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The Multi-Resolution Land Characteristics (MRLC) Consortium — 20 Years of Development and Integration of USA National Land Cover Data

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Abstract: The Multi-Resolution Land Characteristics (MRLC) Consortium demonstrates the national benefits of USA Federal collaboration. Starting in the mid-1990s as a small group with the straightforward goal of compiling a comprehensive national Landsat dataset that could be used to meet agencies' needs, MRLC has grown into a group of 10 USA Federal Agencies that coordinate the production of five different products, including the National Land Cover Database (NLCD), the Coastal Change Analysis Program (C-CAP), the Cropland Data Layer (CDL), the Gap Analysis Program (GAP), and the Landscape Fire and Resource Management Planning Tools (LANDFIRE). As a set, the products include almost every aspect of land cover from impervious surface to detailed crop and vegetation types to fire fuel classes. Some products can be used for land cover change assessments

because they cover multiple time periods. The MRLC Consortium has become a collaborative forum, where members share research, methodological approaches, and data to produce products using established protocols, and we believe it is a model for the production of integrated land cover products at national to continental scales. We provide a brief overview of each of the main products produced by MRLC and examples of how each product has been used. We follow that with a discussion of the impact of the MRLC program and a brief overview of future plans.

Keywords: C-CAP; change detection; Cropland Data Layer (CDL); GAP; LANDFIRE; NLCD

1. Introduction

The Multi-Resolution Land Characteristics (MRLC) Consortium is a bottom-up e-government initiative to provide digital land cover and ancillary data for the nation. In part, the consortium organized in response to the 1984 Land Remote Sensing Commercialization Act (<http://landsat.gsfc.nasa.gov/about/landsat5.html>). Commercialization of Landsat led to rapid cost increases and restrictions on the distribution of the data [1]. By the late 1980s, the cost of a single Landsat scene had increased ~400% to \$4000.00 (USD), which was beyond the means of many in the academic and federal research community. At \$4000.00 per scene, the cost to acquire just one scene for each of the ~430 path/rows that cover the continental United State was \$1.72 million (USD). MRLC formed in the mid-1990s to overcome the cost increases by pooling agency resources to purchase a national dataset of Landsat imagery that could be used by each agency to meet programmatic and research needs. The founding members of MRLC were the USA Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), and the USA Environmental Protection Agency (EPA).

By the late 1990s, the MRLC Consortium had compiled a national dataset of Landsat imagery that was processed to standards agreed upon by its members. Redistribution rules were negotiated successfully with the Landsat commercial vendor that allowed member agencies to share the data at no additional cost. Following the acquisition of a national Landsat dataset, the USGS and EPA entered into a bilateral agreement to develop a national land cover dataset [2]. The outcome of this effort was the 1992 National Land Cover Dataset (NLCD 1992) [3]. Based on the number of citations, completion of NLCD 1992 filled a long-standing need for land cover data across the conterminous USA—the publication [3] has been cited 566 times according to our latest SciVerse Scopus search.

In the early 2000s, the MRLC Consortium built upon its success with NLCD 1992 [3] by strengthening integration and cooperation among its members and making large investments in a USGS led science team to advance key technological aspects of land cover production, including data preprocessing [4,5], classification approaches [6,7], and advancing an integrated database paradigm [8]. NLCD 2001 was re-envisioned as a database that included the continuous field products percentage urban impervious cover and forest canopy density in addition to categorical land cover [9]. Growing demand for land cover information coupled with these new technological developments created an opportunity for agencies to participate in the consortium and enjoy the benefits of NLCD advancements for their own specific product needs. For example, NOAA's initial motivation for participation in MRLC was

to support their initiative to produce digital land cover change data for coastal regions of the USA, the Coastal Change Analysis Program (C-CAP) [10]. The new NLCD database paradigm provided a synergistic and cost efficient approach to further the development of coastal land cover and precipitated a direct agreement between USGS and NOAA to cooperate on the development of land cover. As a result of this agreement, NOAA took on production of NLCD in the coastal regions as part of the production of C-CAP data. The agreement allowed NOAA to integrate USGS methods into the production of C-CAP and reduced USGS costs for production of NLCD by 25%. The Gap Analysis Program (GAP) and the Landscape Fire and Resource Management Planning Tools (LANDFIRE) project also instituted a collaborative approach by underwriting some of the costs of NLCD production and use of NLCD in development of GAP and LANDFIRE products. In addition, LANDFIRE partnered with NLCD to help build the MRLC Landsat image archive and use NLCD land cover to more efficiently map some LANDFIRE data layers. The outcome of this integration was that MRLC became an organizing framework for the development of several national products that cost-effectively used the same Landsat database and classification technology.

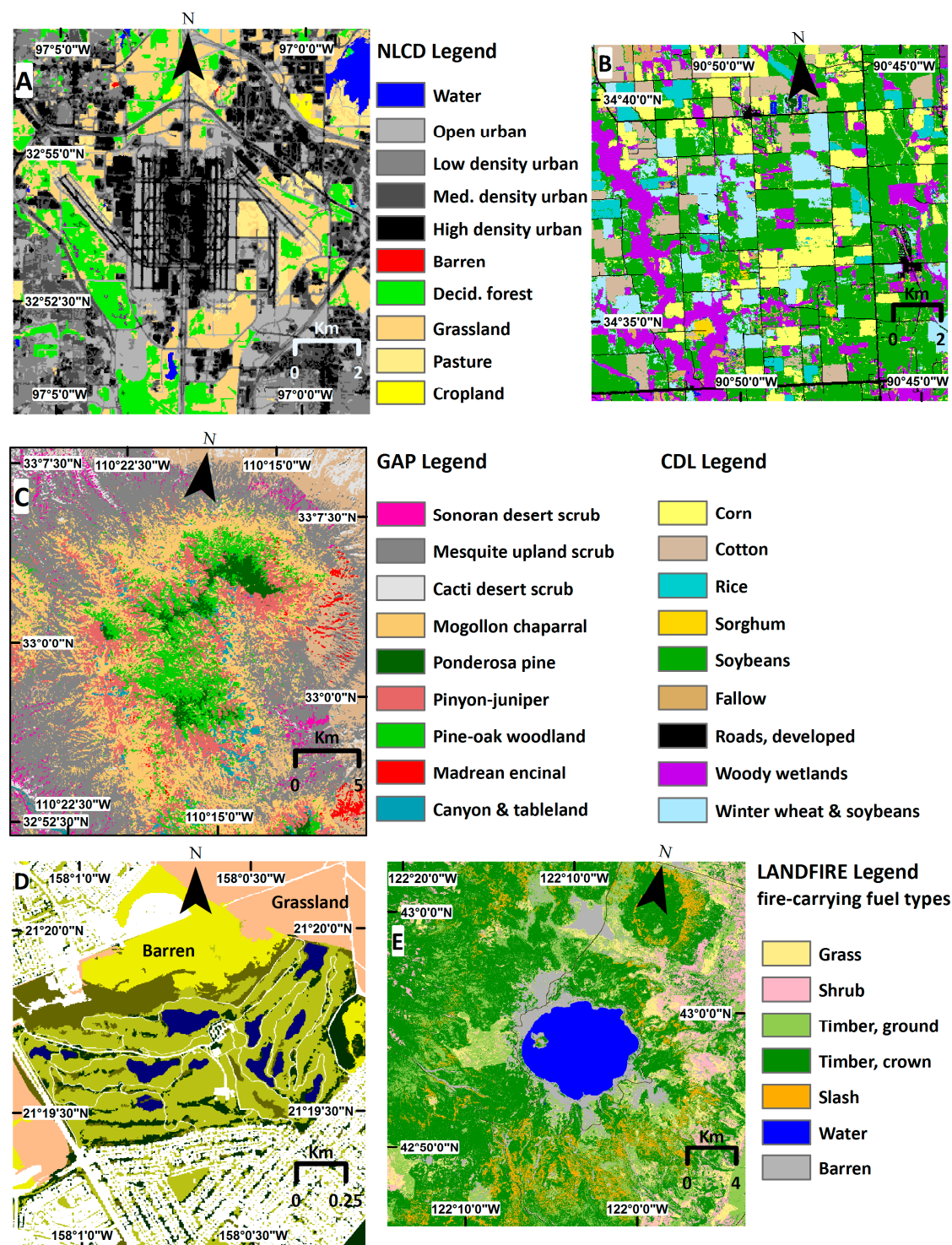
Participation in the MRLC consortium has now grown to 10 federal agencies and five products that cover most aspects of land cover (Table 1). The products are produced collaboratively through participation in MRLC. The five products include NLCD, C-CAP, GAP, LANDFIRE, and the Cropland Data Layer (CDL) (Figure 1, [11]). MRLC Consortium products include land cover, land cover change, impervious cover, impervious cover change, detailed cropland cover, detailed vegetation land cover, forest canopy density, and numerous data layers related to fire. Most products are based on Landsat and thus have spatial resolutions of 30 m; however, C-CAP produces high resolution (e.g., 1 m–5 m) products for some locations. The MRLC Landsat imagery archive has grown to more than 30,000 scenes, and most if not all Landsat-based, national-scale land cover data have been developed through participation in MRLC.

Although the high cost of Landsat data, a reality that contributed to the formation of MRLC, is no longer relevant, pooling of resources to produce land cover products that meet all agencies' needs is still a cost-efficient production model. Within the MRLC cost-efficient production model, each member contributes financial resources and time and material to help ensure the development and completion of MRLC products. For example, EPA contributes ~20% of the funding required to produce NLCD. Through their participation in NLCD, EPA has nationwide land cover data to support mission-related activities in air and water quality protection at one-quarter of the cost that would be required if EPA were to undertake land cover data production independently. The collaborative growth of MRLC further benefits EPA. Detailed cropland information from CDL can be used to map more precisely the relationships between pesticides and water quality and information from LANDFIRE can be used to inform air quality models. Similar benefits extend to all agencies that participate in MRLC.

Table 1. Multi-Resolution Land Characteristics (MRLC) Consortium members (A) and products (B). Under products (B), temporal extent refers to the nominal date of satellite acquisition, not the release date.

(A) Members
USA Department of Interior (DOI), Geological Survey (USGS)
Department of Commerce (DOC), National Oceanic & Atmospheric Administration (NOAA)
USA Environmental Protection Agency (EPA)
USA Department of Agriculture (USDA), Forest Service (USFS)
DOI, Bureau of Land Management (BLM)
DOI, National Park Service (NPS)
DOI, Fish and Wildlife Service (USFWS)
USDA, National Agricultural Statistics Service (NASS)
National Aeronautics and Space Administration (NASA)
Department of Defense (DOD), USA Army Corps. of Engineers (USCOE)
(B) Products
National Land Cover Database (NLCD)
<i>Description:</i> 16-class land cover (LC) (20 classes in Alaska (AK)); impervious cover (IC) in 1% increments; forest canopy density (FC) in 1% increments.
<i>Temporal extent:</i> LC for 1992, 2001, 2006, 2011; IC for 2001, 2006, 2011; FC for 2001 & 2011.
<i>Spatial extent:</i> continental USA; LC and IC for AK in 2001 & 2011.
<i>Details:</i> NLCD eras 2001, 2006, and 2011 can be used to monitor LC and IC change and trends; NLCD 2011 includes updated versions of NLCD 2001 and 2006; there is a specialized 8-class (“retrofit”) LC dataset for comparing NLCD 1992 and NLCD 2001.
Coastal Change Analysis Program (C-CAP)
<i>Description:</i> 23-class LC focused on coastal wetlands; high resolution (e.g., 1 m) LC for selected locations.
<i>Temporal extent:</i> 1985, 1992, 1996, 2001, 2006, 2011 (varies by location).
<i>Spatial extent:</i> coastal USA (including Great Lakes) and US islands (e.g., Hawaii, Puerto Rico, Guam)
<i>Details:</i> LC change and trends for up to 6 eras; C-CAP LC data are used to derived NLCD in coastal locations.
Cropland Data Layer (CDL)
<i>Description:</i> LC map of major (corn, wheat, sorghum, rice, cotton, soybeans) and other crop types.
<i>Temporal extent:</i> 1997–2013.
<i>Spatial extent:</i> continental USA (2008–2013); selected areas within continental USA (1997–2007).
<i>Details:</i> extensive ground truth data (USDA, NASS June Agricultural Survey; USDA Farm Service Agency Common Land Unit) support high thematic accuracies for major crop types; NLCD used to map non-agricultural areas.
LANDFIRE
<i>Description:</i> multiple datasets related to fire behavior, fire regime, and vegetation characteristics.
<i>Temporal extent:</i> 2001, 2008, 2010, 2012 (early 2015).
<i>Spatial extent:</i> USA.
<i>Details:</i> Use of field and remotely sensed data to model vegetation condition and fuel characteristics for conducting wildland fire assessments. The 2008, 2010, and 2012 datasets include updated disturbance information.
GAP
<i>Description:</i> detailed vegetation classification (577 classes at the most detailed level).
<i>Temporal extent:</i> 2001.
<i>Spatial extent:</i> USA.
<i>Details:</i> 2001 release was compiled from regional projects covering the southeast, southwest; northwest and California with LANDFIRE data used to complete the rest of the country; version 2 is in progress in collaboration with LANDFIRE; NLCD is used to map areas that are not “natural” or semi-natural vegetation.

Figure 1. National Land Cover Database (NLCD) in the vicinity of the Dallas-Ft. Worth airport (A); Cropland Data Layer (CDL) in eastern Arkansas (B); Gap Analysis Program (GAP) in southeast Arizona (C); high resolution Coastal Change Analysis Program (C-CAP) in the vicinity of Ewa Beach, Hawaii (D); and Landscape Fire and Resource Management Planning Tools (LANDFIRE) data in the vicinity of Crater Lake, Oregon (E). Many of the GAP and LANDFIRE classes have been simplified for purposes of presentation (e.g., Sonoran desert scrub = Sonoran Paloverde-Mixed Cacti desert scrub). The LANDFIRE classes are a simplification of the 13 Anderson fire behavior fuels models [11].



2. MRLC Products

- *Processed Landsat Imagery.* Following the release of NLCD 1992, a second generation MRLC initiative was launched with two primary goals: (1) to develop a consistent Landsat imagery dataset for the USA; and (2) to develop a second generation National Land Cover Database (NLCD 2001). In order to develop a Landsat imagery dataset capable of national application, key pre-processing enhancements in Tasseled Cap (TC) coefficients, correction to at-sensor, top-of the atmosphere (TOA) reflectance, geo-registration, and other issues needed to be implemented in an image processing protocol for Landsat 5 and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images [5]. These value added image products were made available initially to the MRLC Consortium, and have subsequently been made available free-of-charge to the public. The MRLC imagery database is substantially different than the Landsat archive that was made freely available to the public by USGS in 2008 [12] and the recently released Web-enabled Landsat Data (WELD) archive [13]. The images in the freely available Landsat archive do not possess the level of processing applied to the images in the MRLC imagery database (e.g., TC, TOA, geo-registration), and, unlike the MRLC imagery archive, they are not re-projected into an equal-area projection that is necessary for nationwide land cover mapping. The level of image processing applied to the WELD archive is similar to that applied to the MRLC archive, but the WELD archive includes only Landsat 7 ETM+ images for the years 2006 to 2010 (<http://globalmonitoring.sdstate.edu/projects/weld>). The MRLC image archive extends back in time to 2001 (*i.e.*, NLCD 2001), and the MRLC archive does not include Landsat 7 ETM+ images that suffer from the scan line corrector error that arose in 31 May 2003. The MRLC image archive contains only Landsat 5 TM and Landsat 7 ETM+ images that were acquired before 31 May 2003.
- *The National Land Cover Database (NLCD).* Led by USGS, NLCD has been produced for four eras at a 30 m spatial resolution: NLCD 1992 [3], NLCD 2001 [9], NLCD 2006 [14,15], and the recently released NLCD 2011 [16]. NLCD 2011 is a land-cover monitoring database that includes updated versions of NLCD 2001 and NLCD 2006. NLCD 1992 is not included in the release of NLCD 2011 because mapping methods changed significantly between the production of NLCD 1992 and the first (initial) release of NLCD 2001. The NLCD 2011 database includes land cover, percentage urban impervious surface, and forest canopy density. The percentage urban impervious surface and forest canopy density layers are resolved in 1% increments from 0 to 100 for areas identified as urban and forest, respectively, in the land cover layer of the database. With the release of NLCD 2011, users can monitor trends in land cover and impervious surface across the three eras (2001, 2006, and 2011). Forest canopy density is available for 2001 and 2011, but comparison of the two datasets to identify change is not recommended because of production methods changes between the two dates. Production of NLCD is also supported by formal accuracy assessments [17–23], and accuracy assessment of the NLCD 2011 product is currently underway.

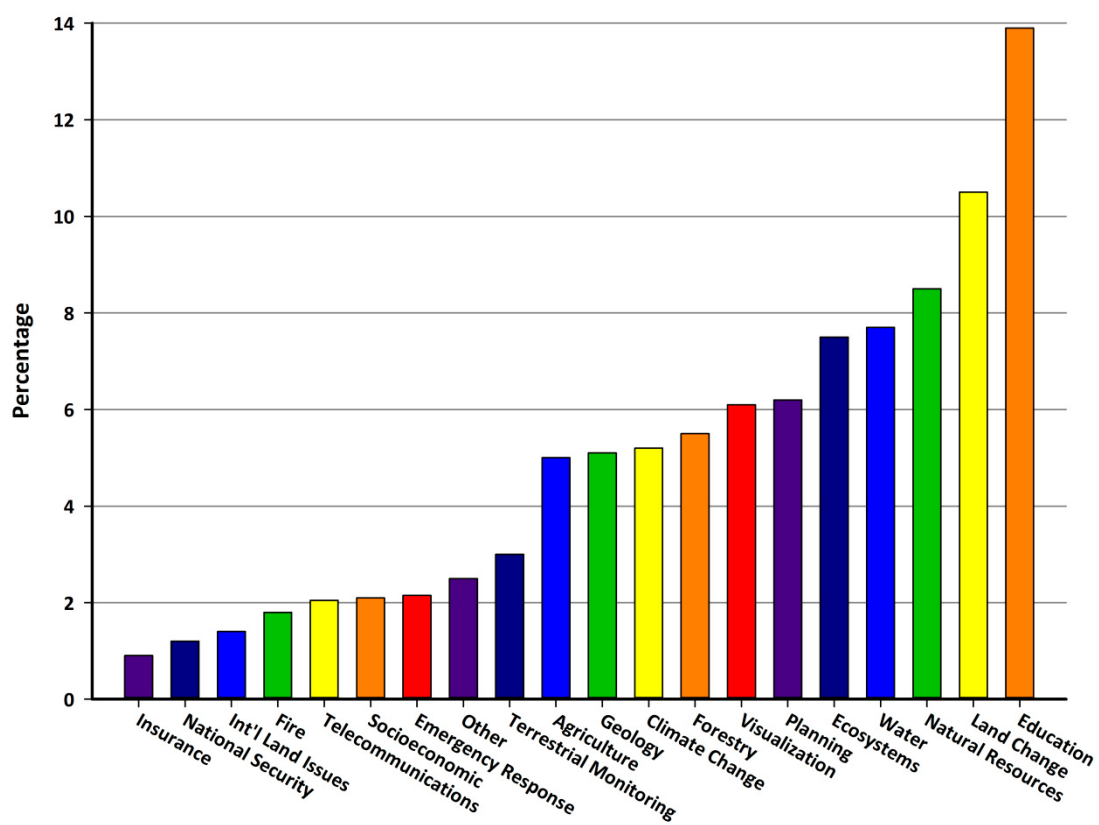
- *Coastal Change Analysis Program (C-CAP)* (<http://www.csc.noaa.gov/digitalcoast/data/ccapregional>). NOAA's Coastal Change Analysis Program (C-CAP) provides a temporal inventory of intertidal areas, wetlands and adjacent uplands for MRLC coastal zones at a 30 m spatial resolution. C-CAP has a detailed legend of wetland classes including palustrine and estuarine expressions of forest, scrub and emergent wetlands, palustrine and estuarine expressions of aquatic bed, and unconsolidated shore. Land cover products are available in most coastal locations for 1996, 2001, 2006, and 2011, and NOAA is working backwards in time to 1992, 1985, or further for many additional areas. The NOAA C-CAP program also produces NLCD for the coastal areas of the continental USA, and is often referred to as "coastal NLCD". The NOAA C-CAP program also produces high resolution (1–5 m) products to bring the national framework to a more localized level for selected locations.
- *Cropland Data Layer (CDL)* (<http://nassgeodata.gmu.edu/CropScape>). The Cropland Data Layer is a land cover dataset that includes a detailed legend of crop types (e.g., corn, wheat, soybeans, cotton, rice) that is produced by the USA Department of Agriculture (USDA), National Agricultural Statistics Service (NASS) and distributed through an interactive data visualization portal called CropScape. CDL was first produced nationally in 2008 [24]. Extensive field data from the USDA, NASS June Agricultural Survey and the USDA Farm Service Agency (FSA) Common Land Unit (CLU) data are used with satellite and ancillary data to distinguish the numerous crop types and practices (e.g., double cropping) [25]. Thematic accuracies for major crop types (e.g., corn, soybeans, wheat, rice, cotton) are reported in the literature [25]. NLCD land cover is used to classify areas that are not agricultural.
- *LANDFIRE* (<http://www.landfire.gov>). The Landscape Fire and Resource Management Planning Tools (LANDFIRE) is a shared program between the USDA Forest Service (USFS) and the USA Department of the Interior (DOI). The program arose over concern about increasing trends in the number of fires, the severity of fires, and the size of fires. In 2000, the President directed the Secretaries of Agriculture and the Interior to recommend how best to respond to severe wildland fires, reduce the impacts of fire on communities, and ensure sufficient firefighting capacity into the future. The objective of LANDFIRE is to help solve problems of gaps and inconsistencies in the landscape data needed for science-based planning. LANDFIRE develops and provides over 20 national geo-spatial data layers of vegetation, fuel, and disturbance, as well as databases of land based information and ecological models for the USA and its territories. The 30 m spatial datasets include several data layers that can be grouped into the three broad themes of vegetation, fire behavior, and fire regime [26]. The first national LANDFIRE database was completed in 2009 and updated versions have since been produced. Updates include refinements and remapping of vegetation data layers, incorporation of disturbance (a new data layer), and refinement of urban, agriculture, and wetland categories [27].
- *GAP* (<http://gapanalysis.usgs.gov>). Led by USGS, the mission of the GAP Analysis Program is to provide the data and tools to support proactive conservation and management of plant communities and animals. It is a geographic approach to biodiversity protection that relies on the development of detailed vegetation maps that are used to model terrestrial vertebrate

species distributions [28]. In combination with the Protected Areas Database ([29]; <http://gapanalysis.usgs.gov/padus>), assessment of conservation status (e.g., representation in the conservation network) for each element of biodiversity can be determined. The vegetation classification system (developed through collaboration between GAP, LANDFIRE, and others) used for mapping is the Ecological Systems Classification [30]. The map legend has been cross-walked to the National Vegetation Classification Standard (NVC) [31] in order to provide the data in the hierarchical framework of the standard. The data are provided for the upper five levels (in increasing detail): Formation Class, Formation Subclass, Formation, Division, and Macro-group of the NVC. An example of an ecological system would be Southern and Central Appalachian Cove Forest. NLCD land cover is used to classify areas that do not represent “natural” or semi-natural vegetation.

3. Applications

MRLC products (Figure 2) have been used widely. Because of the breadth of data products that are part of MRLC, the open access data policy under which they are distributed, and the decade or more over which some products have been available, the number of projects in which the data have been used are simply too many to count. As previously noted, the publication announcing the release of the NLCD 1992 product [3] has been cited over 500 times, and most of these citations discuss applications of the data rather than production of the data. Here we offer a few example applications of MRLC products.

Figure 2. NLCD user applications by category based on USGS earth explorer downloads from February 2011 to September 2012 (N = 2545).



- *Urban Land Use.* Consistent information on land use over large areas is a recognized data gap. Scientists at USGS have begun to address that gap by gathering and combining extensive (and protected) ancillary data with NLCD 2006 to make a national urban land use dataset [32]. The nine-class legend includes 4 classes of residential, 2 classes of commercial-industrial, institutions, roads, and a class for recreation and cultural use. The ancillary data were used to model the nine urban classes using the areas identified as urban in NLCD 2006. The methodology has been tested in 10 cities across the USA, and overall accuracy of the product exceeds 80%. Plans to extend the work nationally are under consideration.
- *Impaired Waters.* As part of the Clean Water Act (CWA) (P.L. 72-500), states are required to monitor and assess their waters on a biennial basis and report assessment results to EPA. Inevitably, some portion of the assessed waters do not meet water-quality standards and are thus identified as impaired. Once a water body is identified as impaired, plans must be put into place to bring it back into compliance. The challenge is that it is much easier to detect impairment than it is to re-establish compliance. Because of the differential between the “ease of detection” and the “ease of re-establishing compliance”, the number of impaired water bodies throughout the USA is very large (>40,000) [33]. Further complicating this large restoration effort is the lack of guidance (within CWA and elsewhere) on priority setting strategies. Such strategies are needed because financial resources do not match the large task of re-establishing compliance for >40,000 impaired waters. Scientists at EPA developed a strategy called recovery potential to address this problem [33]. Recovery potential is comparative site evaluation. It is used to identify water bodies most likely to recover if restoration activities were undertaken. Many of the indicators used for comparative site characterization are based on NLCD. Some examples include: (1) percentage of a watershed or riparian area that is forested or in natural land cover; (2) percentage of the watershed or riparian area that is in cropland or agriculture; (3) percentage of the watershed or riparian area that is in impervious cover; and (4) percentage of the watershed that has cropland on steep slopes. The program has been a success. Watershed managers in all 50 states have been exposed to the program, recovery potential projects are underway in 19 states, and EPA has developed training materials and established a recovery potential website (<http://www.epa.gov/recoverypotential>).
- *Disaster Management.* NOAA C-CAP was conceived as a project to help managers address land management issues. Use of the data to address such problems has been a key measure of the project’s success and relevance, and the NOAA C-CAP project has documented many such successes (<http://www.csc.noaa.gov/digitalcoast/data/ccapregional/action>). C-CAP data were used in the National Marine Fisheries Service’s (NMFS) [34] report to the USA Congress on the impacts of hurricanes Katrina, Rita, and Wilma on fishery habitat on the Gulf Coast. C-CAP data were used to document loss of more than 400 km² of emergent wetland in Louisiana from hurricanes Katrina and Rita. From that data, NMFS [34] estimated that these two hurricanes increased the rate of loss of emergent wetlands along approximately 50% of the Gulf of Mexico coastline. Emergent wetlands are habitat for commercially important

fisheries such as blue crab, shrimp, and oysters [34], and thus there is a direct link between land cover change and the provision of important ecosystem services.

- *Fire Fighting Efficiency.* Fire fighting efficiency is one of the many areas where LANDFIRE data are being used. LANDFIRE's fire behavior fuels models were used in conjunction with weather and topographic information to study how fire characteristics affect firefighters' ability to put out wildland fires [35]. In the analysis, LANDFIRE data were used to model flame height and rate of fire spread, which permitted an assessment of fire suppression success using one or more different types of aircraft. The availability of LANDFIRE data for this analysis advanced understanding of fire fighting efficiency because previous, similar studies were not able to incorporate such data. An expanded list of LANDFIRE applications can be found at http://www.landfire.gov/documents_dataproducts.php.
- *Crop Condition.* Ethanol production in the United States increased by 9 billion gallons between 2000 and 2009 [36]. Wright and Wimberly [37] used the Cropland Data Layer (CDL) to study agricultural land cover changes related to this trend since corn is the primary source of ethanol [36]. They compared CDL 2006 and CDL 2011 for the western Corn Belt (North Dakota, South Dakota, Nebraska, Minnesota, and Iowa) and found that more than 500,000 ha had been converted from grasslands to a corn-soybeans rotation, much of which occurred on lands that were marginal for agriculture or in the vicinity of prairie pothole wetlands. This work highlights the influence of policy on land cover change, and potential conflicts between policies related to ethanol production and policies related to grassland conservation [37].
- *Biodiversity Protection.* Each year the State of the Birds report focuses attention on conservation issues that impact bird populations in the United States. In the 2011, the report focused on the value of public lands and waters for the conservation of the nation's bird populations [38]. GAP's National Land Cover data were used to estimate the extent of each primary habitat within public lands. The 590 Ecological Systems and land-use classes were categorized into primary habitat designations for this analysis. These data were then overlaid with the Protected Areas Database ([29]; <http://gapanalysis.usgs.gov/padus>) to calculate the area of each primary habitat on public lands (not including coasts, islands, and oceans). These types of assessments are important not only because they demonstrate the importance public lands have in conserving birds; but also because they show stewardship opportunities available for the agencies managing these lands. The availability of the high thematic resolution GAP land cover product made this analysis possible.
- *Strategic Forest Monitoring and Assessment.* The USFS relies on the NLCD for several strategic monitoring and assessment activities. Strategic assessments, such as the Resource Planning Act (RPA) Assessment, which was mandated by the 1974 Forest and Rangeland Resource Planning Act (PL 93–378, 88 Stat 475, as amended), partially rely on NLCD products. The purpose of the decadal RPA assessments is to summarize findings about the status, trends, and the projected future of natural resources to aid managers and policymakers as they develop sustainability strategies. The 2010 RPA Assessment [39] includes assessment

of forest, grassland, and shrubland fragmentation that were developed from a pattern analysis of the NLCD land cover data. Additionally, the 2001 NLCD percent tree canopy cover map provides information about tree resources in urban areas and therefore was used as part of the assessment of urban forests. Strategic monitoring efforts such as the Forest Inventory and Analysis (FIA) program also rely on NLCD products. The FIA collects information on land use, vegetative community type, biomass, carbon, and disturbances at over 300,000 sampling locations across the United States. The NLCD land cover map is used to post-stratify the sample which substantially reduces the sampling error of population estimates such as total forest carbon [40]. In many cases, the FIA program would need to increase their sample size by 15% or more to reach the same level of precision that is provided by using NLCD products for post-stratification. The NLCD product lines provide a nationally consistent portrayal of land cover which are an important component of the USFS strategic monitoring and assessment activities.

4. Discussion

4.1. Impact

MRLC has had many successes. They include: inter-agency cooperation and collaboration, breadth of product, realizing a vision of Landsat TM, making land cover change information common, innovation and relevance, a well-developed remote sensing research component to support product development, and contribution of essential data to an active and growing applied research community. One noteworthy success was the announcement by the USA Census Bureau, which is not an MRLC member, that it was using NLCD 2001 to aid in the identification of urban areas for the 2010 Census [41]. MRLC growth over its nearly 20 year history is testimony to what can be accomplished by the federal government.

Interagency cooperation and collaboration may be the most significant MRLC accomplishment. Fertile ground for cooperation was established during the formation of MRLC through its objective of creating a now large and shared Landsat archive. Most of the MRLC projects use the same imagery to produce their products and rely on the products of other members for development of their data. As noted earlier, CDL uses NLCD to map non-agricultural areas; GAP uses NLCD to map areas that are not “natural” or semi-natural vegetation, GAP and LANDFIRE collaborate on vegetation classification standards (in alignment with FGDC standards), and GAP uses LANDFIRE vegetation data where regional GAP products are lacking. A significant accomplishment early on was the close collaboration that developed between USGS and NOAA on the production of NLCD and C-CAP, which has led to a deeper integration of the two products. Such capacity building has continued as the MRLC consortium has matured. The USFS led the development and production of percentage tree canopy for NLCD 2011, and will lead the production of percentage tree canopy for the NLCD 2016 effort. In addition, the USA Bureau of Land Management (BLM) is sponsoring development of percentage shrub and bare ground products for incorporation into NLCD 2016, and collaborative research between USGS and BLM is currently underway to support these new NLCD 2016 products. The close cooperation and collaboration among participants has led to: (1) decreased duplication

among member agency products and therefore significant cost savings to the taxpayer; and (2) a broadly scoped and integrated picture of our nation's land cover. The culture of cooperation among MRLC partners is also supported by annual partners meetings and quarterly, web-enabled conference calls.

Landsat Thematic Mapper (TM) was launched in 1982, providing improved spatial resolution and re-configured spectral bands designed specifically to provide better discrimination of vegetation than its predecessor, Landsat MultiSpectral Scanner (MSS). Better discrimination of earth surface features was part of the motivation for re-designing the Landsat satellite, with three of the eight mission objectives being: (1) mapping agricultural land use; (2) surveying forest resources; and (3) land cover change detection [42]. MRLC is the first national-scale realization of these mission objectives. The CDL provides detailed data on crop types suitable for planning and management. In combination, NLCD, C-CAP, GAP, and LANDFIRE constitute a survey of many aspects of forest resources, including detailed depictions of forest types and composition, forest canopy height, forest canopy density, and many aspects of the fire characteristics of forests. The third Landsat TM mission objective [42] (land cover change detection) has experienced a renaissance in recent years as land change science has emerged as a new discipline due to growing concerns over environmental sustainability [43], and land cover monitoring is one of the objectives of the newly emerging area of research [44]. Prior to the emergence of MRLC, information on land cover change was rare, scattered throughout the internet and research community as local efforts using one or two Landsat images. Through NLCD, C-CAP, CDL, and LANDFIRE, land cover change data are now readily available to the user community. MRLC products have made the Landsat TM mission objective of land cover change detection [42] a reality.

Innovation has been an integral component of MRLC since its inception, from correctly conceiving land cover as fluid and ever-changing rather than static (C-CAP), to envisioning land cover as a database [8,26,28] to using satellite data as a foundation for biodiversity (GAP), fire (LANDFIRE) and cropland management (CDL). Among these innovations, development of percentage urban impervious cover and the detection of change in percentage urban impervious cover may be the most significant. It is unlikely that impervious cover was within the vision of the developers of Landsat TM [42] because it did not emerge as an important indicator of environmental degradation until the mid-1990s [45]. Since then, impervious cover has become a standard and widely used indicator of extant aquatic condition [46,47] such that the states of Connecticut and Maine have adopted impervious cover thresholds for the identification of water-quality impairment [48,49]. Impervious cover is not an indicator that can be conveniently or cost-effectively measured in the field; it has to be measured remotely. The development of percentage urban impervious cover, a component of NLCD, marks perhaps the first nationwide dataset generated using Landsat for water-related environmental policy applications.

Product development research is a foundation for the widespread use of MRLC data. MRLC product development research includes image processing [4,5,50], classification [6,7], database design [8,26,28,51], change detection [16,27,52,53], modeling of forest canopy cover [54], and accuracy assessment [55–58]. This research is needed to support the continued refinement and increased efficiency in producing MRLC products for the nation. It is the seamless and consistent data at regional and national scales that, in part, fosters a broad user community. MRLC data have been used widely for environmental assessments, such as water quality degradation, deforestation, fire, biodiversity,

and overall landscape condition. Less well known are uses of MRLC data for understanding aspects of human health and well-being. Diversity of MRLC land cover has been used to map spatial patterns of crime, with the authors noting the novelty and potential importance of such data for uncovering the spatial patterns [59]. MRLC land cover was used as a measure of green space to map vulnerability to heat stress for major cities of the USA [60], and, in a process-based study, MRLC land cover was used to show that preservation of large wetlands and their attendant bird communities may be a useful approach for controlling outbreaks of West Nile Virus [61].

4.2. Future Plans

MRLC members are committed to ensuring the future success of the consortium in delivering land cover and land cover change information for the nation. Like all programs, MRLC's plans are contingent on externalities. Therefore, future activities are contingent on resource availability. Out of respect for those externalities, our comments on future plans are intentionally brief.

Following on the recently released 2011 products, planning is underway for production of NLCD and C-CAP 2016. The 2016 versions of the products will continue to build on the land cover monitoring objective of the programs, providing a 15-year time series of land cover change. Consideration is being given to the introduction of new products, such as percentage bare ground and percentage shrub cover [62]. These products would be conceptually analogous to percentage urban impervious cover and percentage canopy density, and add thematic resolution by making it possible to compute estimates of shrub density, which should be valuable in the western United States. Their potential inclusion is also an example of the importance MRLC places on integration and collaboration since production of these database elements will be led by the USA Bureau of Land Management (BLM). Consideration and research is also underway to complete NLCD land cover and imperviousness products retroactively for every five-year era back to 1985, creating a much longer history of USA land cover change for users. LANDFIRE is planning a major re-mapping during the same general time period and continued development of natural vegetation updating and change detection capabilities, including a vegetation health assessment that is relevant to the fire management community [27]. GAP and LANDFIRE are working collaboratively on mapping approaches that will continue to provide thematically rich vegetation maps to support both fire management and conservation planning in a nested framework. At the present time, plans for CDL are to continue producing annual maps of detailed crop types for the USA.

5. Conclusions

The MRLC consortium started as a small group with the modest goal of pooling resources to purchase Landsat TM imagery for the continental United States. Over the past 20 years, it has grown into a group that is comprised of 10 federal agencies that produce five different land cover products. As a set, the five products constitute a comprehensive database of United States land cover. MRLC products include generalized land cover, impervious cover, and detailed classifications of croplands, natural vegetation, and forests. In addition, many of the MRLC products have been produced for several time periods so that assessments of land cover change and trends can be undertaken.

The breadth of MRLC product development would not have been possible without the culture of collaboration that developed within the consortium. The culture of collaboration includes shared resources (e.g., MRLC imagery archive), shared mapping responsibilities (e.g., NLCD and C-CAP, GAP and LANDFIRE, USFS-USGS collaboration on NLCD forest canopy density), and shared research responsibilities (e.g., USGS-BLM collaboration on NLCD 2016 percentage bare ground). The comprehensive MRLC land cover product set, fostered by the MRLC culture of collaboration, has provided tangible societal benefits. Examples of societal benefits include development of impervious cover data for Clean Water Act monitoring and assessment [33,48,49], potential relationships between land cover patterns and human well-being [59–61], impact of natural disasters on ecosystem services [34], and the influence of federal energy policies on land use change and potential environmental degradation that could arise from the land use change [37].

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Author Contributions

James Wickham developed and organized the MRLC program review. James Wickham, Collin Homer, and James Vogelmann wrote and edited the manuscript. Alexa McKerrow, Rick Mueller, Nate Herold, and John Coulston contributed to the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Goward, S.N. Landsat 1989: Remote sensing at the crossroads. *Remote Sens. Environ.* **1989**, *28*, 3–4.
2. Loveland, T.R.; Shaw, D.M. Multi-resolution land characterization: Building collaborative partnerships. In *Gap Analysis: A Landscape Approach to Biodiversity Planning*; Scott, J.M., Tear, T., Davis, F., Eds.; American Society of Photogrammetry and Remote Sensing: Bethesda, MD, USA, 1996; pp. 83–89.
3. Vogelmann, J.E.; Howard, S.M.; Yang, L.; Larson, C.R.; Wylie, B.K.; van Driel, J.N. Completion of the 1990s national land cover dataset for the conterminous United States. *Photogramm. Eng. Remote Sens.* **2001**, *67*, 650–652.
4. Huang, C.; Wylie, B.; Homer, C.; Yang, L.; Zylstra, G. Derivation of tasseled cap transformation based on Landsat 7 at-satellite reflectance. *Int. J. Remote Sens.* **2002**, *23*, 1741–1748.

5. Chander, G.; Huang, C.; Yang, L.; Homer, C.; Larson, C. Developing consistent Landsat data sets for large area application: The MRLC 2001 protocol. *IEEE Geosci. Remote Sens.* **2009**, *6*, 777–781.
6. Yang, L.; Huang, C.; Homer, C.; Wylie, B.; Coan, M. An approach for mapping large-area impervious surfaces: Synergistic use of Landsat 7 ETM+ and high spatial resolution imagery. *Can. J. Remote Sens.* **2002**, *29*, 230–240.
7. Huang, C.; Homer, C.; Yang, L. Regional forest land cover characterization using medium spatial resolution satellite data. In *Remote Sensing of Forests Environments: Concepts and Case Studies*; Wulder, M., Franklin, S., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2003; pp. 389–410.
8. Homer, C.; Huang, C.; Yang, L.; Wylie, B.; Coan, M. Development of a 2001 national land cover database for the United States. *Photogramm. Eng. Remote Sens.* **2004**, *70*, 829–840.
9. Homer, C.; Dewitz, J.; Coan, M.; Hossain, N.; Larson, C.; Herold, N.; McKerrow, A.; VanDriel, N.; Wickham, J. Completion of the 2001 national land cover database for the conterminous United States. *Photogramm. Eng. Remote Sens.* **2007**, *73*, 337–341.
10. Dobson, J.E.; Bright, E.A.; Ferguson, R.L.; Field, D.W.; Wood, L.L.; Haddad, K.D.; Iredale, H., III; Jenson, J.R.; Klemas, V.V.; Orth, R.J.; et al. *Coastal Change Analysis Program (C-CAP): Guidance for Regional Implementation*; NOAA Technical Report, NMFS 123; Department of Commerce: Seattle, WA, USA, 1995.
11. Anderson, H.E. *Aids to Determining Fuel Models for Estimating Fire Behavior*; General Technical Report INT-122; U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: Ogden, UT, USA, 1982.
12. Loveland, T.R.; Dwyer, J.L. Landsat: Building a strong future. *Remote Sens. Environ.* **2012**, *122*, 22–29.
13. Roy, D.P.; Ju, J.; Kline, K.; Scaramuzza, P.L.; Kovalsky, V.; Hansen, M.; Loveland, T.R.; Vermote, E.; Zhang, C. Web-enabled Landsat Data (WELD): Landsat ETM+ composited mosaics of the conterminous United States. *Remote Sens. Environ.* **2010**, *114*, 35–49.
14. Fry, J.A.; Xian, G.; Jin, S.; Dewitz, J.A.; Homer, C.G.; Yang, L.; Barnes, C.A.; Herold, N.D.; Wickham, J. Completion of the 2006 national land cover database for the conterminous United States. *Photogramm. Eng. Remote Sens.* **2011**, *77*, 858–864.
15. Xian, G.; Homer, C.; Dewitz, J.; Fry, J.; Hossain, N.; Wickham, J. Change of impervious surface area between 2001 and 2006 in the conterminous United States. *Photogramm. Eng. Remote Sens.* **2011**, *77*, 758–762.
16. Jin, S.; Yang, L.; Danielson, P.; Homer, C.; Fry, J.; Xian, G. A comprehensive change detection method for updating the national land cover database to circa 2011. *Remote Sens. Environ.* **2013**, *132*, 159–175.
17. Greenfield, E.J.; Nowak, D.J.; Walton, J.T. Assessment of 2001 NLCD percent tree and impervious cover estimates. *Photogramm. Eng. Remote Sens.* **2009**, *75*, 1279–1286.
18. Nowak, D.J.; Greenfield, E.J. Evaluating the national land cover database tree canopy and impervious cover estimates across the conterminous United States: A comparison with photo-interpreted estimates. *Environ. Manag.* **2010**, *46*, 378–390.

19. Selkowitz, D.J.; Stehman, S.V. Thematic accuracy of the National Land Cover Database (NLCD) 2001 land cover for Alaska. *Remote Sens. Environ.* **2011**, *115*, 1401–1407.
20. Stehman, S.V.; Wickham, J.D.; Smith, J.H.; Yang, L. Thematic accuracy of the 1992 National Land Cover Data (NLCD) for the eastern United States: Statistical methodology and regional results. *Remote Sens. Environ.* **2003**, *86*, 500–516.
21. Wickham, J.; Stehman, S.V.; Smith, J.H.; Yang, L. Thematic accuracy of MRLC-NLCD land cover for the western United States. *Remote Sens. Environ.* **2004**, *91*, 452–468.
22. Wickham, J.; Stehman, S.V.; Fry, J.A.; Smith, J.H.; Homer, C.G. Thematic accuracy of the NLCD 2001 land cover for the conterminous United States. *Remote Sens. Environ.* **2010**, *114*, 1286–1296.
23. Wickham, J.; Stehman, S.V.; Gass, L.; Dewitz, J.; Fry, J.A.; Wade, T.G. Accuracy assessment of NLCD 2006 land cover and impervious surface. *Remote Sens. Environ.* **2013**, *130*, 294–304.
24. Johnson, D.M.; Mueller, R. The 2009 cropland data layer. *Photogramm. Eng. Remote Sens.* **2010**, *76*, 1201–1205.
25. Boryan, C.; Yang, Z.; Mueller, R.; Craig, M. Monitoring US agriculture: The US department of agriculture, national agriculture statistics service, cropland data layer program. *Geocarto Int.* **2011**, *26*, 341–358.
26. Rollins, M.D. LANDFIRE: A nationally consistent vegetation, wildland fire, and fuel assessment. *Int. J. Wildland Fire* **2009**, *18*, 235–249.
27. Vogelmann, J.E.; Cost, J.R.; Tolk, B.; Howard, S.; Short, K.; Chen, X.; Huang, C.; Pabst, K.; Rollins, M.G. Monitoring landscape change for LANDFIRE using multi-temporal satellite imagery and ancillary data. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2011**, *4*, 252–264.
28. Jennings, M.D. Gap analysis: Concepts, methods, and recent results. *Landsc. Ecol.* **2000**, *15*, 5–20.
29. DellaSala, D.A.; Stauss, N.L.; Strittholt, J.R.; Hackman, A.; Iacobelli, A. An updated protected areas database for the United States and Canada. *Nat. Areas J.* **2001**, *21*, 124–135.
30. Comer, P.; Faber-Langedoen, D.; Evans, R.; Gawler, S.; Josse, C.; Kittle, G.; Menard, S.; Pyne, M.; Reid, M.; Schulze, K.; *et al.* *Ecological Systems of the United States: A Working Classification of U.S. Terrestrial Systems*; NatureServe: Arlington, VA, USA, 2003.
31. FGDC (Federal Geographic Data Committee). National Vegetation Classification Standard, Version 2. Federal Geographic Data Committee-Vegetation Subcommittee. FGDC0STD-005–2008 (Version 2), 2008. Available online: http://www.fgdc.gov/standards/projects/FGDC-standards-projects/vegetation/NVCS_V2_FINAL_2008-02.pdf/ (accessed on 14 July 2014).
32. Falcone, J.A.; Homer, C.G. Generation of a U.S. national urban land-use product. *Photogramm. Eng. Remote Sens.* **2012**, *78*, 1057–1068.
33. Norton, D.J.; Wickham, J.; Wade, T.G.; Kunert, K.; Thomas, J.V.; Zelph, P. A method for comparative analysis of recovery potential in impaired waters restoration planning. *Environ. Manag.* **2009**, *44*, 356–368.
34. NMFS (National Marine Fisheries Service). *Report to Congress on the Impact of Hurricanes Katrina, Rita, and Wilma on Commercial and Recreational Fishery Habitat of Alabama, Florida, Louisiana, Mississippi, and Texas*; U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service: Silver Spring, MD, USA, 2007.

35. LANDFIRE. Aircraft Analysis Using LANDFIRE Data in the Western United States, 2012. Available online: http://www.landfire.gov/documents_dataproducts.php (accessed on 14 July 2014).
36. Wallander, S.; Claasen, R.; Nickerson, C. *The Ethanol Decade: An Expansion of Corn Production, 2000–2009*; EIB-79, U.S. Department of Agriculture, Economic Research Service: Washington, DC, USA, 2011.
37. Wright, C.K.; Wimberly, M.C. Recent land use change in the western Corn Belt threatens grasslands and wetlands. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 4134–4139.
38. NABCI (North American Bird Conservation Initiative, U.S. Committee). *The State of the Birds 2011 Report on Public Lands and Waters*; U.S. Department of Interior: Washington, DC, USA, 2011.
39. USDA Forest Service. *Future of America's Forest and Rangelands: Forest Service 2010 Resources Planning Act Assessment*; General Technical Report WO-87; USDA Forest Service: Washington, DC, USA, 2012.
40. Westfall, J.A.; Patterson, P.L.; Coulston, J.W. Post-stratified estimation: Within-strata and total sample size recommendations. *Can. J. Forest Res.* **2011**, *41*, 1130–1139.
41. Department of Commerce. Proposed urban criteria for the 2010 Census. *Fed. Regist.* **2010**, *75*, 52174–52184.
42. NASA (National Aeronautics and Space Administration). *Landsat-D Thematic Mapper Technical Working Group: Final Report. JSC-09797*; National Aeronautics and Space Administration, Lyndon Johnson Space Center: Houston, TX, USA, 1975.
43. MEA (Millennium Ecosystem Assessment). *Ecosystems and Human Well-Being: General Synthesis*; World Resources Institute: Washington, DC, USA, 2005.
44. Turner, B.L., II; Lambin, E.F.; Reenberg, A. The emergence of land change science for global environmental change and sustainability. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 20666–20671.
45. Arnold, C.L.; Gibbons, C.J. Impervious surface coverage: The emergence of a key environmental indicator. *J. Am. Plan. Assoc.* **1996**, *62*, 243–258.
46. Brabec, E.; Schulte, S.; Richards, P.L. Impervious cover and water quality: A review of current literature and its implications for watershed planning. *J. Plan. Lit.* **2002**, *16*, 499–514.
47. Schueler, T.R.; Fraley-McNeal, L.; Cappiella, K. Is impervious cover still important? Review of recent research. *J. Hydrol. Eng.* **2009**, *14*, 309–315.
48. Bellucci, C. Stormwater and aquatic life: Making the connection between impervious cover and aquatic life impairments for TMDL development in Connecticut streams. *Proc. Water Environ. Federation* **2007**, *2007*, 1003–1018. Available online: <http://dx.doi.org/10.2175/193864707786619819> (accessed on 14 July 2014).
49. Maine Department of Environmental Protection. *Maine Impervious Cover Total Maximum Daily Load (TMDL) for Impaired Streams*; DEPLW-1239; Maine Department of Environmental Protection: Augusta, ME, USA, 2012.
50. Jin, S.; Homer, C.; Yang, L.; Xian, G.; Fry, J.; Danielson, P.; Townsend, P.A. Automated cloud and shadow detection and filling using two-date Landsat imagery in the USA. *Int. J. Remote Sens.* **2013**, *34*, 1540–1560.
51. Rollins, M.D.; Keane, R.K.; Parsons, R.A. Mapping fuels and fire regimes using remote sensing, ecosystem simulation, and gradient modeling. *Ecol. Appl.* **2004**, *14*, 75–95.

52. Nelson, J.K.; Connot, J.; Peterson, B.; Martin, C. The landfire refresh strategy: Updating the national dataset. *Fire Ecol.* **2013**, *9*, 80–101.
53. Xian, G.; Homer, C.; Fry, J. Updating the 2001 national land cover database land cover classification to 2006 by using Landsat imagery change detection methods. *Remote Sens. Environ.* **2009**, *113*, 1133–1147.
54. Coulston, J.W.; Moisen, G.G.; Wilson, B.T.; Finco, M.V.; Cohen, W.B.; Brewer, C.K. Modeling percent tree canopy cover: A pilot study. *Photogramm. Eng. Remote Sens.* **2012**, *78*, 715–727.
55. Smith, J.H.; Stehman, S.V.; Wickham, J.; Yang, L. Effects of landscape characteristics on land-cover class accuracy. *Remote Sens. Environ.* **2003**, *84*, 342–349.
56. Stehman, S.V.; Wickham, J.; Wade, T.G.; Smith, J.H. Designing a multi-objective, multi-support accuracy assessment of the 2001 National Land Cover Data (NLCD 2001) of the United States. *Photogramm. Eng. Remote Sens.* **2008**, *74*, 1561–1571.
57. Stehman, S.V.; Wickham, J.; Fattorini, D.; Wade, T.G.; Baffeta, F.; Smith, J.H. Estimating accuracy of land-cover composition from a two-stage cluster design. *Remote Sens. Environ.* **2009**, *113*, 1236–1249.
58. Stehman, S.V.; Wickham, J. Pixels, blocks of pixels, and polygons: Choosing a spatial unit for thematic accuracy assessment. *Remote Sens. Environ.* **2011**, *115*, 3044–3055.
59. Sparks, C.S. Violent crime in San Antonio, Texas: An application of spatial epidemiological methods. *Spat. Spatio-Temporal Epidemiol.* **2011**, *2*, 301–309.
60. Reid, C.E.; O'Neill, M.S.; Gronlund, C.A.; Brines, S.J.; Brown, D.G.; Diez-Rouz, A.V.; Schwartz, J. Mapping community determinants of heat vulnerability. *Environ. Health Persp.* **2009**, *117*, 1730–1736.
61. Ezenwa, V.O.; Milheim, L.E.; Coffey, M.F.; Godsey, M.S.; King, R.J.; Gupitill, S.C. Land cover variation and West Nile Virus prevalence: Patterns, processes, and implications for disease control. *Vector-Borne Zoonot.* **2007**, *7*, 173–180.
62. Xian, G.; Homer, C.; Meyer, D.; Granneman, B. An approach for characterizing the distribution of shrubland ecosystem components as continuous fields as part of NLCD. *ISPRS J. Photogramm.* **2013**, *86*, 136–149.