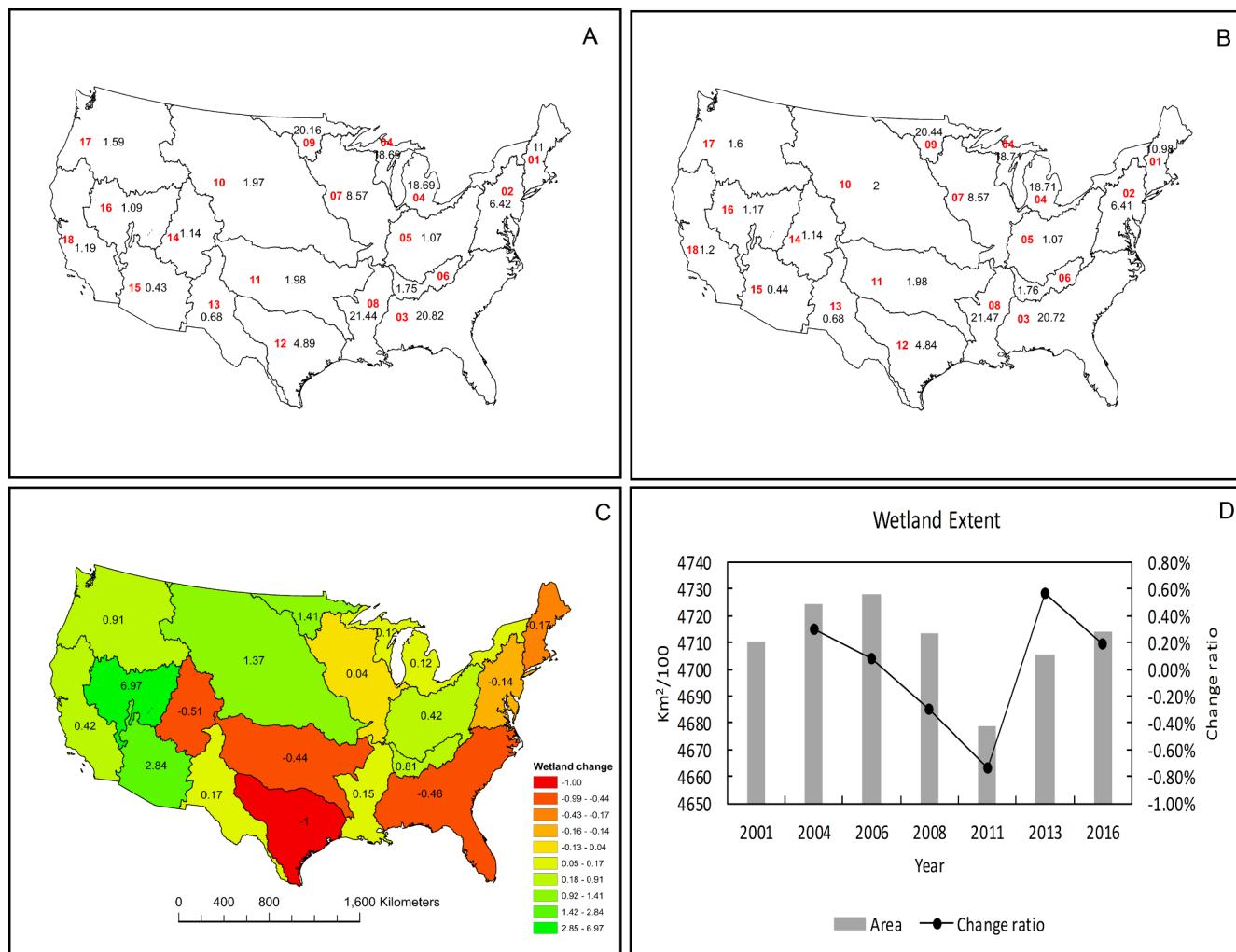


Fig. 10. Proportions of wetland extent to the total extent of each drainage basin by percentage in 2001 (A), 2016 (B), wetland extent change between 2001 and 2016 by percentage in each drainage basin (C), and total wetland extent in km² divided by 100 for CONUS between 2001 and 2016 with changes between each mapping period (D). Red numbers in A and B represent different drainage basins and are defined in the Fig. 9 caption. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Region where both wetland and water extents were negatively correlated with precipitation. Terrain, water use patterns and precipitation inputs from outside the region likely provided the major drivers of land cover change rather than precipitation inputs within the region.

Fig. 9 Proportions of water extent to the total extent of each drainage basin by percentage in 2001 (A, in black numbers), 2016 (B, in black numbers), water extent change between 2001 and 2016 by percentage in each drainage basin (C), and total water extent in km² divided by 100 for CONUS between 2001 and 2016 with changes between each mapping period (D). Red numbers in A and B represent different drainage basins: 01: New England Region; 02: Mid-Atlantic Region; 03: South Atlantic-Gulf Region; 04: Great Lakes Region; 05: Ohio Region; 06: Tennessee Region; 07: Upper Mississippi Region; 08: Lower Mississippi Region; 09: Souris-Red-Rainy Region; 10: Missouri Region; 11: Arkansas-White-Red Region; 12: Texas-Gulf Region; 13: Rio Grande Region; 14: Upper Colorado Region; 15: Lower Colorado Region; 16: Great Basin Region; 17: Pacific Northwest Region; 18: California Region.

3.3.4. Shrub, grass and bare ground

Total shrub extent in CONUS was 1,760,134 km² in 2016 and the change rate varies between 0.52% to −0.82% during the mapping period (Fig. 12). Between 2001 and 2016, the total shrub extent increased 4512 km² or 0.26%. This increase was largely at the expense of

forest loss and grassland change to shrubland (Fig. 1). The total extent of herbaceous was 1,118,412 km² in 2016, with the change rate varying from 2.33% to −1.32% during the mapping periods (Fig. 12). The herbaceous extent increased 25,421 km² or 2.33% from 2001 to 2016, mostly from forest and shrub class losses (Fig. 1). Most shrub and grass fluctuations are heavily influenced by forest cutting, and regeneration, especially away from the semiarid areas of the West where most ecological climax shrub communities occur. Barren ground had about 82,897 km² in spatial extent in 2016. Between 2001 and 2016, barren ground increased 1077 km² or a 1.32% increase, mostly from water loss (Fig. 1). Most of this change is simply fluctuating shorelines in CONUS lakes, reservoirs and rivers.

3.3.5. Developed land

With few exceptions, the U.S. developed footprint continues to expand (Figs. 1 and 2). NLCD developed change was examined at both national and state levels. Nationally, developed areas added about 13,612 km², 8928 km², and 6086 km² in 2001–2006, 2006–2011, and 2011–2016 periods respectively. The rate of change for developed land was respectively 3.40%, 2.16%, and 1.44% in these same three periods. By 2016, the total developed area reached 428,575 km², (an area about the size of California) which is a net increase of 28,626 km² or 6.7% from 2001 (an area slightly larger than Massachusetts) (Table 7). Developed had high rates (up to nearly 10%) of epoch-to-epoch change

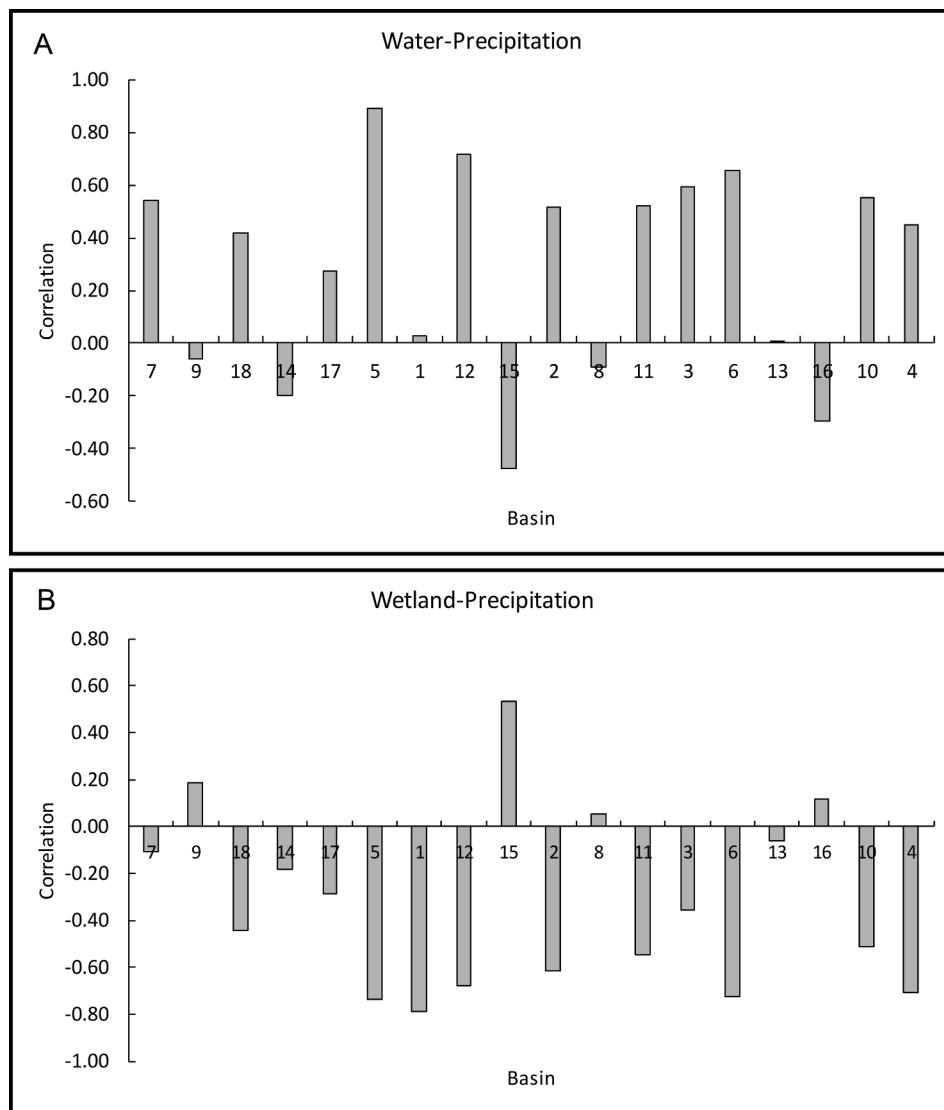


Fig. 11. Correlations between annual precipitation and water extent (A), annual precipitation and wetland extent (B) for every CONUS drainage basin labeled by number names in x-axis. The number names of drainage basins are defined in the Fig. 9 caption.

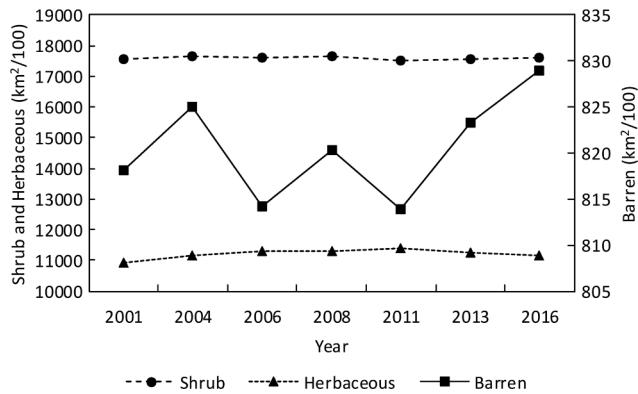


Fig. 12. Extent and change trends of shrub, herbaceous, and barren classes across CONUS, 2001–2016 in km² divided by 100.

and a much greater increase in developed classes with greater impervious cover, but the overall trend is a declining rate of urbanization, suggesting that such factors as the 2008 global recession may have dampened urban growth. At the state level, change rates varied in different states in different periods. Fig. 13 shows proportions of

developed land to the total area of each state in 2001 (A), 2006 (B), 2011 (C), and 2016 (D). Generally, coastal states have relatively larger proportions of developed lands than non-coastal states. As developed expansion continued, such proportions went up continuously from 2001 to 2016. For example, the developed proportion in New Jersey increased from 24.48% in 2001 to 26.18% in 2016 and the total developed land increased by about 6.96%. Fig. 13C shows the rate of developed land increase from 2001 to 2016 in every state, with southern states exhibiting developed expansion greater than most of the northern states. The urban increase rates in five southern states (South Carolina, Georgia, Texas, New Mexico, and Arizona) reached double digit percentages. Fig. 13D shows the total developed areas in the four periods and change rates between these times. It exhibits the slowing developed rate increase from 3.40% in the 2001–2006 period to 1.44% in the 2011–2016 period.

4. Conclusions

The release of the NLCD 2016 database demonstrates the continued maturation of national land change monitoring from archived satellite data. It also provides new information on land change patterns across the CONUS landscape from 2001 to 2016, revealing that land cover

Table 7NLCD Developed class results across four land cover epochs from 2001 to 2016, in km².

Developed class	2001	Change 2001–2006	2006	Change 2006–2011	2011	Change 2011–2016	2016	% of 2016 Area	15-year Increase (%)
Developed – Open Space	225,434	3873	229,307	2126	231,433	843	232,276	54	6842 (2.9%)
Developed – Low Intensity	112,228	3193	115,421	2264	117,685	2071	119,756	28	7528 (6.3%)
Developed – Medium Intensity	45,991	4803	50,794	3158	53,952	2331	56,283	13	10,292 (18.3%)
Developed – High Intensity	16,296	1743	18,039	1380	19,419	841	20,260	5	3964 (19.5%)
Total	399,949	13,612	413,561	8928	422,489	6086	428,575	100	28,626 (6.7%)

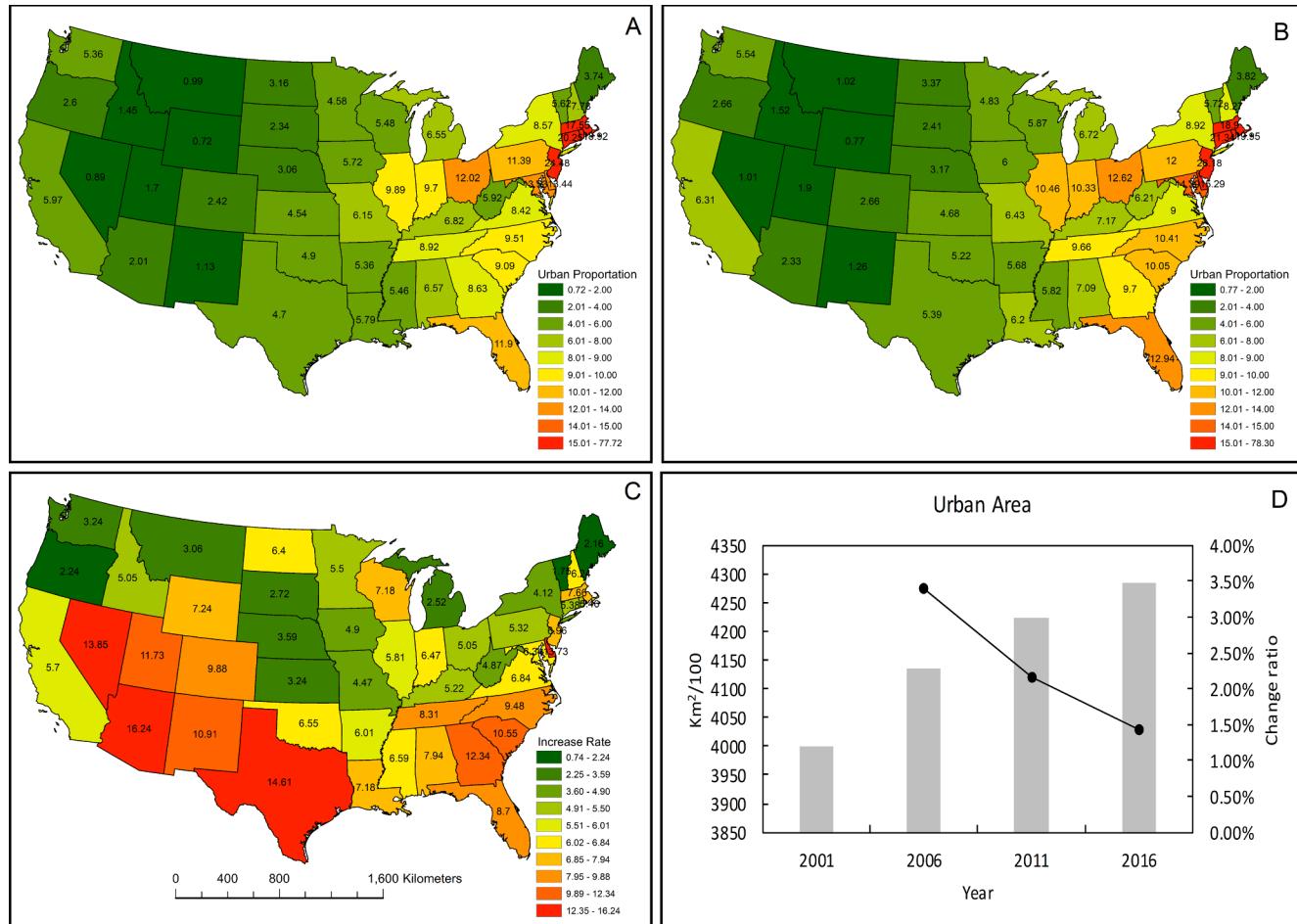


Fig. 13. Proportions of developed land for the total area of each state in 2001 (A), 2016 (B), the developed increase rates for each state between 2001 and 2016 (C), and the total developed land area divided by 100 for CONUS between 2001 and 2016 with increase rates between 2001–2006, 2006–2011, and 2011–2016 (D).

change remains substantial and dynamic across almost all land cover classes and time periods. The U.S. landscape is encountering significant change, with almost 8% of the landscape having experienced a land cover change at least once during this time period. Nearly 50% of that change involves forest, driven by change agents of harvest, fire, disease and pests resulting in an overall forest decline. This decline is especially underscored by the increasing fragmentation and loss of interior forest.

The U.S. developed landscape shows the most persistent and permanent land change increase. CONUS added almost 29,000 km² in new developed lands over 15 years. Although persistently increasing, developed land change across the 15 years is not uniform in either space or time. Spatially, southern states exhibit developed land expansion faster than most of the northern states. Temporally, the rate of increase steadily declined across the 15 years, with the first interval of 2001–2006 having almost twice the developed change as 2011–2016—likely a reflection of changing economic activity across

this time. Class-specific change exhibits several interesting patterns also, among them the developed high intensity class had the largest within-class percentage increase at 15.5%, suggesting the U.S. urban footprint is also densifying as well as expanding. Developed open space is by far the largest developed class in 2016 (54%) and is still increasing. The demand for low intensity development in open spaces impacts fire risk (Radeloff et al., 2005), wildlife habitat, (Bar-Massada et al., 2014), providing adequate municipal infrastructure (Cova et al., 2013) and further fragmenting the natural landscape (Terando et al., 2014, Seto et al., 2012).

Water and wetlands are highly dynamic land cover classes from period to period, heavily influenced by precipitation. Our analysis by major U.S. watershed boundaries further supports this conclusion, finding significant precipitation correlation to change in water and wetland extent over time. Spatially, water change is highest in the more arid western U.S. where the natural episodic influences of precipitation

and temperature are amplified. However, the change in wetland extent was greatest in the southeast U.S., driven by precipitation and the historical pattern of human caused land cover change influencing natural processes (Hefner and Brown 1984).

The change in cropland footprint (including both classes of pasture/hay and cultivated crop) was nearly static across the 15 years with only a slight increase of 4778 km². However, there was a substantial decline (7.94%) in pasture/hay during this time, going mostly to cultivated crop. Driving this pasture/hay change was not only the normal crop cycling of agriculture in general, but the more notable permanent conversion of pasture and hay areas in the midwestern and eastern U.S. in part driven by changing climate and economic conditions (Auch et al., 2018).

NLCD will continue to monitor the changing U.S. land cover landscape into the future. NLCD is developing new innovations and partnerships to increase monitoring frequency, reduce the turnaround time between satellite imaging and product delivery and expand the variety of products available in an integrated database to allow a more comprehensive understanding of the dynamics of U.S. land cover change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.isprsjprs.2020.02.019>.

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