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A land cover change detection and classification protocol for updating Alaska NLCD 2001 to 2011

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ABSTRACT

Monitoring and mapping land cover changes are important ways to support evaluation of the status and transition of ecosystems. The Alaska National Land Cover Database (NLCD) 2001 was the first 30-m resolution baseline land cover product of the entire state derived from circa 2001 Landsat imagery and geospatial ancillary data. We developed a comprehensive approach named AKUP11 to update Alaska NLCD from 2001 to 2011 and provide a 10-year cyclical update of the state's land cover and land cover changes. Our method is designed to characterize the main land cover changes associated with different drivers, including the conversion of forests to shrub and grassland primarily as a result of wildland fire and forest harvest, the vegetation successional processes after disturbance, and changes of surface water extent and glacier ice/snow associated with weather and climate changes. For natural vegetated areas, a component named AKUP11-VEG was developed for updating the land cover that involves four major steps: 1) identify the disturbed and successional areas using Landsat images and ancillary datasets; 2) update the land cover status for these areas using a SKILL model (System of Knowledge-based Integrated-trajectory Land cover Labeling); 3) perform decision tree classification; and 4) develop a final land cover and land cover change product through the postprocessing modeling. For water and ice/snow areas, another component named AKUP11-WIS was developed for initial land cover change detection, removal of the terrain shadow effects, and exclusion of ephemeral snow changes using a 3-year MODIS snow extent dataset from 2010 to 2012. The overall approach was tested in three pilot study areas in Alaska, with each area consisting of four Landsat image footprints. The results from the pilot study show that the overall accuracy in detecting change and no-change is 90% and the overall accuracy of the updated land cover label for 2011 is 86%. The method provided a robust, consistent, and efficient means for capturing major disturbance events and updating land cover for Alaska. The method has subsequently been applied to generate the land cover and land cover change products for the entire state of Alaska.

1. Introduction

Monitoring land cover condition and changes is important to evaluate the status and transition of ecosystems such as forest harvest (Jin and Sader, 2005; Cohen et al., 2010; Kennedy et al., 2010; Zhu et al., 2012), glacial retreat (Bolch, 2007; Berthier et al., 2007; Wei et al., 2014; Burns and Nolin, 2014), urban expansion (Weng, 2001; Yang et al., 2003; Song et al., 2016), wildfire (Turner et al., 1994; Schroeder et al., 2011), flooding, and drought (Jeyaseelan, 2003; Asner and Alencar, 2010; Thomas et al., 2011). In the Arctic and sub-Arctic region, changes in vegetation and other land cover types have direct impacts on land surface energy and water balance, the surface boundary layer climate, the carbon cycle, and many other ecosystem services (Amiro et al., 2006; Beck et al., 2011; Huang et al., 2013; Huang et al., 2015). Research has shown that substantial changes have taken place in the Arctic and sub-Arctic region, including a warming trend over the past 30 years (Overpeck et al., 1997; Serreze et al., 2000; ACIA, 2004), ice melting and glacial thinning (Overpeck et al., 2005; Bolch et al., 2010; Screen and Simmonds, 2010), transition and alteration of vegetation communities such as shrub expansion (Tape et al., 2006; Myers-Smith et al., 2011), vegetation shifts and species changes (Chapin et al., 2005; Pearson et al., 2013), and higher frequency of large fires over the past half century across Alaska and Canada (Kasischke and Turetsky, 2006).

Wildfire occurrence and associated postfire succession are the most important mechanisms driving the vegetation changes in Alaska. The

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secondary succession in Alaska's boreal forest generally follows five stages after fire occurrence (Alaska's Forest & Wildlife 2001): regrowth herbaceous stage within the first 1–3 years postfire, regrowth shrub thicket within 3 to 25 years, regrowth young forest stage from 25 to 45 years, mature forest from 45 to 150 years, and climax forest (or old growth) from 150 to 300 years. However, successional patterns in burned areas of interior Alaska are also heavily influenced by burn severity and its local environment and microenvironment (Johnstone and Chapin, 2006; Chapin et al., 2006). Climate change is another major driving force in Alaska that causes land cover change such as glacial retreat, water surface change, and shrub expansion. A study by Lu and Zhuang (2011) reported three major types of land cover change in Alaska's Yukon River Basin from 1984 to 2008: 1) forests decreasing due to wildfire; 2) shrinking of closed water bodies possibly due to permafrost degradation in discontinuous permafrost regions; and 3) expansion of shrubs and conversion of grassland to shrub due to forest fire and warming.

For Alaska, a consistent monitoring protocol on vegetation and land cover change is crucial for understanding the past and current ecosystem condition and for predicting its future in response to climate change. The Alaska National Land Cover Database (NLCD) 2001, derived from Landsat imagery at 30-m spatial resolution, was the first baseline land cover product that covered the entire state (http://www.mrlc.gov, Selkowitz and Stehman, 2011; Homer et al., 2004). NLCD 2001 was intended to represent land cover condition at the nominal year 2001; however, because of the lack of cloud-free imagery Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) scenes from 1999 to 2004 were required to be used in some places, though the vast majority of scenes were acquired between 1999 and 2002. The Alaska NLCD 2001 was released in 2008 and the product depicts 8 Level I and 19 Level II land cover classes (Homer et al., 2004). An accuracy assessment of the dataset was conducted using a design-based approach. A geographically stratified three-stage sampling was used to select the reference samples from high-resolution digital photos collected via a fixed-wing aircraft (Selkowitz and Stehman, 2011), considering limited availability of source imagery and the unique land cover composition of the state. Overall thematic accuracy for the Alaska NLCD was 76.2% at Level II (12 classes evaluated) and 83.9% at Level I (6 classes evaluated) when agreement was defined as a match between the map class and either the primary or alternate reference class label. When agreement was defined as a match between the map class and primary reference label only, the overall accuracy was 59.4% at Level II and 69.3% at Level I.

The Alaska NLCD 2001 is already dated, and new information on vegetation and land cover condition and changes is needed to update the status over the past decade. This effort represents the first time Alaska NLCD land cover has been targeted for an update on a 10-year cycle, with the associated change quantified. However, such an effort is challenging because of Alaska's sheer size, complex ecosystem dynamics, short growing season, terrain variation, the limited availability of cloud-free satellite imagery, and financial constraint. Therefore, a new update approach was explored to customize a methodology to Alaska's unique circumstances. The method was designed to leverage on ancillary data, capture the main land change drivers, and derive the updated land cover types of circa 2011. The targeted land cover changes include those caused by forest disturbance and succession, and change of water extent and glacier ice/snow related to variability of weather and climate. This paper describes the core design we made for updating Alaska NLCD 2001 to the 2011 era by presenting the concept, data sources, and methodology, along with test results and accuracy assessment from pilot studies.

2. Study area and data preprocessing

2.1. Study area

Three pilot study areas are in two geographic regions within Alaska (Fig. 1). Each pilot study area is composed of four Landsat Worldwide Reference System 2 (WRS2) path/row footprints. The first region has two pilot study areas connected to each other and extends approximately from 61°N to 66°N and from 141°W to 153°W, covering portions of Yukon Flats, Interior Bottomlands, Interior Highlands, Alaska Range, Copper Plateau, and Cook Inlet. The second region extends roughly from 62°N to 67°N and from 151°W to 159°W, and is located within the Brooks Range and the Interior Forested Lowlands and Uplands ecoregions. Major land cover types of the two regions are forest, shrublands, herbaceous, wetlands, glacial ice and snow, and open water. The first region is dominated by fire disturbance, glacial retreat, and water change. The second region is dominated by fire disturbance.

2.2. Landsat data and preprocessing

The primary remote sensing data used for the study were Landsat 5 TM and Landsat 7 ETM+ imagery. Because the methods and models developed for the pilot study will be applied to the entire state, it is important to develop a consistent protocol for Landsat image selection and preprocessing. By following the protocol, we can create a cloud-free Landsat image mosaic for each mapping unit for both circa 2001 and 2011. A mapping unit is a set of several Landsat image footprints with the same or similar acquisition dates along a single WRS-2 path. The image selection takes into consideration the amount of cloud and cloud shadow, haze, and the image acquisition date. The image selections were made using the U.S. Geological Survey (USGS) Global Visualization Viewer (GloVis; http://glovis.usgs.gov/), with the Landsat WRS2 swath mode. Swath mode allows users to select several cloud-free (or nearly cloud-free) images acquired from the same date along a path. These can then be used to form a larger image mosaic (or a single mapping unit) so that a higher efficiency for land cover change modeling and mapping can be achieved over single path/row processing. All selected Landsat images were radiometrically and geometrically calibrated and converted from the digital number to top-of-atmosphere reflectance using a protocol previously developed for the NLCD project (Chander et al., 2009). All images were also terrain-corrected and co-registered to one another with a spatial uncertainty of less than one 30-m pixel. After this processing, all clouds and their shadows within the Landsat images were detected, masked out, and then filled using the method developed by Jin et al. (2013a). Additional reference images were used in this method to fill the masked-out areas in order to generate a final cloud-free image. Those processed cloud-free Landsat images of the same circa year were then mosaicked to form a mapping unit. Table 1 lists the acquisition dates and image quality in terms of cloud contamination of all Landsat images used for the pilot study areas.

2.3. Geospatial ancillary datasets

To facilitate the land cover change modeling and mapping process, a group of ancillary geospatial datasets were collected and processed for this study:

1) USGS Digital Elevation Model (DEM) data from the National Elevation Dataset (NED; http://ned.usgs.gov) and derivatives
2) Monitoring Trends in Burn Severity (MTBS) burned area boundaries dataset from 1984 to 2010 and individual fire burn severity data of 2011 (http://www.mtbs.gov)
3) LANDFIRE disturbance datasets from 1999 to 2010 (http://www.landfire.gov); LANDFIRE 2011 disturbance datasets were not available at the time of method development
4) Alaska Fire Service fire map for 1940 to 1984 (http://agdc.usgs.gov/data/)
5) Alaska Statewide Digital Mapping Initiative's (SDMI) orthoimagery mosaic images circa 2011 (http://www.alaskamapped.org/ortho)
6) MODIS ice/snow dataset from 2010 to 2012 (http://nsidc.org)

The best available DEM data for Alaska developed by the USGS were assembled and processed using an in-house processing script. The

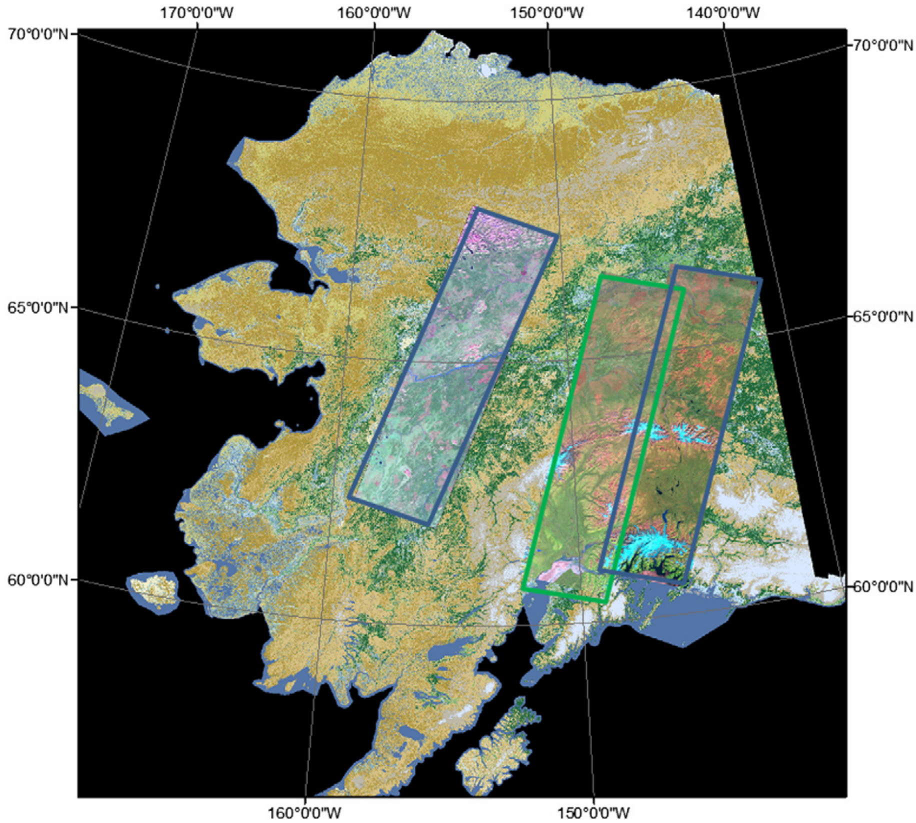

Fig. 1. Three pilot mapping units overlaid on Alaska NLCD 2001. Each mapping unit is composed of four Landsat 5 images, which are displayed in RGB bands 7, 4, and 3.

process generates raster DEM and several derivatives, including slope and aspect. The MTBS dataset for 1984–2010 and Alaska fire map for 1940–1984 were rasterized to generate disturbance-year images with 30-m spatial resolution and were reprojected into the Albers (WGS84) projection to be consistent with the NLCD map projection. LANDFIRE disturbance data were developed through a multistep process employing a number of varied geospatial datasets including MTBS to identify and label changes in vegetation cover. We compiled the LANDFIRE disturbance file of each year from 1999 to 2010 into one disturbance-year grid file while keeping the detailed attribute information from the LANDFIRE datasets. The datasets assign each change pixel with a legend that records the causes of the change (19 possible causes), severity levels (low, medium and high), and severity confidences (low, medium, and high). Fig. 2 shows the three datasets that contain statewide disturbance information for the years 1940–2010.

Table 1
Landsat images used for the pilot study areas. In the Cloud status column, "Cloud" indicates the presence of clouds in the image, "Free" indicates no clouds, and "Smoke" indicates fire smoke in the image.

Circa	Path/row	Base image date	Cloud status	Reference image date
2001	69/14	9/29/2001	Cloud	5/27/2002
	69/15	9/29/2001	Cloud	5/27/2002
	69/16	9/29/2001	Cloud	8/10/2003
	69/17	9/29/2001	Cloud	8/10/2003
	67/14	8/10/2003	Cloud	8/1/2002
	67/15	8/1/2002	Cloud	9/15/2001
	67/16	8/1/2002	Free	
	67/17	8/1/2002	Free	
	74/13	8/2/2002	Cloud	8/26/1999, 7/20/2003
	74/14	8/2/2002	Free	
	74/15	8/2/2002	Free	
	74/16	8/2/2002	Smoke	6/15/2002
2011	69/14	9/14/2010	Cloud	8/21/2010, 7/17/2009, 9/3/2009
	69/15	9/14/2010	Cloud	9/22/2010, 7/17/2009
	69/16	9/14/2010	Free	
	69/17	9/14/2010	Cloud	8/10/2009
	67/14	9/16/2010	Cloud	8/15/2010, 9/5/2009
	67/15	9/16/2010	Free	
	67/16	9/16/2010	Free	
	67/17	9/16/2010	Free	
	74/13	9/17/2010	Cloud	8/29/2009
	74/14	9/17/2010	Cloud	8/29/2009
	74/15	9/17/2010	Cloud	8/29/2009
	74/16	9/17/2010	Cloud	8/29/2009

To aid land cover change mapping of snow and ice, the Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra Snow Cover 8-Day L3 Global 500 m Grid (MOD10A2) dataset of 2010 to 2012 was obtained from the USGS/National Aeronautics and Space Administration (NASA) Earth Observing Systems (EOS) Distributed Active Archive Center (DAAC). MOD10A2 consists of 1200-km by 1200-km tiles of 500-m resolution data gridded in a Sinusoidal map projection. The MODIS snow cover data contain the maximum snow cover extent over an 8-day compositing period and a chronology of snow occurrence observations along with corresponding metadata. A script developed in-house was applied to subset, select bands, and reproject the data for subsequent use. We recognize that the spatial resolution of the MODIS data (500 m) is coarser than that of Landsat images (30 m) but with much higher temporal resolution. Our main purpose in using the multi-year MOD10A2 product is to infer persistence of ice/snow to overcome limitation of using only one-date Landsat imagery from circa 2011. Using MODIS and Landsat as a convergence of evidence can improve the confidence of mapping perennial ice/snow increase from 2001 to 2011. The Alaska Satellite Pour l'Observation de la Terre (SPOT) orthoimagery data were downloaded from the Alaska Statewide Digital Mapping Initiative (SDMI) webpage at http://www.alaskamapped.org/ortho. The original data source is SPOT 5 imagery acquired from 2009 to 2012, with each image covering a 20,000-m × 20,000-m area. Each image tile includes three separate files: CIR (24-bit false color-infrared, 2.5-m, pan-sharpened), RGB (24-bit simulated natural color, 2.5-m, pan-sharpened),

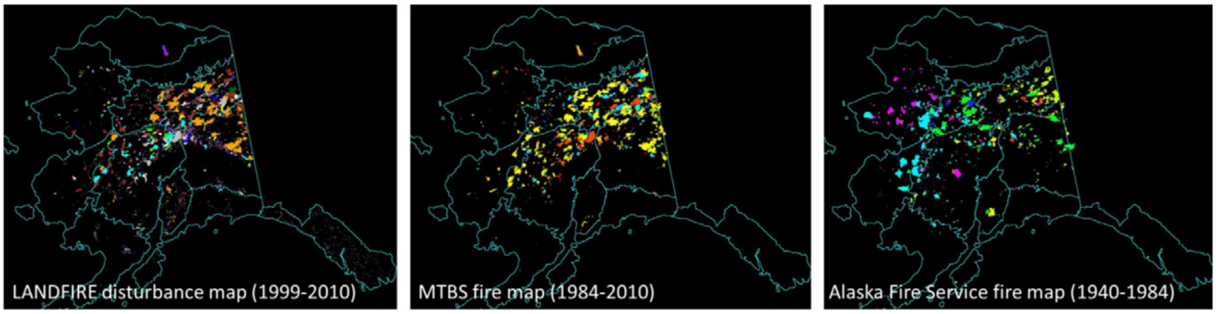

Fig. 2. Disturbance areas from the three ancillary data sources (the disturbed area of each dataset was shown in a different color according to the disturbed time: cool to warm colors correspond to early to late dates).

and PAN (8-bit panchromatic, 2.5-m). This dataset was used primarily as a supplementary reference image for a visual check of the results during the method development.

3. Methods

3.1. General description

We developed a comprehensive approach named Alaska Land Cover Update 2011 (AKUP11) to update Alaska NLCD from 2001 to 2011 on Level II land cover classes. The approach was designed to capture the main land change disturbances (including forest fire and harvest disturbance and succession, and water and glacier ice/snow changes) and update the land cover for those changed areas. For land cover no-change areas, the original land cover class label of NLCD 2001 is assumed to be correct and retained in the 2011 product. Within the AKUP11 approach, two components were developed to update the land cover status. For updating land cover in vegetation disturbed and successional areas, a component named AKUP11-VEG was developed; for updating land cover in areas where changes in water and ice/snow occurred, another component named AKUP11-WIS was created. Each component includes a set of models that are described in detail in Sections 3.2 and 3.3.

3.2. AKUP11-VEG

The approach includes four main steps (Fig. 3): 1) identify potential disturbed and successional areas; 2) assign an initial land cover label using the System of Knowledge-based Integrated trajectory Land cover Labeling (SKILL) model; 3) perform decision tree land cover classification using the SKILL model output as a training dataset; and 4) refine incorrect initial land cover labels in targeted areas (missed fire burned areas not shown in three ancillary datasets and areas within deep terrain shadow), and integrate the SKILL model output, refined land cover results, and the decision-tree generated land cover map to produce the final products of NLCD 2011 and land cover change between 2001 and 2011. These four steps are further described below.

3.2.1. Identify potential disturbed and successional areas

To identify potential disturbed and successional areas, we first compiled the disturbed areas where disturbances may lead to land cover change between 2001 and 2011 from three data sources: LANDFIRE disturbance data, MTBS data, and Alaska Historical Fire data (as described above in Section 2.3). Second, we used the Multi-Index Integrated Change Analysis (MIICA) method (Jin et al., 2013b) to identify two spectral change classes (potential biomass increase and biomass decrease) using two-date Landsat imagery from circa 2001 and 2011. Then, we added the potential biomass increase area detected by the MIICA to the disturbed area from ancillary data to derive a more complete data layer of potential disturbed and successional areas, where updates of land cover status will be made using the SKILL model. We did not add the potential biomass decrease area detected by the MIICA to the potential disturbed and successional areas because we discovered that 1) biomass decrease areas were much less likely to be missed by the three ancillary data sources because they were caused mainly by abrupt disturbance and often reflected by a large magnitude of spectral change, and 2) biomass decrease area derived from MIICA spectral change detection would bring unnecessary commission errors. Furthermore, we

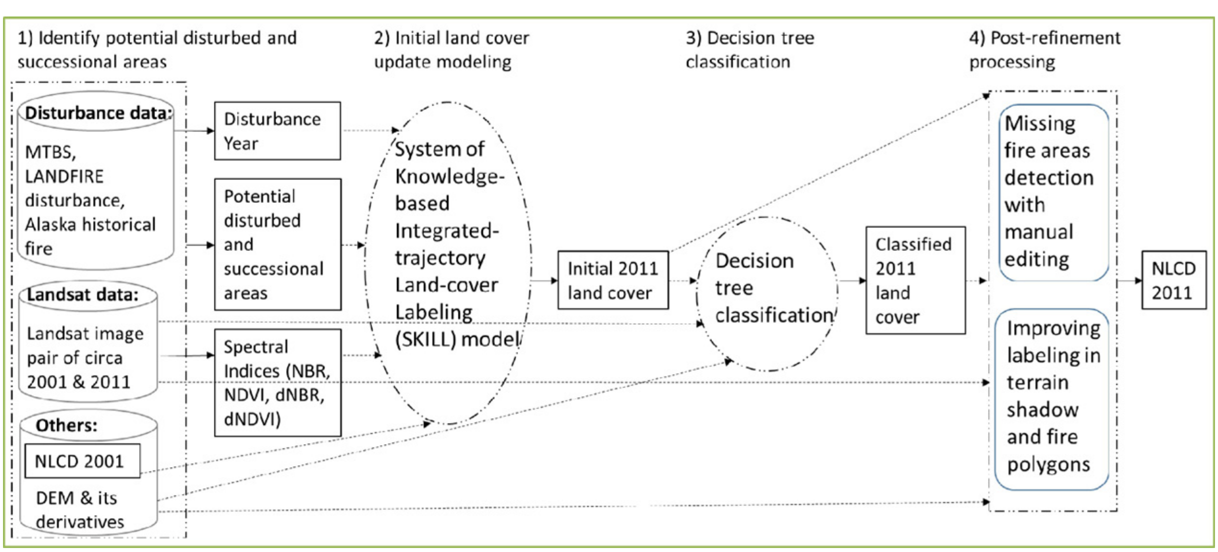

Fig. 3. Flowchart showing the four major steps of the AKUP11-VEG component.

included a process to address the fire areas missed by the three ancillary data sources in the postprocessing.

3.2.2. Initial land cover update modeling (SKILL model)

The SKILL model was developed to update the land cover label for the potential disturbed and successional area to circa 2011 while keeping the land cover label from NLCD 2001 for the remaining area. The foundation for the SKILL model is based on an understanding of the ecological processes related to vegetation disturbance and succession in Alaska. In the SKILL model, we integrated information of land cover type prior to disturbance, multitemporal and multispectral data and derivatives, disturbance characteristics (i.e. date and severity), and succession trajectory to deduce the land cover label of circa 2011 for the potential disturbed and successional area.

Inputs required by the SKILL model include 1) NLCD 2001, which provides historical land cover type in circa 2001; 2) disturbance year map, which provides the time of disturbance; 3) Normalized Burn Ratio (NBR) of 2001 and 2011, which indicates vegetation status of the year; and 4) Normalized dNBR and dNDVI between 2001 and 2011, which provides the information about disturbance magnitude. dNBR is the difference between the NBR of 2001 and 2011 (Miller and Thode, 2007). The NBR is a spectral index frequently used to identify the fire burn area and burn severity, and it is calculated by using the reflectance of near-infrared (Landsat TM/ETM+ band 4) and mid-infrared (Landsat TM/ETM+ band 7) (Key and Benson, 1999). dNDVI is the difference between the Normalized Difference Vegetation Index (NDVI) of 2001 and 2011. NDVI is calculated by using the reflectance of red (Landsat TM/ETM+ band 3) and near-infrared (Landsat TM/ETM+ band 4) (Rouse et al., 1974). dNBR and dNDVI were normalized using the statistical mean and standard deviation calculated for each land cover type from no-change area between 2001 and 2011.

The SKILL model integrated all of these inputs and then made reasonable projections about the land cover label of 2011 according to the ecological vegetation successional trajectory in Alaska (Table 2). Table 2 contains a set of decision rules for the projection. For example if land cover of NLCD 2001 is forest, and it was disturbed between 1999 and 2010, the magnitude of Normalized dNBR indicates a high severity burn, and NBR of circa 2011 indicates low vegetation cover, then the pixel is assigned to the Herbaceous land cover class in 2011 (first row in the Table 2). In the end we combined the SKILL projections for the land cover change area and the NLCD 2001 for land cover no-change area to produce an initial land cover map of 2011.

3.2.3. Decision tree classification

The initial land cover map of 2011, which has combined the NLCD 2001 for no-change area with the trajectory-projected land cover for change area, was used as the training dataset for decision tree classification. The combined training data, along with all Landsat images from circa 2011 and the DEM and its derivatives, were used as input data into a decision-tree-based classifier to produce a new land cover map for 2011. During model training, patterns and trends that linked the input data to individual land cover types were used to establish model classification rules. Although the combined training data are not error-free, the size of the training data is so large that the small percentage of training pixels with an uncertainty land cover label should have little impact on decision tree performance. Decision trees have been found to be reliable techniques for land cover classification in many contexts (Hansen et al., 2000; Hansen et al., 2013; Homer et al., 2007). In fact, one advantage of using decision trees is that they generally are not sensitive to outliers since the splitting rules are established based on the majority of the training samples rather than individual ones. Unlike the SKILL-projected land cover label for 2011 (Section 3.2.2), which is based primarily on vegetation disturbance and succession trajectory, the land cover map produced from the decision-tree classifier is mainly based on spectral information from Landsat images. Those two sets of land cover maps are complementary and were used as inputs in subsequent postprocessing steps to obtain a final land cover map for 2011 for all change areas.

3.2.4. Post-refinement processing

We refined the initial land cover label of circa 2011 from the SKILL model by correcting errors such as missing fire areas out of the potential disturbed and successional area and inappropriate land cover labels in terrain shadow areas. The potential disturbance and successional areas from the ancillary data may exclude some small fire areas that the SKILL model will treat as no-change and keep the original NLCD 2001 land cover label in the output. To correct this, we visually identified the missing areas by comparing the land cover label from the decision tree classification with the initial land cover of circa 2011 from the SKILL model. The missing-fire areas are likely to have a solid patch of Herbaceous class in the decision tree classification but Forest class in the SKILL output. After we confirm it was a fire, we manually edited the missing-fire areas, and adopted the land cover type from decision tree classification for these areas in 2011. For the shadow areas within fire polygons, it is difficult to determine whether the area was burned because spectral information alone cannot reflect the real status of the

Table 2
SKILL model decision rules.

NLCD 2001	Disturbance year	Normalized dNBR	NBR 2011	NBR 2001	Normalized dNDVI	SKILL LC 2011
Forest	1999–2010	High severity (>mean + 2.0std)	Low vegetation (<mean − 1.5std)			Herbaceous
Forest	1999–2010	Moderate severity (mean + 1.0std; mean + 2.0std)	Intermediate vegetation (<mean − 0.5std)			Shrub
Forest	1999–2010		Low vegetation (<mean − 1.5std)	Low to moderate vegetation (<mean − 1.0std)		Herbaceous
Conifer	1984–2010			Low to moderate vegetation (<mean − 1.0std)		Shrub
Shrub	1999–2010	High severity (>mean + 1.0std)	Low vegetation (<mean − 1.5std)			Herbaceous
Shrub	2008–2010 (recent 3 years)		Low to moderate vegetation (<mean − 1.0std)	Low to moderate vegetation (<mean − 1.0std)		Herbaceous
Woody wetland	2008–2010 (recent 3 years)	High severity (>mean + 1.6std)	Low vegetation (<mean − 1.5std)			Herbaceous wetland
Woody wetland	1999–2007	High severity (>mean + 1.0std)	Low vegetation (<mean − 1.5std)			Herbaceous wetland
Herbaceous	1984–2002	Biomass increase or no decrease (<mean + 0.5std)			Biomass increase or no decrease (<mean + 0.5std)	Shrub
Herbaceous wetland	1984–2002	Biomass increase (<mean − 1.0std)			Biomass increase (<mean − 1.0std)	Woody wetland

vegetation. We determined whether the shadow areas were burned by checking the neighborhood conditions (i.e., the percentage of pixels burned within the five-pixel buffer zone of the shadowed area). If 50% of neighborhood pixels were burned, then the shadow areas were labeled as burned pixels. After running all the refinements, we integrated the SKILL model output, decision tree classification output, and refinements to produce the final NLCD 2011 and the land cover change between 2001 and 2011 for all vegetated areas.

3.3. AKUP11-WIS: water & ice/snow change detection and land cover update

This section describes methods and modeling steps for detecting and mapping land cover changes that occurred in perennial snow and ice (glaciers) and water bodies between circa 2001 and 2011.

3.3.1. Ice/snow change detection and land cover update

The ice/snow change detection was designed to primarily target areas with decreasing ice and snow but still accommodate the limited areas where ice and snow were increasing over the decade. The data used for this change detection include Landsat image pairs circa 2001 and 2011, and the MODIS 500-m time series snow extent estimate for each 8-day period over circa 2011 (i.e. 2010–2012). The MODIS data provided extra detection capability to assist in identifying persistent ice/snow changes rather than transient changes such as seasonal and interannual fluctuations resulting from using Landsat images alone. The models and steps are explained below (Fig. 4).

First, we generated initial snow, ice, and water extent maps of 2001 and 2011 using the Normalized Difference Water Index (NDWI) derived from circa 2001 and 2011 Landsat images. The NDWI is calculated by using the reflectance of green (Landsat TM/ETM+ band 2) and mid-infrared (Landsat TM/ETM+ band 5) (McFeeters, 1996). NDWI has high values for snow, ice, and water areas. The threshold value of NDWI was set in such a way that it ensures a very low omission error but allow some commission error in the output maps.

Second, we generated terrain shadow images for 2001 and 2011 using respective Landsat image, along with NLCD 2001 and slope derived from DEM data. In Alaska, due to its high latitude and complex terrain, Landsat image pairs with different acquisition dates exhibit a considerable amount of spatial shift in shadows that will likely be picked up as spectral change especially for perennial ice/snow area and so, these areas needed to be excluded.

Third, we developed a snow change detection model, integrating information derived from the first two steps (i.e. potential ice/snow/water extent of circa 2001 and 2011, and terrain shadow of circa 2001 and 2011), a change vector index from the MIICA model, and a Tasseled Cap brightness index of 2011, slope, and NLCD 2001 to produce an initial ice/snow change map. The initial ice/snow change map has four classes: 1-ice/snow decrease, 2-ice/snow increase, 3-ice/snow decrease and change to water, and 4-ice thinning.

Fourth, the updated land cover labels of 2011 for the ice/snow retreat areas were determined. During this step we further modified the initial ice/snow change map based on NLCD 2001 base and MODIS snow products. For a pixel to be mapped as decrease in ice/snow, it needs to be classified as permanent ice/snow in NLCD 2001 and show substantial decrease by the ice/snow spectral change model using Landsat image pairs between 2001 and 2011. For detecting increase in ice/snow over the 10-year period, we took a conservative approach under the condition that any increase has to be persistent overtime and be supported by convergence of evidence from MODIS and Landsat. Therefore, for a pixel to be qualified as an increase in ice/snow, it has to be classified as non-ice/snow in NLCD 2001 and show an increase by the ice/snow change detection model; furthermore, the frequency of ice/snow mapped by the MODIS 8-day ice/snow estimate over a 3-year period (2010, 2011, 2012) needs to be higher than 80%, and the 2011 land cover class by decision tree classification needs to be ice/snow. For the glacial retreat areas, barren and water were the two candidate classes to be assigned to the 2011 land cover. An index, which is simply calculated as the Sum of Landsat TM/ETM+ Infrared bands 4, 5, and 7 (SLIR), was developed and used to determine if the land cover should be water

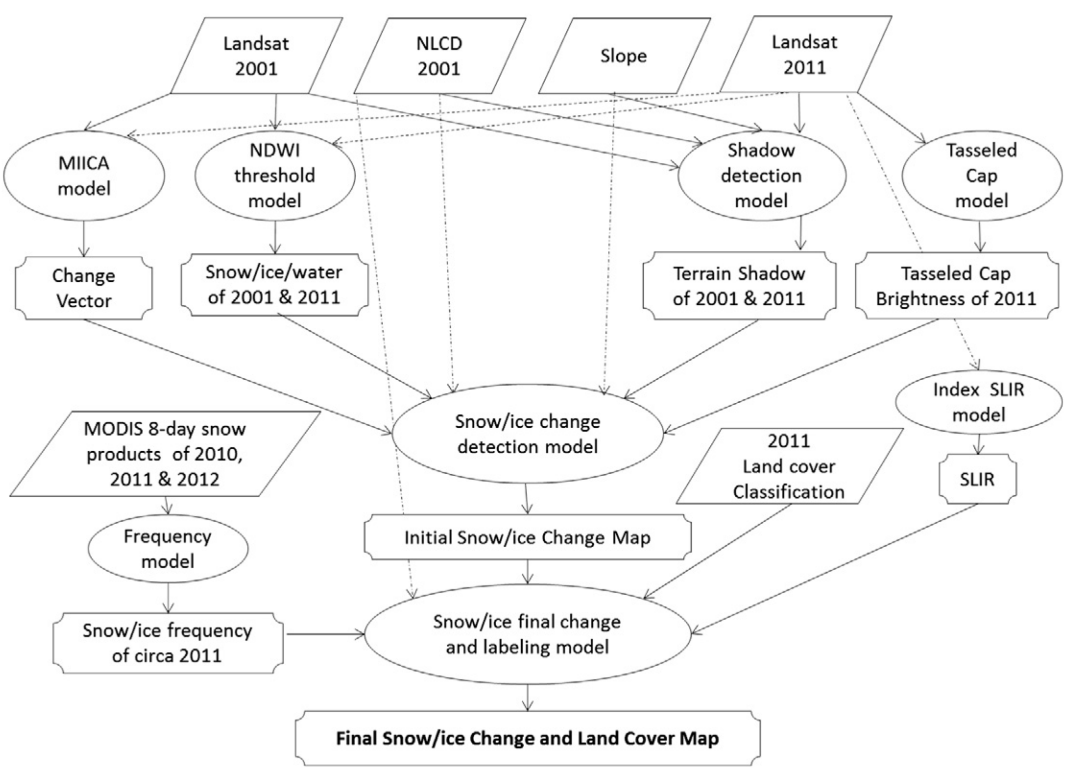

Fig. 4. The flowchart of producing ice/snow change between 2001 and 2011 and land cover of 2011 for those changed areas.

or barren based on the fact that water has a lower SLIR value than barren.

3.3.2. Water change detection and land cover update

Change in water bodies was identified in a similar way as snow and ice. The first step was the same: use NDWI to produce initial estimates of snow, ice, and water areas based on the Landsat images. The second step integrated information from the Tasseled Cap brightness index, the ice/snow/water maps of the two time periods (circa 2001 and 2011), slope, and terrain shadow to identify potential water change areas. The Tasseled Cap brightness index was used to differentiate water from ice/snow. The third step integrated information from potential water change area, NLCD 2001, the 2011 decision tree land cover classification, and the SLIR index to update the 2011 land cover label for water change areas.

3.4. Accuracy assessment

An assessment of the proposed method was conducted to evaluate two different steps in the process, the accuracy of initial change detection, and the subsequent accuracy of change labeling. Prototype method development is heavily scrutinized in subjective ways as the process is developed, the goal of this assessment is to provide additional objective feedback to confirm the subjective review of the prototype methods; it is not intended to have the rigor of a final product assessment. For all final products of NLCD, an independent and rigorous accuracy assessment will be conducted to report the accuracy as has been carried out and reported in published papers (Selkowitz and Stehman, 2011, Wickham et al., 2013, Stehman et al., 2003). Additionally, the assessment focused only on changed areas, since the goal of the method was to update NLCD 2001 to NLCD 2011 only within change areas. Two sets of sample points were selected: the first set was used to evaluate the overall accuracy of the method to map land cover change or no-change for the potential change area; the second set was used to assess the accuracy of the new 2011 land cover label for the changed area.

To draw the first set of sample points, a sampling domain was made by combining all the potential disturbed and successional areas with water and ice/snow areas from three pilot study areas. For simple random sampling and targeting overall accuracy as the estimation objective, 96 points can provide a reasonably good accuracy estimate (i.e. 90% confidence interval) with the assumption of an overall accuracy of 90% according to Cochran (1977).

We randomly selected 100 sample pixels from the sampling domain. For each pixel, a reference point of a binary call as either land cover change or no-change was derived by visual interpretation from high resolution images available from Google Earth and Bing Maps. In addition, growing-season Landsat images of circa 2001 and circa 2011 were used for assisting interpretation.

A separate second sampling domain was created for 2011 land cover label accuracy assessment. We combined the land cover change areas from three pilot studies into one map with an updated 2011 land cover label, from which a stratified random sampling was conducted to select 250 pixels with a minimum of 30 pixels for each land cover class. Only six classes were sampled because the other classes were too few to be sampled from the updated 2011 land cover map restricted within land cover change area from 2001 to 2011. The six classes are open water (class 11), barren land (class 31), shrub/scrub (class 52), grassland/herbaceous (class 71), woody wetlands (class 90), and emergent herbaceous wetlands (class 95). After the sampling, reference data of 2011 land cover type for each sample pixel were interpreted from the multi-source datasets, including high-resolution images from Google Earth, Bing Maps, NLCD 2001, and growing-season Landsat images of 2011. The level I wetland classes from NLCD 2001 were referenced to help discriminate shrub from woody wetland and grass from herbaceous wetland when there was confusion in interpreting these land cover categories that were not discernible from imagery alone.

4. Results

4.1. Image preprocessing

In total, 24 Landsat base images with 20 reference images were processed to create 6 cloud-free mosaics for circa 2001 and 2011 for the three pilot study areas. Fig. 5 shows the original individual Landsat images of circa 2001 and 2011 before preprocessing (the left column of Fig. 5) and the mosaicked images after preprocessing (the right column of Fig. 5). The quality of the image mosaics is much improved, with cloud and shadow areas in the original individual Landsat image being detected and filled reasonably well without seam lines.

4.2. Spectral change and land cover changes for natural vegetated areas

The normalized differences of NBR (Fig. 6a) were calculated from the three pairs of Landsat image mosaic from circa 2001 and 2011. The dNBR was one of the four indices employed in MIICA to derive biomass decrease and biomass increase, and was one of the input data for the SKILL model used to indicate the magnitude of spectral change. In Fig. 6a, the bright areas show high value of normalized dNBR, indicating potential biomass decrease likely caused by fire that occurred between circa 2001 and 2011, whereas the dark areas with low normalized dNBR values indicate potential biomass increase (successional growth) likely the result of fire that occurred before circa 2001. Fig. 6b shows the disturbed areas that were combined from the three ancillary datasets and displayed in a time sequence according to disturbance year. Spatially, it is clear to see that the location of the disturbance areas in Fig. 5b corresponds well with the dNBR spectral change map in Fig. 6a, especially over the fires that occurred between circa 2001 and 2011.

The potential biomass increase area from MIICA was added to the disturbed area from ancillary data to derive the potential disturbed and successional areas where the SKILL model was applied to update the land cover to circa 2011. Fig. 7 shows the NLCD 2001 and the updated NLCD 2011 from the SKILL model for the vegetated disturbed and successional areas. A visual evaluation of the map shows that the majority of the areas were severely burned and the type of land cover circa 2011 was dominated by the shrub/scrub and grassland except those small forest patches unaffected by fire. The map also shows that over a 10-year period from 2001 to 2011, almost no shrub or grass grew into forest. Overall, the forest classes reduced from about 51% within the potential disturbed and successional areas in circa 2001 to only 16% in circa 2011. In contrast, shrub coverage increased from 30% in circa 2001 to 54% in circa 2011. Grassland increased from 1% in circa 2001 to 12% in circa 2011. Shrub is the most dominant class of circa 2011 and accounts for 68% of the entire land cover change areas between circa 2001 and 2011. Grassland, which occupies about 29%, is the second dominant class of circa 2011. Shrub and Grassland classes, which mainly represented the vegetation successional stage in 2011 after the fire disturbance, comprised 98% of the land cover change areas between NLCD 2001 and NLCD 2011 over the potential disturbed and successional areas. The remaining 2% was wetlands change.

4.3. Land cover change in ice/snow and water areas

Fig. 8 shows an example of ice/snow change between circa 2001 and 2011. Note that images used to produce Alaska NLCD 2001 are not necessarily the same as those selected for this study as shown in Fig. 8a. During the recent decade, glacial ice patches have shrunk and some small patches disappeared due to changes in weather and climate conditions. The land cover type in coastal areas after glacial retreat changed to either Barren or Water. Increase in perennial snow was rare in our pilot study areas. The general trend of perennial ice/snow change mapped in this study matches the results from others (Overpeck et al., 2005, Bolch et al., 2010, Screen and Simmonds, 2010).

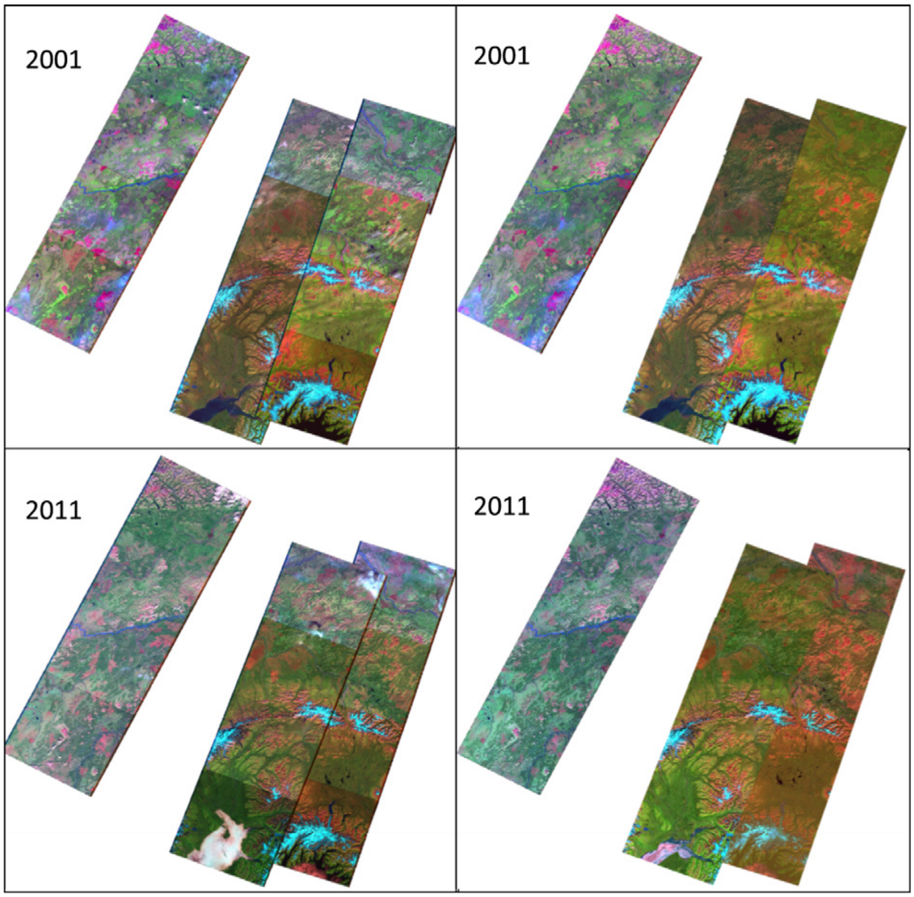

Fig. 5. Original individual Landsat images (left) and cloud-filled mosaicked images (right) of circa 2001 and 2011 for the pilot study areas. Images are displayed in RGB bands 7, 4, and 3.

Fig. 9 shows an example of water change between circa 2001 and 2011. In Alaska, one of the main sources for river/stream water is melted snow. Streamflow fluctuated substantially from year to year and in some places, changed the channel geometry completely. The majority of those dried-out areas were classified as Barren. Our method captured the changes well.

4.4. Accuracy assessment results

As described in Section 3.4, two types of accuracy assessment were performed to evaluate effectiveness of the method. The first assessment focused on accuracy in detecting and mapping areas of land cover change and no-change only, and the second one focused on correctness

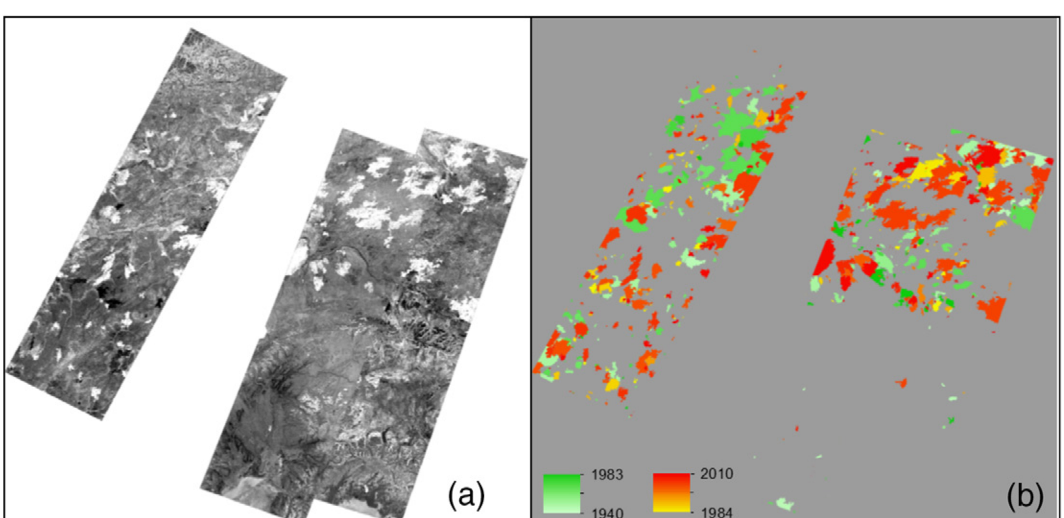

Fig. 6. Potential disturbed and successional area: (a) spectral change index between circa 2001 and 2011 (i.e. the normalized difference of NBR between circa 2001 and 2011); (b) disturbed areas from the three ancillary data sources.

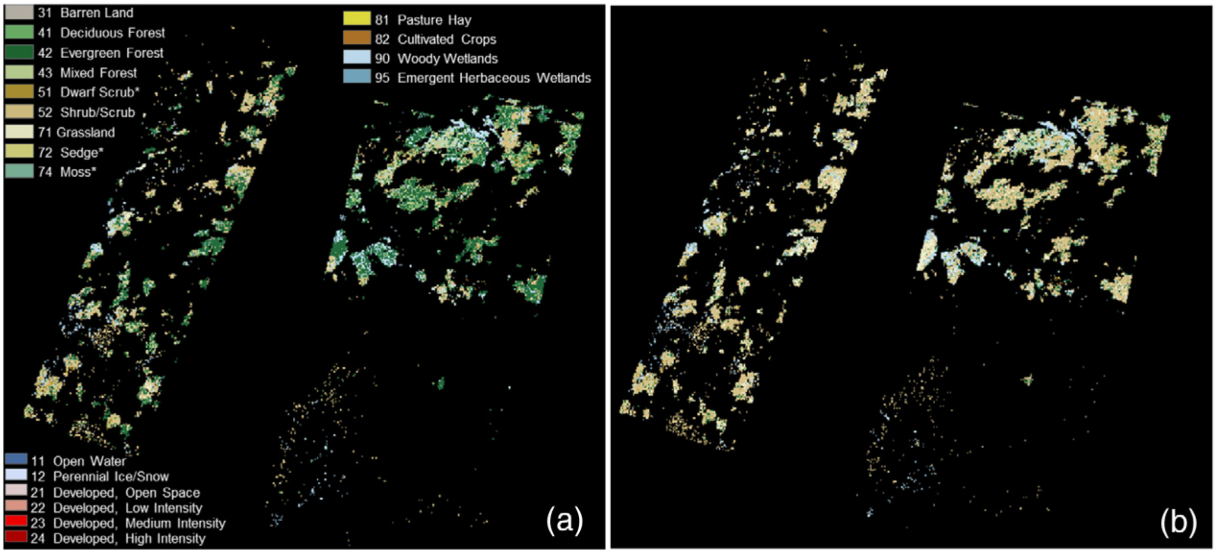

Fig. 7. (a) NLCD 2001 and (b) updated NLCD 2011 from SKILL model for the vegetated disturbed and successional areas within the three pilot study areas.

of the updated land cover label of 2011 within land cover change areas. For the change/no change only assessment, a sample of 100 points yielded an overall accuracy of 90% (Table 3) with the producer's and user's accuracies for both change and no-change categories relatively high at 83% and 93%, respectively (Table 3).

For the updated 2011 land cover label assessment (Table 4), a total of 250 samples were generated based on a stratified random design with a minimum of 30 samples each for the six major change classes. However, due to the limited ability to decipher high-resolution imagery in 2011 for some classes, 18 out of the 250 samples were eliminated. By adjusting for the areal extent each land cover class occupies (Olofsson et al., 2013, Olofsson et al., 2014), the overall accuracy is greater than 86% with most categories having both producer's and user's accuracies close to 80% (Table 4). The Woody Wetland class (90) had confusions mainly with Herbaceous Wetland (95) and Shrub (52). The results indicate that the SKILL model did reasonably well for determining forest successional stage after fire but had difficulty differentiating Woody Wetland from Herbaceous Wetland, possibly because the spectral differences of wetland classes are more affected by soil wetness than by vegetation stage. The results also show that the accuracy of updated land cover labels (Water and Barren) for 2011 in water and ice/snow change areas is high.

5. Discussion

Alaska is a challenging mapping environment, due to the sheer size of the state, the short growing season, and the limited availability of cloud-free satellite imagery. Our methods were customized to Alaska's unique circumstances in each step and proved to be an efficient approach for product production.

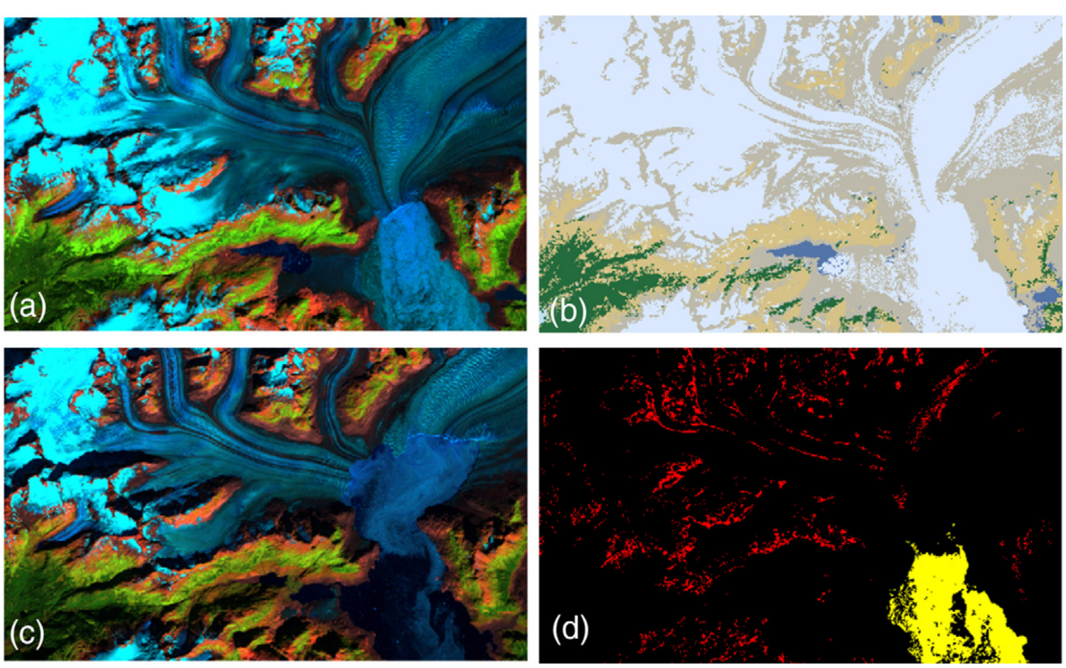

Fig. 8. Ice/snow change between circa 2001 and 2011 for a subset area: (a) Landsat image of circa 2001, (b) NLCD 2001, (c) Landsat image of circa 2011, (d) ice/snow land cover change between circa 2001 and 2011 (red indicates ice/snow retreat to land; yellow indicates ice/snow retreat to water).

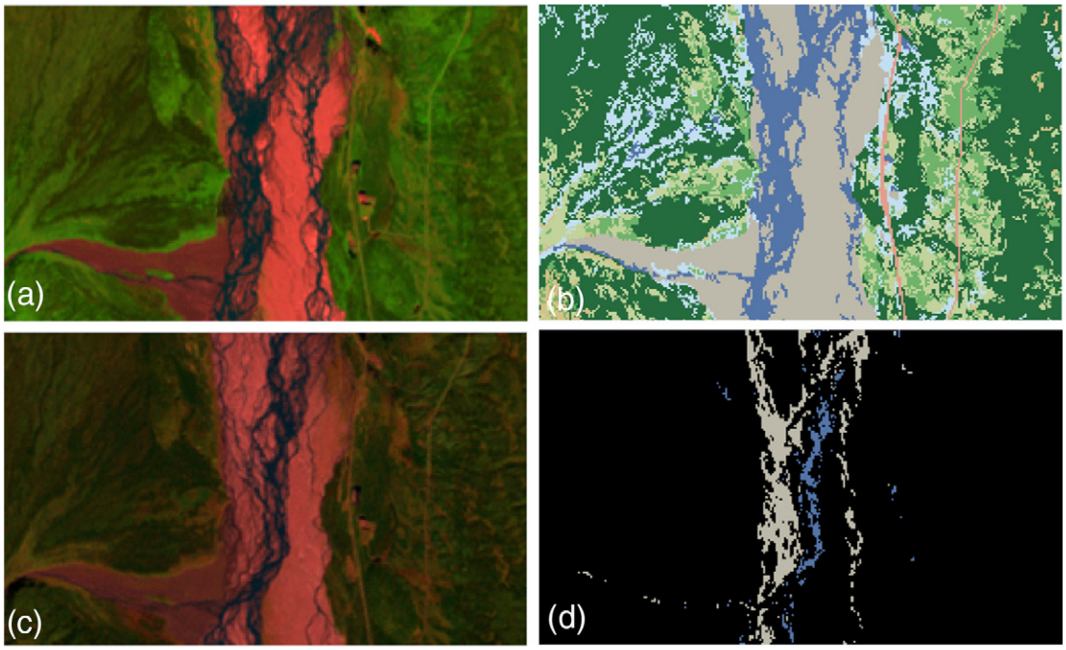

Fig. 9. Water change between circa 2001 and 2011 for a subset area: (a) Landsat image of circa 2001, (b) NLCD 2001, (c) Landsat image of circa 2011, (d) water land cover change pixels with 2011 land cover label.

5.1. Image preparation

We maximized efficiency by selecting images from the USGS GloVis user interface using the swath-mode to identify multiple cloud-free Landsat images along the same WRS-path. These images from the same date are more easily mosaicked to form a large mapping unit without needing to normalize the phenology variation among images. This mapping unit approach enabled us to dramatically improve operational efficiency because all the remaining procedures could operate on a mapping unit instead of individual Landsat path/row. This is especially useful in Alaska where Landsat path/row geographies have a large high latitude overlap area between each other. However, for this mapping unit approach to properly work, each Landsat base image still needed to be processed individually to remove clouds and shadows. The ability to execute the land cover change modeling at the mapping unit scale was essential to ensure enough efficiency in the process to keep the approach cost effective.

5.2. Change identification

Our strategy to employ a specialized method to ensure the capture of the primary change from only a few land change drivers works well in Alaska because the vast majority of land cover change is caused by these drivers. For example, the bulk of landscape change comes from wildland. An approach like this may not be relevant in geographies that have more varied change processes. To aid in identifying potentially disturbed vegetation areas, we leveraged on fire ancillary data along with our MIICA model to derive a comprehensive potential change area map with low commission and omission errors. Making full use of ancillary data not only improved the mapping efficiency but also increased accuracy. The approach of the SKILL model was innovative and can update land cover types to circa 2011 based on information of land cover type before disturbance, disturbance characteristics (i.e. date and severity), and succession trajectory. The SKILL model also helped mitigate land cover training data deficiency in disturbed areas and reduced intrinsic classification errors by the classifier due to spectral confusions among land cover classes. However, developing the SKILL model required understanding of the ecological processes related to vegetation disturbance and succession in Alaska. While the concept of the SKILL model can be applied somewhere else, the particular conditional statements developed for Alaska would need to be adjusted for a different geography and situation. The greatest potential limitation of the SKILL approach is that it is applied only to the pre-defined potential change area and may potentially miss some real land cover changes occurring in the assumed no change area. To mitigate this risk, we have used a decision tree classification with training data sampled from the SKILL projection and NLCD 2001 land cover data to compensate for the limitation. Overall the advantage of this approach is the ability to target change processes on the landscape and identify methods to ensure the best capture of those changes.

Table 3
Accuracy assessment of change and no change detection between 2001 and 2011.

Reference map	Change	No-change	User's accuracy
Change	24	5	82.76%
No-change	5	66	92.96%
Producer's accuracy	82.76%	92.96%	Overall: 90.00%

5.3. Water and ice/snow change

The main challenges for carrying out ice/snow change detection in Alaska includes the pronounced terrain shadow shift apparent in multitemporal Landsat images caused by different acquisition date and the difficulty of separating perennial ice/snow and seasonal ice/snow. We developed a terrain shadow detection model to remove the spurious change from real ice/snow change and used 3 years (2010 − 2012) of 8-day MODIS snow-cover images to ensure that temporary ice/snow was not included in the perennial ice/snow in the final NLCD 2011 update. When interpreting the perennial ice/snow change amount between 2001 and 2011, we have assumed NLCD 2001 to be correct. For the Alaska NLCD product, our goal was to credibly capture snow and ice change without too much additional effort, since NLCD resources needed to be able to capture all of the land cover change adequately across the state. Hence, users are cautioned that this is not intended to be the final authoritative portrayal of snow and ice change

Table 4
NLCD 2011 land cover classification accuracy assessment in changed areas. The accuracy parameters are calculated with area adjusted.

	Reference						Total	Area (sq.km)	Weight	User's accuracy
Land cover classes	C11	C31	C52	C71	C90	C95				
Water (C11)	26	2	1	0	1	0	30	113	0.01	87%
Barren (C31)	3	32	0	0	2	0	37	379	0.02	86%
Shrub (C52)	0	0	67	0	5	0	72	13,078	0.67	93%
Grassland (C71)	0	0	9	22	0	0	31	5564	0.28	71%
Woody wetland (C90)	0	1	0	0	14	15	30	131	0.01	47%
Herbaceous wetland (C95)	0	0	0	3	4	25	32	310	0.02	78%
Total	29	35	77	25	26	40	232	19,574	1.00	
Producer's accuracy	76%	97%	88%	99%	6%	79%			Overall accuracy	86%

during a very dynamic time, but rather a reasonable portrayal of what change occurred in the context of the space and time we examined.

5.4. Comprehensive integration approach

In challenging mapping landscapes such as Alaska, comprehensive and complex integration of various methods is required to be successful. In this case, a combination of image and ancillary data preprocessing, robust training and classification model development, prioritized postprocessing enhancement, and final integration of all processes was required to successfully identify and label change. Additionally, in developing a product across such a vast landscape, consideration is needed for the distribution, availability and robustness of any dataset that is used. Ultimately, if the process cannot be implemented at a statewide scale, it is of no use. We think this combination of methods maximized all the relevant data for the state, and the integration of all these processes created a superior product that achieves the accuracy goals of NLCD.

5.5. Accuracy assessment

Our accuracy assessment was intended to provide additional objective feedback to confirm the subjective review of the prototype methods. It was not intended to be the kind of comprehensive assessment required for a final product. In addition, lack of high-resolution aerial photos affected our ability to assess the land cover change and land cover classification accuracy in Alaska. Furthermore it is not always possible to determine the change status of a 30 m pixel from photointerpretation of two eras of Landsat imagery. Despite the difficulty, we have made every effort to follow good practices of accuracy assessment (Olofsson et al., 2013, Olofsson et al., 2014) to ensure the statistical validity of the results. Another factor to keep in mind is that the land cover change between NLCD 2001 and NLCD 2011 is sometimes different from that detected between Landsat imagery of circa 2001 and Landsat imagery of circa 2011 because in the land cover change models, the legacy NLCD 2001 was used as a base and assumed to be correct. Our land cover change and no-change accuracies actually are higher than the numbers in Table 3 if based on images only. We believe that our methods are not only innovative but also efficient based on the accuracy assessment.

6. Conclusion

This paper introduced a new operational method designed to update Alaska NLCD 2001 to circa NLCD 2011. Because of Alaska's sheer size, unique ecosystems, short growing season, terrain variation, the limited availability of cloud-free satellite imagery, and resource-intensive nature for NLCD 2011 production, our method was designed to overcome these limitations and effectively capture and characterize the main land cover changes associated with different drivers. Alaska primary land cover drivers include 1) wildland fire, forest harvest and vegetation successional process after disturbance; and 2) changes in weather and climate condition. The developed method consists of several major steps including image preprocessing, ancillary data collection, land cover modeling and image classification, postprocessing refinement, and integration of all processed results to generate the final NLCD 2011 product.

The overall accuracy of land cover change detection is 90%. The overall accuracy of NLCD 2011 over land cover change area is higher than 86%, and most of the categories have both producer's and user's accuracies close to or higher than 80%, except for the Woody Wetland class. Both the visual check and statistical accuracy assessments of the output maps from the test area indicate that our method is a robust, consistent, and efficient approach for capturing major disturbances and updating land cover. This methodological approach was implemented across the entire state of Alaska in an operational design to produce NLCD 2011 land cover. The final NLCD Alaska 2011 is provided online for free download at http://www.mrlc.gov/nlcd11_data.php.

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