1. Introduction

Urban area expansion is a key process of land-use and land-cover (LULC) change with implications for social, economic, and ecological research (d’Amour et al., 2017; Stefanov, Ramsey, & Christensen, 2001). The extent of urban LULC has grown rapidly across the U.S. and globally for decades as population increases and people move out of rural areas (Henderson, Yeh, Gong, Elvidge, & Baugh, 2003; Seto, Fragkias, Güneralp, & Reilly, 2011). In the U.S., the urban population had already surpassed 50% of total population by 1920, rose to 60% during the early 1950s, and was above 75% by 1990 (US Census Data). Because of the rate, magnitude, and implications of urbanization for human and natural systems, developing information about spatiotemporal characteristics is important (Bhatta, Saraswati, & Bandyopadhyay, 2010; Herold, Goldstein, & Clarke, 2003; Masek, Lindsay, & Goward, 2000).

As cities and suburbs expand, the surrounding landscape is changed in numerous ways. Urban expansion can affect other land uses, wildlife habitat, hydrology, biogeochemical cycles, weather and climate (Biggs, Atkinson, Powell, & Ojeda-Revah, 2010; Grimm et al., 2008). This can include substantial impact on productive farmland (d’Amour et al., 2017). The composition and patterns of urban LULC also affect the local internal ecology of the city, creating unique combinations of impervious surfaces, introduced vegetation, air particulates, microclimate, and soil and other land disturbances (Alberti, 2008; Meir et al., 2013; Ramalho & Hobbs, 2012). Urban areas have the potential to affect multiple ecosystem services such as offsetting urban heat island effects with the cooling effects of urban forests (Alberti, 2008; Dobbs, Kendal, & Nitschke, 2014; Lovell & Taylor, 2013) or changing the balance between local farmland, natural areas, and new development (Güneralp et al., 2013).

LULC interpretations of urban landscapes have varied in spatial, temporal, and thematic resolution. For expediency, time series maps are frequently based on Landsat satellite imagery (1973 to present), and analyses suggest that 30-meter resolution imagery widely available since 1984 is effective for identifying basic characteristics of urban development (Masek et al., 2000; Seto et al., 2011). Alternatively, higher resolution satellite data and aerial photography allow for greater LULC detail; however, the process of interpretation can be time consuming. High-resolution satellite data such as QuickBird, IKONOS and WorldView satellites have been available since about 2000 (Pu & Landry, 2012; Sawaya, Olmanson, Heinert, Brezonik, & Bauer, 2003; Seto et al., 2011). Aerial photography acquired through many different image collection efforts with various acquisition schedules and coverages is available from 1937 to present and is used here to map historical urban LULC in northern Colorado.
In this paper, we describe data on the historical progression of the northern Colorado Front Range urban landscape that includes the City and County of Denver (Figure 1). The area of interest contains an expanse of productive agriculture as well as natural land cover types including coniferous forest in the Rocky Mountain foothills to the west and high plains grassland in the Great Plains to the east. Geologic resources also contribute to the LULC through energy extraction, such as petroleum and natural gas pads, and aggregate mining (Fishman, 2005; Knepper et al., 2001). Detailed information on LULC was interpreted for the years 1937, 1957, 1977, and 1997 using manual interpretation techniques, aerial photographs, historical maps, and other available information. Initial examination of the data revealed a highly dynamic urban landscape (Mladinich, 2006). The final historical time-series maps presented here (Figure 1 and Main Map) will allow for a better understanding of the progression of urban growth and its effects on land cover and social and ecological processes.

2. Study area

The study area, which covers 1,023,600 hectares, occurs at the convergence of the western edge of the Great Plains and the eastern foothills of the Rocky Mountains. Urban growth is particularly concentrated in an area including Denver and its suburbs in the south part of the study area extending to Fort Collins in the north. Denver, which is also known as the City and County of Denver, is the state capital of Colorado, is the highest elevation major city in the U.S., and is currently the nation’s 19th largest city by population (U.S. Census Bureau, 2016). The larger Denver-Aurora combined Census Bureau statistical area is the 16th most populous metropolitan area in the U.S. with more than 3 million people in 2000 (U.S. Census Bureau, 2016). Residential and other developed land covers also extend up into the forested foothills to the west.

The study areas include agricultural land that has been affected by urbanization. Agricultural land uses include irrigated and non-irrigated crops as well as confined animal feeding operations. During the 1990s, conversion of these agricultural lands to urban was estimated at approximately 36,000 ha per year (Long, 1996; Strange, Fausch, & Covitch, 1999). Along with this, water from major sources such as the South Platte River, which runs northeast through Denver, is consistently allocated away from agriculture to meet the demands of urban and industrial development (Smith et al., 1996).
3. Methods

Procedures involved in compiling the detailed accounting of temporal LULC data included (1) obtaining historical aerial photographs, digital orthophoto quadrangles (DOQs) and ancillary data for collecting, interpreting and classifying the land surface features, (2) scanning, georeferencing and mosaicking the historical aerial photographs, (3) compiling the LULC data by 7.5-minute U.S. Geological Survey (USGS) historical aerial photographs, (3) compiling the LULC data by 7.5-minute U.S. Geological Survey (USGS) historical aerial photographs, digital orthophoto quadrangles (DOQs) and ancillary data for collecting, interpreting and classifying the land surface features, (2) scanning, georeferencing and mosaicking the historical aerial photographs, and (4) merging the final LULC data.

3.1. Aerial photograph and ancillary source acquisition

The main source materials used during LULC collection were historical aerial photographs, 1-meter resolution DOQs, and 1:24,000-scale digital line graphs (DLGs). Historical aerial photographs at a scale larger than 1:40,000 were acquired from the Natural Resources Conservation Service (NRCS) and USGS archives. Archived photos included acquisitions from the Farm Service Agency (FSA), NRCS, National High Altitude Photography program (NHAP), and National Aerial Photography Program (NAPP). Aerial photographs were ideally color or color infrared taken during the growing season so that vegetation cover classes were discernible. The color imagery also enhanced the ability to differentiate land use features such as agricultural uses, types of industry, and mining activities. For the 1937 and 1957 time periods, only black-and-white photographs were available. However, the older photographs were useful for discerning any changes in the patterns or types of land use from the previously completed LULC map. The presence of farmstead buildings, vegetation texture, and other indicators were used by experienced air photo interpreters to differentiate agriculture from natural land cover types. Ancillary material, such as National Wetlands Inventory data (https://www.fws.gov/wetlands/), USGS 7.5-minute maps (https://nationalmap.gov/historical/), and the Bureau of Reclamation’s Land Use Trend Analysis data, enhanced the interpretation and classification of land surface features.

3.2. Image processing and georectification

After acquiring the data sources, the historical aerial photographs for each timeframe were scanned. During the scanning, every other photograph in a stereo-pair was used to obtain complete coverage for each 7.5-minute quadrangle. Georeferenced control points were created by transferring coordinates of well-defined points (i.e., road intersections) from a DLG to the scanned image. At least nine georeferenced control points per image were required. In areas of high-terrain relief, a minimum of 15 points were used. The controlled part of each photograph was then clipped and mosaicked to adjacent georeferenced aerial photographs. This approach created a historical georeferenced image covering each USGS 7.5-minute quadrangle within the project area.

3.3. LULC collection criteria

The LULC feature collection requirements included a minimum mapping unit of 1.0 ha (~2.5 acres) and a minimum width of 0.038 km (~125 feet). The LULC classification used here was modified and expanded from the original Anderson classification system (Anderson, Hardy, Roach, & Witmer, 1976) (see Supplemental data). The data collection was performed on a quadrangle-by-quadrangle basis. By using the more recent LULC data set as the foundation for collecting earlier time periods, the redundant collection of unchanged LULC features between temporal periods was avoided (Anderson, 1977).

Once a specific LULC time period was completed for all quadrangles, the delineation and attribution of all LULC features were interactively checked for consistency and quality assurance by an additional air photo interpreter and corrected when needed. In addition, individual quadrangle edges were checked for consistent LULC feature delineation and attribution between adjacent quadrangles. The individual 7.5-minute quadrangles were then merged together to form a seamless LULC data set for each time period of the project area. The final maps were saved as 1-meter raster images once the LULC classification was revised and finalized (Main Map).

3.4. Additional LULC interpretation with fewer LULC classes

An additional 20-USGS quad area in south Denver, which was not part of the original study area, was completed using fewer LULC classes and provided full coverage of the Denver area in a cost-efficient way. The more-detailed land categories used in the original northern 45-quad Front Range Project area were combined to match the fewer classes in the southern addition and create the larger urban area map shown in Figure 1. This allowed the study area to be enlarged seamlessly to cover the entire Denver metropolitan area.

The process to collect the temporal LULC data for the south Denver metro area was similar to the mapping processes performed in the north Denver metro area. After acquiring the necessary historical imagery, DOQs were created for each of the 20 quadrangles for 1937, 1957, 1977, and 1997. These DOQs were used as the primary source material for LULC data.
collection. Unlike the earlier mapping effort, automated remote sensing techniques using spectral classification were used to collect surface water and vegetation. Those land categories that could not be classified using spectral pixel signatures were collected through manual photo interpretation and attribution of the land cover classes.

The map of the entire 65-quad study area was created by combining the two LULC classifications into a single 1-meter raster map. Because the 20-quad southern Denver metro area had fewer classes, it dictated the final categories that could be used when combining the two areas. Therefore, the LULC data classes of the northern part were aggregated into a more general classification to match the classes used in the southern 20-quad project area (see Supplemental data). This process resulted in a map that seamlessly shows consistent land class types for the entire Denver metropolitan area and nearby areas.

4. Conclusions

The northern Colorado urban Front Range LULC raster maps were interpreted using high-resolution imagery from the NRCS, FSA, NHAP, and NAPP archives and other detailed spatial information including USGS digital orthophoto quadrangles and historical maps. Because the final data were developed primarily through manual interpretation for use in change detection analysis, the interpretations of older time periods were informed by the more recent LULC time period. This approach allowed for spatial consistency and precision for further analysis of LULC change. The more detailed Main Map identifies 38 LULC classes. The larger map (Figure 1) identifies only 8 LULC classes consistently across the entire study area, but provides the basic urban land cover pattern for the entire Denver metropolitan area.

The aim of the final LULC maps shown here is to provide consistent data for understanding the historical progression of the northern Colorado Front Range urban landscape. These data will be used as the basis for future studies related to urbanization of this region and its impacts on human and natural systems. The relatively high temporal, spatial, and thematic resolution of the data allows detailed studies of urbanization dynamics and the linking of observed changes through time with local land use policy, growth in road networks, and changes in the local economy and culture. An understanding of urban growth will generate historical insights on how land cover progressed, impacted regional water use, and affected urban heat islands. In addition, the data can be used to understand how urban growth has impacted both terrestrial and aquatic ecosystems via studies of habitat loss and fragmentation, and changes to watersheds and water quality.

Software

The data were collected using ESRI ARC/INFO Workstation and ERDAS Imagine remote sensing software. The final raster maps were created with ERDAS Imagine version 11.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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