International Journal of Remote Sensing

ISSN: 0143-1161 (Print) 1366-5901 (Online) Journal homepage: http://www.tandfonline.com/loi/tres20

An overview of 21 global and 43 regional land-cover mapping products

George Grekousis, Giorgos Mountrakis & Marinos Kavouras

To cite this article: George Grekousis, Giorgos Mountrakis & Marinos Kavouras (2015) An overview of 21 global and 43 regional land-cover mapping products, International Journal of Remote Sensing, 36:21, 5309-5335, DOI: 10.1080/01431161.2015.1093195

To link to this article: http://dx.doi.org/10.1080/01431161.2015.1093195

Published online: 26 Oct 2015.

Submit your article to this journal

Article views: 79

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
http://www.tandfonline.com/action/journalInformation?journalCode=tres20

Download by: [SUNY College of Environmental Science and Forestry] **Date:** 17 November 2015, At: 13:19

International Journal of Remote Sensing, 2015
Vol. 36, No. 21, 5309–5335, http://dx.doi.org/10.1080/01431161.2015.1093195

Taylor & Francis
Taylor & Francis Group

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

An overview of 21 global and 43 regional land-cover mapping products

George Grekousis[a]*, Giorgos Mountrakis[b], and Marinos Kavouras[a]

[a]School of Rural and Surveying Engineering, National Technical University of Athens, Athens, Greece; [b]Department of Environmental Resources Engineering, State University of New York College of Environmental Science and Forestry, Syracuse, NY 13210, USA

(*Received 18 May 2015; accepted 1 September 2015*)

Land-cover (LC) products, especially at the regional and global scales, comprise essential data for a wide range of environmental studies affecting biodiversity, climate, and human health. This review builds on previous compartmentalized efforts by summarizing 23 global and 41 regional LC products. Characteristics related to spatial resolution, overall accuracy, time of data acquisition, sensor used, classification scheme and method, support for LC change detection, download location, and key corresponding references are provided. Operational limitations and uncertainties are discussed, mostly as a result of different original modelling outcomes. Upcoming products are presented and future prospects towards increasing usability of different LC products are offered. Despite the common realization of product usage by non-experts, the remote-sensing community has not fully addressed the challenge. Algorithmic development for the effective representation of inherent product limitations to facilitate proper usage by non-experts is necessary. Further emphasis should be placed on international coordination and harmonization initiatives for compatible LC product generation. We expect the applicability of current and future LC products to increase, especially as our environmental understanding increases through multi-temporal studies.

1. Introduction

Land cover (LC) is defined as the biophysical material over the surface of the Earth and immediate subsurfaces including, among others, grass, shrubs, forests, croplands, barren, waterbodies (including groundwater), and man-made structures (Meyer and Turner 1994; Lambin and Geist 2010; Giri 2012). Land cover change (LCC) is the conversion from one LC category to another or/and the modification of land within a LC (Meyer and Turner 1994). LCC causes significant environmental changes at the local, regional, and global scales. For example, forest transition to agricultural land or urban expansion into croplands affects the biodiversity, soil quality, climate, and human health (Lambin and Geist 2010; Feddema 2005; DeFries, Asner, and Houghton 2004).

Understanding and monitoring LC distribution and dynamics are important factors in environmental studies. Updated LC information is essential for governments, non-governmental organizations, and other stakeholders assisting in the development and implementation of environmental policies for a sustainable future (Grekousis and Mountrakis 2015; Yan, Shaker, and Ashmawy 2015; Giri 2012; Feranec et al. 2007). Human activities related to serving specific societal and individual needs are the main

---

*Corresponding author. Email: geograik@gmail.com

© 2015 Taylor & Francis

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

drivers of contemporary LC dynamics (Grekousis, Kavouras, and Mountrakis 2015; Turner 2006; Jarnagin 2004). In fact, humans have been modifying land (mainly for food production) for thousands of years. Still, the LCC magnitude and related modifications are greater than ever before (Ellis and Pontius 2007). Constraining the negative implications of LCC while sustaining the production of essential resources is currently a major concern for the scientific community and policymakers around the world (Ellis and Pontius 2007).

To estimate the extent of LC dynamics and assess their environmental implications, various regional and global land cover (GLC) data sets exist. A wide range of institutions, organizations, and agencies comprising scientists and policymakers gather, analyse, and use land-related data and various regional and global LC products and provide policy suggestions, in order to align with sustainable development visions. One recent example is the Rio+20 conference (UN 2012a) with a produced report that clearly highlights the importance of global LC mapping for achieving sustainable development through scientific studies and initiatives that will help sustainable land management policies and practices (UN 2012b). LC products serve as decision support systems helping decision-makers apply policy objectives. For this reason, it is essential that LC products are as accurate and reliable as possible so that the outcomes are reliable and consistent. In reality though, because of the wide differences in the methodological approaches for each product (e.g. classification schemes, classification techniques, time of data acquisition, spatial resolution), there is often poor agreement among different data sets when applied at the regional or global level (Gong et al. 2013; Herold et al. 2008). The above-mentioned inconsistencies, uncertainties, and inaccuracies make the use of LC products problematic, as it is difficult to effectively apply these data sets to the diverse range of applications by multiple users (Tsendbazar, Bruin, and Herold 2015; Congalton et al. 2014). In addition, most of the current GLC products describe the spatial distribution of various LC types, but they do not assess LC changes and processes (Zhang et al. 2014). Change detection analysis is not independent of the original data sources and their associated accuracy and therefore it is of crucial importance to carefully select the associated data sets.

With the advent of technology and the continuously decreasing satellite data cost, various global and regional LC products have been created and more are expected to be operational in the near future. With the proliferation of remotely sensed products and improvements in variability, accessibility, and cost, LC products have become essential inputs for interdisciplinary studies, for instance related to climate and carbon sequestration dynamics. Still, due to the plethora of existing LC products, with different specifications obtained and accuracies achieved, the issue of selecting the appropriate product according to the various users' needs is crucial. Several reviews offer descriptive and in-depth comparison analysis. For example, Congalton et al. (2014) performed a review and uncertainty analysis in the following widely used GLC products: International Geosphere-Biosphere Program's Data and Information System Cover (IGBP DISCover); University of Maryland (UMD); Global Land Cover 2000 (short name: GLC 2000); and GlobCover 2009. Mora et al. (2014) summarized the characteristics of seven GLC products (IGBP DISCover, UMD, Moderate Resolution Imaging Spectroradiometer 500 m (MODIS), GLC 2000, Global Land Cover by National Mapping Organizations (GLCMNO), GlobCover, and GlobCover v2). Herold et al. (2008) analysed the agreement and accuracy in four 1 km GLC products (IGBP DISCover, UMD, MODIS 1 km, and GLC 2000). Jung et al. (2006) highlighted the strengths and weaknesses of Global Land Cover

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Characteristics (GLCC), GLC 2000, and MODIS. At the regional level, Bai et al. (2014) tested the consistencies of five GLC products in China (GLCC, UMD, MODIS, GLC 2000, and GlobCover) and Tchuente, Roujean, and Jong (2011) made a quality assessment of the GLC 2000, GlobCover, and MODIS for Africa.

The above-mentioned reviews provide valuable information and suggestions. For example, conclusions are made by rescaling products to the same spatial resolution or by aggregating their classification systems to a unified legend. Owing to the high volume, existing reviews focus on a limited subset of LC products. Still, a review of the characteristics, limitations, and prospects as well as lessons that can be learned not only from the study of some specific LC products but also based on the majority of global and regional LC products is missing. Building on existing efforts and motivated by the high importance of these LC data sets, our scope is to: (1) summarize the characteristics and the state of practice for the majority of global and regional LC products and (2) make recommendations for upcoming LC products. In total, we provide characteristics and accuracy assessment results for 64 LC products, along with their properties, discuss general weaknesses and strengths to serve as a repository, as complete as possible, and assist scientists from diverse fields, decision-makers, and users worldwide.

We focus on characteristics such as spatial and temporal coverage, spatial resolution, overall accuracy, sensor and satellite, classification method, classification scheme, and ability to detect changes. Furthermore, we provide a key reference paper for each LC product for in-depth information and a web link where each LC product can be downloaded. We concentrate on global and regional LC products containing multiple land categories created by national or multinational institutions and organizations, and not on single thematic products dedicated to only one LC class, e.g. vegetation or imperviousness. We include 23 global and 41 regional (17 continental and 24 national) products in our study. At the continental level, we present LC products of Europe, North and South America, and Africa (Table 3). Although Oceania and Asia can be covered through the various global LC products, currently no LC products exist solely developed and validated for these areas. In the national scale we include LC products from the seven largest countries of the world (Russia, Canada, China, USA, Brazil, Australia, and India) (Table 4) as they occupy almost half (48%) of the land worldwide (United Nations Statistics Division – UNSD 2007). Limitations and suggestions of current LC products are presented in order to assist from the operational point of view leading to a further discussion on current trends and future prospects towards increasing the usability of different LC products through international coordination and harmonization initiatives (Table 5).

2. GLC products

The most widely available GLC data sets include GLCC 2.0, International Satellite Land Surface Climatology Project (ISLSCP II), MODIS, UMD, GLC 2000, GlobCover, GLCNMO, GLC-SHARE (Global Land Cover-SHARE), GeoWiki, Climate Change Initiative-Land Cover (CCI-LC), Global Land Cover 250 m China (GLC250 m_CN), Finer Resolution Observation and Monitoring-Global Land Cover (FROM-GLC), and GlobeLand30 (Table 1). The timeline of the GLC products regarding the reference year (year that the GLC status is depicted) is presented in Figure 1. In addition, the year the product was released to public is also presented to determine the most recent product for

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Table 1. Global land-cover products.

Data set/ product name	Spatial resolution	Overall accuracy (%)	Period of data acquisition	Sensor	Classification scheme-level I	Classification method	Change detection	Creator	Download data URL	Reference paper
GLCC 2.0 IGBP DISCover	1 km	66.9	Apr1992–Mar 1993	AVHRR	IGBP 17 classes	Unsupervised classification	Not supported	USGS, UNL	http://edc2.usgs.gov/glcc/tabgoode_globe.php	Loveland et al. (2000)
ISLSCP II IGBP DISCover and SiB	0.25°, 0.5°, 1.0°	66.9	Apr1992–Mar 1993	AVHRR	IGBP 17 classes and SiB 15 classes	Unsupervised classification	Not supported	ORNL-DAAC/ UMD	http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=969	Loveland et al. (2009)
MODIS Land Cover Type/ MCD12Q1 collection 5.1	500 m	71.6	Yearly since 2001	MODIS	IGBP 17 classes	Supervised classification	Not recommended	NASA	http://e4ftl01.cr.usgs.gov/MOTA/MCD12Q1.051/	Friedl et al. (2010)
UMD	1 km	65.0	1992–1993	AVHRR	Simplified IGBP 12 classes	Supervised classification	Not supported	UMD	http://www.landcover.org/data/landcover/index.shtml	Hansen et al. (2000)
GLC 2000	1 km	68.6	Nov 1999–Dec 2000	SPOT4 VEGETATION	FAO LCCS 22 classes	Unsupervised classification	Not supported	JRC	http://bioval.jrc.ec.europa.eu/products/glc2000/products.php	Bartholomé and Belward (2005)
GlobCover				MERIS FR	FAO LCCS 22 classes	Supervised and unsupervised classification	Not recommended	ESA	http://due.esrin.esa.int/globcover/	Bicheron et al. (2008) Bontemps et al. (2011)
GlobCover2005 v2.2	300 m	73.1	2004–2006							
GlobCover2009	300 m	67.5	2009							
GLCNMO				MODIS	FAO LCCS 20 classes	Supervised classification	Not recommended	ISCGM	https://www.iscgm.org/gmd/	Tateishi et al. (2011)
GLCNMO V1	1 km	76.5	2003							Tateishi et al. (2014)
GLCNMO V2	500 m	77.9	2008							
GLC SHARE	1 km	80.2	Various, depending on database source	Various, depending on database source	FAO LCCS 11 classes	Data fusion	Not supported	FAO UN	http://www.glcn.org/databases/lc_glcshare_downloads_en.jsp	Latham et al. (2014)
GeoWiki			Data from: GLC2000	MODIS, SPOT4, MERIS FR	FAO LCCS 10 classes	GWR	Not supported	GeoWiki	http://geo-wiki.org/Application/index.php	See et al. (2015)
Hybrid 1	300 m	87.9	MODIS 2005							
Hybrid 2	300 m	82.8	GlobCover2005							

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

CCI-LC				MERIS Full and Reduced Resolution/ SPOT VGT	FAO LCCS 22 classes	Unsupervised classification	Yes	ESA	http://maps.elie.ucl.ac.be/CCI/viewer/index.php	ESA (2014)
2000	300 m	Validation in process	1998–2002				Yes			
2005	300 m		2003–2007							
2010	300 m		2008–2012							
GLC250 m_CN				MODIS	11 classes	Random forest	Yes	CAS	Not available yet	Wang et al. (2015)
2001	250 m	74.93	2000–2001							
2010	250 m	75.17	2009–2011							
FROM-GLC					9 classes			CESSC	http://data.ess.tsinghua.edu.cn/	
FROM-GLC	30 m	63.69	Circa 2010	Landsat TM, ETM+		Supervised classification	No			Gong et al. (2013)
FROM-GLC-seg	30 m	64.42	Circa 2010	Landsat TM, ETM+		Supervised classification	No			Yu, Wang, and Gong (2013b)
FROM-GLC-agg	30 m	65.51	Circa 2010	Landsat TM, ETM+		Aggregation procedure	No			Yu, Wang, et al. (2014)
FROM-GLC-Hierarchy	30 m up to 100 km	69.50 for the 30 m	Circa 2010	Landsat TM, ETM+		Decision tree	No			Yu, Wang, et al. (2014)
GlobeLand30				Landsat TM, ETM7, HJ-1A/b/	10 classes	Supervised classification	Yes	UN/ NASG	http://www.globallandcover.com	Chen et al. (2015)
2000	30 m	78.6	2000							
2010	30 m	80.3	2010							

Notes: USGS, US Geological Survey; UNL, University of Nebraska-Lincoln; ORNL-DAAC, Distributed Active Archive Center; UMD, University of Maryland; NASA, National Aeronautics and Space Administration; JRC, European Commission's Joint Research Center; ESA, European Space Agency; ISCGM, International Steering Committee for Global Mapping; FAO UN, Food and Agriculture Organization of the United Nations; CESSC, Centre for Earth System Science China; NASG, National Administration of Surveying, Mapping and Geoinformation.

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

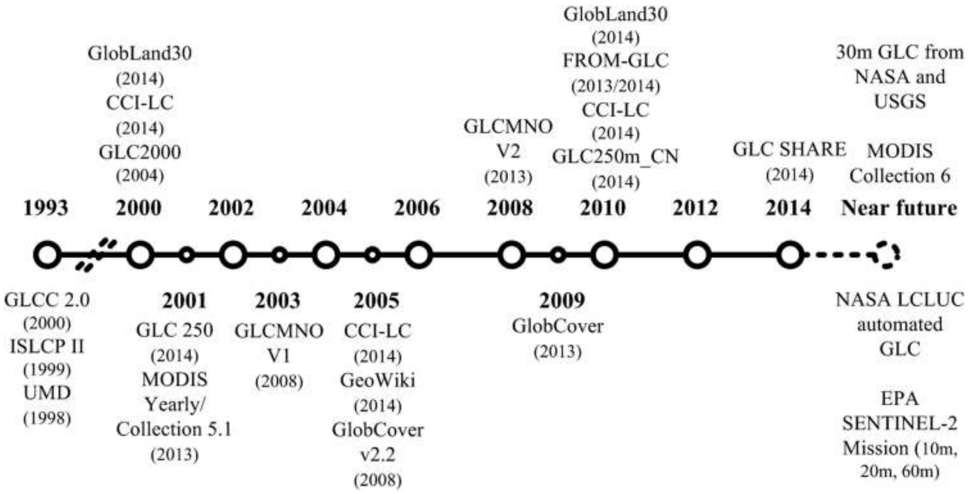

Figure 1. Timeline of GLC products reference year. Public release year in parenthesis. Most current products for the same reference year are listed first. Expected products in the near future are also listed. Further details for future products can be found in the 'Discussion' section.

the same reference year. Finally, products expected to be created in the near future are also listed and further details can be found in the 'Discussion' section (Figure 1).

The GLCC 2.0 has a 1 km spatial resolution with 17 general LC classes, covering the years 1992–1993, and presents a detailed interpretation of the extent of human development with an area-weighted overall accuracy estimated to be 66.9% (Scepan 1999; Loveland et al. 2000). The same product was aggregated later to spatial resolutions of 0.25°, 0.5°, and 1° as a contribution to the ISLSCP initiative II data collection (Loveland et al. 2009).

The MODIS Land Cover Type collection (MCD12Q1) is designed to support research related to the current state and the seasonal to decadal status of global land properties. It contains five classification schemes with the primary being the IGBP, which identifies 17 LC classes at a 500 m spatial resolution and yearly temporal coverage with a 71.6% overall accuracy (Friedl et al. 2010; Friedl and Sulla-Menashe 2011). The University of Maryland developed the UMD GLC product from images acquired between 1992 and 1993 to distinguish 12 classes at 1 km spatial resolution with 65% overall agreement for all classes (Hansen et al. 2000). The GLC 2000 project is based on the Food and Agriculture Organization of the United Nations, Land Cover Classification System (FAO LCCS) at a 1 km spatial resolution for the year 2000 with 23 classes with a 68.6% overall accuracy, focusing on the major ecological systems such as forests, grasslands, and croplands (Bartholomé and Belward 2005). GlobCover is the first produced 300 m GLC map and the 22 classes used are extracted from the FAO LCCS classification system. It covers two periods: December 2004–June 2006 (short name: GlobCover 2005) (73.1% overall accuracy) and January 2009–December 2009 (short name: GlobCover 2009) (67.5% overall accuracy) (Bicheron et al. 2008; Arino et al. 2008; Bontemps et al. 2011).

GLCNMO has published two versions. Version I with 20 classes has a spatial resolution of 1 km based on MODIS data for 2003 and has an overall accuracy of 76.5% (Tateishi et al. 2008, 2011). Version II, also known as GLCMNO2008, has 20

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

classes, with 500 m spatial resolution, based on MODIS data acquired in 2008 with 77.9% overall accuracy (Tateishi et al. 2014). GLC-SHARE was published by FAO United Nations in 2014 and it is the collection of already existing LC information integrated into one harmonized database to create 11 LC classes with an overall accuracy of approximately 80% (Latham et al. 2014).

A different approach in LC mapping is the Geo-Wiki network. It is based on the idea of volunteered geographic information, in which users around the globe validate, based on their personal knowledge, three LC products (GLC 2000, MODIS 2005, GlobCover 2005) (Fritz et al. 2012, 2009). Two hybrid LC maps for the year 2005 have been created based on crowdsourced validation data and geographical weighted regression (GWR) with 82.8% overall accuracy (hybrid map 2) (See et al. 2015). The difference in the production of the two hybrid LC products lies in the way that GWR was applied in the methodological stage.

European Space Agency (ESA) released in 2014 the CCI-LC product at 300 m spatial resolution for three epochs considering the importance of LC as an input in climate modelling (ESA 2014). Validation of the product is under way and change products are available for 2000–2005 and 2005–2010. This is the only product in this spatial resolution producing LC change data sets.

GLC250 m_CN is the only 250 m spatial resolution GLC product and is offered for the nominal years 2001 and 2010 based on annual MODIS data. The overall accuracies are 74.93% for 2001 and 75.17% for the 2010 product (Wang et al. 2015). It also provides change detection estimations for the period 2001–2010.

GLC products have advanced to a 30 m spatial resolution, adding significant land information content. The first 30 m GLC product is the FROM-GLC produced using Landsat images for the nominal year of 2010 (Gong et al. 2013). FROM-GLC has a unique classification system using four supervised classifiers to produce four LC maps with nine classes at the first level of hierarchy and 25 classes at the second level. The maximum overall accuracy of the four LCs is 63.69%. Recognizing product limitations, e.g. low accuracy over LC types relying on information of phenological dynamics (grassland, agriculture), a newer version was developed named FROM-GLC-seg (Yu, Wang, and Gong 2013). Multi-resolution data sets were integrated with the original FROM-GLC, such as MODIS enhanced vegetation index (EVI) time series (250 meter), bioclimatic variables (1 km), and soil-water variables (1 km). Overall accuracy was improved to 64.42%, but small patches were underestimated due to the use of coarser-resolution data. A combined product (aggregated) of FROM-GLC and FROM-GLC-seg led to the FROM-GLC-agr product (Yu, Wang, et al. 2014). The overall accuracy for this new 30 m product has improved compared with the two previous versions (65.51%). This version was further improved using LC information from coarser-resolution data sources leading to a product (FROM-GLC Hierarchy) offered at various spatial resolutions (30 m, 250 m, 500 m, 1 km, 5 km, 25 km, 50 km, and 100 km) to better accommodate specific user needs (Yu, Wang, et al. 2014). Overall accuracies for the first four levels of spatial resolution are 69.50%, 76.65%, 74.65%, and 73.47%, respectively. Finally, the most recent GLC product is the GlobeLand30 (released on September 2014). This product was offered to the United Nations by the Chinese National Administration of Surveying, Mapping and Geoinformation (NASG) at a 30 m resolution product with 10 classes for the years 2000 and 2010 with preliminary validation results for overall accuracy reaching 78.6% and 80.3%, respectively (Chen et al. 2015).

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

3. Continental LC products

For the regional LC products we do not include those that have been produced at the global level and then used for regional analysis, neither those that were fine-tuned per region and then aggregated into a global project. For example, GLC 2000 and GlobCover provide LC for all regions worldwide, with regionally specific legend, to provide as much detail as possible. European LC products are presented in Table 2 and LC products for North America, South America, and Africa are presented in Table 3. Although Oceania and Asia can be covered through the various global LC products, currently no LC products exist solely developed and validated for these areas. Figure 2 depicts the count of various LC products at the regional level for North America, South America, Europe, Africa, Asia, and Oceania. As Asia and Oceania are not covered from regional products, we map national LC products instead, e.g. Russia, India, China, and Australia. National LC products are further analysed in the following section. These countries cover to a large extent these continents and their products offer valuable information. In the same context we also include in this map, LC for Canada, the US, and Brazil due their size and especially for the US and Canada due to the continuous efforts made for accurate and detailed LC mapping through various high-resolution products regularly released.

3.1. Europe

Focusing on the European region, several LC products exist. Coordination of Information on the Environment (CORINE) Land Cover (short name of product, CLC) is the first LC map produced for Europe and is based on photographic interpretation of satellite images for the reference years of 1990, 2000, and 2006 leading to CLC1990, CLC2000, and CLC2006 products, respectively. There are two product spatial resolutions at 100 m and 250 m and there is an explicit product on change between the three time instances (EAA 2007; Buttner et al. 2012a; Buttner and Kosztra 2012b; Buttner et al. 2004; Buttner, Feranec, and Jaffrain 2002; Buttner et al. 1998). The standard CLC scheme includes five classes. The approach of computer-assisted image interpretation allows for a detailed product that covers the 38 EU participating countries. A new CLC2012 has already been published from European Environment Agency (EEA), but has not yet achieved full coverage (almost 50% as of February 2015). The full coverage product is expected in late 2015. A direct product for LC change for the European region is the Corine Land Cover-Change between 1990 and 2000 and between 2000 and 2006 (CLC-Change) (EEA 2013). In fact CLC2006 is the outcome of the integration of the CLC2000 with the CLC-Change2000-2006 product (Buttner and Kosztra 2012b).

A more recent source of LC and land-use data for Europe is the Land Use and Cover Area frame Survey (LUCAS) product. In contrast with the various satellite-derived approaches implemented in other LC products, LUCAS is an *in situ* survey, based on field data and aerial photography in order to gather integrated data and then calculate their changes every three years starting in 2006 (Martino and Fritz 2008; LUCAS 2009, 2013). GlobCorine is another LC product for the European region and is based on the GlobCover data set for the years 2005 and 2009 at 300 m spatial resolution. GlobCorine classification is compatible with the Corine Land Cover (CLC) aggregated typology and the UN LCSS (Defourny et al. 2010a, 2010b). Although GlobCorine has been produced for two time-stamps (2005 and 2009), it is suggested to avoid comparisons, as to some extent GlobCorine 2009 is less detailed than GlobCorine 2005 (Defourny et al. 2010b).

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Table 2. European land-cover products.

Dataset/ product name	Spatial resolution	Overall accuracy (%)	Period of data acquisition	Sensor	Classification scheme-level I	Classification method	Change detection	Creator	Download data URL	Reference paper
CORINE								EEA	http://www.eea.europa.eu/data-and-maps/data#c12=corine+land+cover+version+13	Buttner et al. (1998)
CLC1990	100 m, 250 m	Minimum 85.0 not achieved in most countries.	1986–1998	Landsat 4,5 TM	5 classes	Photographic interpretation				
CLC2000	100 m, 250 m	>85.0 achieved.	1999–2001	Landsat 7 TM	5 classes	Photographic interpretation	Yes			Buttner et al. (2004)
CLC2006	100 m, 250 m	87.8 for the Change Product	2005–2007	SPOT4,5, IRS P6	5 classes	Photographic interpretation	Yes			Buttner et al. (2012a)
CLC2012	100 m, 250 m	Expected to be >85.0	2011–2012	RapidEye, IRS P6, IRS LISS III	5 classes	Photographic interpretation	Yes		Not ready yet. Status athttp://land.copernicus.eu/pan-european/corine-land-cover/clc-2012	Buttner and Kosztra (2012b)
LUCAS						*In situ*:	-	Eurostat	http://epp.eurostat.ec.europa.eu/portal/page/portal/lucas/data	Martino and Fritz (2008)
2006	2 km	70.8	2006	Not used	7 classes	170 000 geo-referenced points	Yes			
2009	2 km	Not available	2009	Not used	8 classes	235 000 geo-referenced points	Yes			LUCAS (2009)
2012	2 km	Not available	2012	Not used	8 classes	270 000 geo-referenced points				LUCAS (2013)
GlobCorine				MERIS FR		Supervised and unsupervised classification	Not recommended	ESA	http://due.esrin.esa.int/prjs/prjs114.php	Defourny et al. (2010a)
GlobCorine 2005	300 m	79.9	2004–2006		14 classes					
GlobCorine 2009	300 m	78.0	2009		14 classes					Defourny et al. (2010b)
PELCOM	1 km	69.2	1995–1999	AVHRR	16 classes	Supervised classification	Not supported	JRC	http://www.geo-informatie.nl/projects/pelcom/public/	Mucher et al. (2000)

Note: EEA, European Environmental Agency.

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Table 3. Continental land-cover products for North and South America and Africa.

Data set/ product name	Spatial resolution	Overall accuracy (%)	Period of data acquisition	Sensor	Classification scheme-level I	Classification method	Change detection	Creator	Download data URL	Reference paper
North America										
NALCMS							Yes	NRCan/CCRS, USGS, INEGI	http://www.cec.org/Page.asp?PageID=924&ContentID=2336	Latifovic et al. (2012)
NALCD 2005	250 m	69.0–85.0	Monthly composites of 2005	MODIS	FAO LCCS 19 classes	Decision classifier tree				
NALCD 2010	250 m	69.0–85.0	Monthly composites of 2010	MODIS	FAO LCCS 19 classes	Decision classifier tree				
South America										
LBA-ECO LC-08	1 km	Not available	1987–1991	AVHRR	41 classes	Visual interpretation	No	WHRC	http://webmap.ornl.gov/wcsdown/dataset.jsp?ds_id=1155	Stone et al. (1994)
MERISAM2009	300 m	Only tropical forest assessed	2009–2010	MERIS	9 classes	Unsupervised	Not supported	JRC	ftp://h05-ftp.jrc.it/evahugh/samericamaps/hojas2009	Gascon et al. (2012)
SERENA	500 m	84.2	2008	MODIS	FAO LCCS 22 classes	Supervised classification	No	Red LaTIF network	http://www.redlatif.org/en/proyectos/	Blanco et al. (2013)
South America 30 m of 2010	30 m	89.0%	2010	Landsat 5TM Landsat 7 ETM+	FAO LCCS 5 classes	Supervised decision classifier tree	Not supported	USGS/ EROS	http://edcftp.cr.usgs.gov/edcuser/lancover/	Giri and Long (2014)
Africa										
AFRICOVER	30 m	80.0%	1995–2002	Landsat TM/ETM+	FAO LCCS 21 classes	Automatic with visual interpretation	Not supported	FAO	Upon request	Di Georgio and Jansen (1996)

Note: NRCan/CCRS, Natural Resources Canada/Canadian Centre for Remote Sensing (NRCan/CCRS); USGS, United States Geological Survey; INEGI, Insituto Nacional de Estadística y Geografía; WHRC, Woods Hole Research Centre; Red LaTIF network, Red Latinoamericana de Teledetecion e Incendios Foresatles.

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Finally, Pan-European Land Cover Monitoring (PELCOM) is a 1 km product with 10 major classes based on AVHRR data spanning from 1995 to 1999 (Mucher et al. 2000).

3.2. North and South America

North American Land Cover Monitoring System (NALCMS) has developed a harmonized multi-scale LC monitoring approach for Canada, USA, and Mexico for the years 2005 and 2010 (short name, NALCD 2005 (North American Land Cover Database), NALCD 2010) at 250 m spatial resolution (Latifovic et al. 2012). The overall accuracy for the product is calculated per country. For both reference years the overall accuracy obtained is 70% for Canada LC, 69% for USA, and 85% for Mexico. A change detection product has also been released for 2005–2010 with the same spatial resolution.

The first LC product for South America covers the period 1987–1991 at a 1 km spatial resolution using 39 LC classes (Stone et al 1994). This product is included in the LBA-ECO LC-08 (Large-Scale Biosphere-Atmosphere Experiment in Amazonia) data set, which also includes soil and vegetation maps for Brazil and is intended for regional-, national-, and sub-national-level LC analyses (Bliss 2013).

MERISAM2009 (MERIS South America) is a product for LC mapping in South America at 300 m spatial resolution for the reference year 2009 (Gascon et al. 2012). Comparison of this product with GLC2000 and MODIS shows good agreement only for the forest LC type.

SERENA (Seguimiento y Estudio de los Recursos Naturales – ‘Latin American Network for Monitoring and Studying of Natural Resources’) is an LC map for South America and Caribbean for the reference year 2008 with 500 m spatial resolution and overall accuracy 84% (Blanco et al. 2013). It has been produced using a similar legend and classification system with the NALCMS LC product for North America, so that a combination of both maps can lead to a consistent coverage across the continent.

The most detailed and recent LC product for South America is provided by US Geological Survey (USGS) called ‘South America 30 m land cover of 2010’ at a 30 m spatial resolution with an overall accuracy of 89% (Giri and Long 2014).

3.3. Africa

AFRICOVER is a project to provide accurate LC information for the whole continent of Africa (Di Georgio and Jansen 1996). Still, currently only East Africa (12 countries participating) has a completed product. Each country develops its own LC product based on common specifications aiming at achieving more than 80% overall accuracy.

4. National LC products

4.1. USA

The Multi-Resolution Land Characteristics (MLRC) consortium develops and maintains a 30 m spatial resolution LC product for the US named National Land Cover Database (NLCD). NLCD provides LC data for 1992 (Vogelmann et al. 2001), 2001 (Homer et al. 2007), 2006 (Fry et al. 2011; Wickham et al. 2013), and 2011 (Jin et al. 2013). Apart from NLCD 1992, which uses the 21-class classification scheme, all others follow a 16-class classification scheme, giving the ability to detect changes and trends across the nation

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Table 4. National LC products for the seven largest area countries of the world.

Country data set/ product name	Spatial resolution	Overall accuracy (%)	Period of data acquisition	Sensor	Classification scheme-level I	Classification method	Change detection	Creator	Download data URL	Reference paper
USA										
NLCD								MLRC		
NLCD 1992	30 m	Validated only for regions and not across the nation.	Early 1990s	Landsat 5TM	Anderson LCCS, 21 classes	Unsupervised	Not supported		http://www.mrlc.gov/nlcd92_data.php	Vogelmann et al. (2001)
NLCD 2001	30 m	79.0	1999–2003	Landsat 5TM Landsat 7 ETM+	Anderson LCCS, 16 classes	Decision classifier tree	Yes. Retrofit product for regional use only.		http://www.mrlc.gov/nlcd01_data.php	Homer et al. (2007)
NLCD 2006	30 m	78.0	1999–2007	Landsat 5TM Landsat 7 ETM+	Anderson LCCS, 16 classes	Decision classifier tree	Yes		http://www.mrlc.gov/nlcd06_data.php	Fry et al. (2011)
NLCD 2011	30 m	Not validated yet	2006, 2011	Landsat 5TM Landsat 7 ETM+	Anderson LCCS, 16 classes	Decision classifier tree	Yes		http://www.mrlc.gov/nlcd11_data.php	Jin et al. (2013)
LCT	60 m	Not available	1973, 1980, 1986, 1992, 2000	Landsat MSS, TM, ETM+	Modified Anderson Level I, 11 classes	Manual interpretation	Yes	USGS	http://landcovertrends.usgs.gov/download/download.html	Loveland et al. (2002)
Canada										
LCC85-05	1 km	62.0	1985–2005	AVHRR	12 classes,	Decision rule	Yes	NRCan	ftp://ftp.ccrs.nrcan.gc.ca/ad/NLCCLandCover/Landcover Canada1985_2005_1 KM/	Latifovic and Pouliot (2005)
LCC05	250 m	70.0	2005	MODIS	12 classes,	Unsupervised classification	No	NRCan	ftp://ftp.ccrs.nrcan.gc.ca/ad/NLCCLandCover/Landcover Canada2005_250 m/	Latifovic, Pouliot, and Olthof (2009)
250 m Canada LC Time Series 2000–2011	250 m	70.0–80.0	2000–2011	MODIS	19 FAO LCCS classes	Decision trees	Yes	NRCan	To be announced at: https://neodf.nrcan.gc.ca/neodf_cat3/index.php?lang=en	Pouliot et al. (2014)

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

20 m Canada LC 2005–2010	20 m	71.0	2005–2010	SPOT4/5	16 classes	Enhancement classification and classification by progressive	generalization methods	No	NRCan	https://neodf.nrcan.gc.ca/neodf_cat3/index.php?lang=en
Olthof, Latifovic, and Pouliot (2015)										
Brazil										
LC Brazil	1:250.000 and 1:100.000	Not available	Various years	Landsat 5TM	5 classes	Supervised classification	Not supported	IBGE	ftp://geoftp.ibge.gov.br/mapas_tematicos/uso_da_terra/	IBGE (2013)
LULC Brazil	250 m	Not available yet	2000, 2010	MODIS	9 classes	Unsupervised classification	Yes	NISR	Not available	Macedo et al. (2013)
India										
LULC 1:250 k	1:250.000	90.0	Yearly since 2004	AWiFS	18–19 classes depending on year	Different approaches through years	Not recommended	NRSC	http://bhuvan.nrsc.gov.in/gis/thematic/index.php	NRSA (2006)
LULC 1:50 k 2005–2006	1:50.000	Varying from 79.0 to 97.0	2005–2006	Resource-sat1, LISS III	9 classes	On-screen visual interpretation	Not supported	NRSC	http://bhuvan.nrsc.gov.in/gis/thematic/index.php	NRSC (2006)
2011–2012	1:50.000	Varying from 79.0 to 97.0	2011–2012	Resource-sat2, LISS III	8 classes	On-screen visual interpretation	Not supported	NRSC	http://bhuvan.nrsc.gov.in/gis/thematic/index.php	NRSC (2014)
Australia										
DLCD	250 m	65.0 exact or very similar match	2000–2008	MODIS	6 ISO classes	Support Vector Clustering	Yes	NEOG	http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_71071	Lymburner et al. (2011)
China										
NLUD-C	30 m	92.9	1987–1990	Landsat TM/ETM+	6 classes	Hierarchical classification	Yes	CAS	http://www.resdc.cn/Default.aspx	Deng and Liu (2012)
	30 m	98.7	1995–1996				Yes			
	30 m	97.6	1999–2000				Yes			Zhang, Liang, et al. (2014)
	30 m	95.0	2004–2005				Yes			
	30 m	98.6	2005–2008				Yes			
	30 m	97.2	2008–2010							

(Continued)

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Table 4. (*Continued*).

Country data set/ product name	Spatial resolution	Overall accuracy (%)	Period of data acquisition	Sensor	Classification scheme-level I	Classification method	Change detection	Creator	Download data URL	Reference paper
LC China with CBEST	30 m	71.7	2007–2010	Landsat TM	9 classes	Unsupervised classification	Not supported	Not available.		Hu et al. (2014)
Russia										
HLCR	1 km	98.0	Nov 1999–Dec 2000	SPOT4 Vegetation	8 classes	Decision rules	Not supported	IIASA	Upon request from: http://www.iiasa.ac.at/web/home/research/researchPrograms/EcosystemsServicesandManagement/Hybrid-Land-Cover-of-Russia..en.html	Schepaschenko et al. (2011)
RLC	15 km	Not validated	1984–1993	AVHRR	14	Unsupervised	No	ORNL-DAAC	http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=689	Stone, Houghton, and Schlesinger (2000)

Note: MLRC, Multi-Resolution Land Characteristics Consortium; NRCan/CCRS, Natural Resources Canada/Canadian Centre for Remote Sensing; IBGE, Instituto Brasileiro de Geografia e Estatistica; NISR, National Institution of Spatial Research of Brazil; NRSC, National Remote Sensing Centre of India; NEOG, National Earth Observation Group; CAS, Chinese Academy of Sciences; IIASA, International Institute for Applied Spatial Analysis; ORNL DAAC, Oak Ridge National Laboratory Distributed Active Archive Center; CBEST, Clustering by Eigen Space Transformation.

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

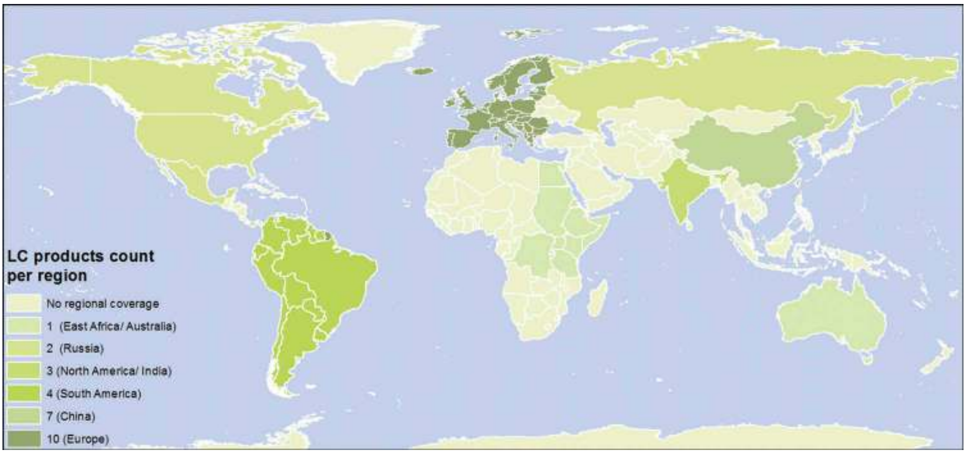

Figure 2. Regional LC products count by location. Names of LC products per region along with the reference year in parenthesis are also included. Europe, China, and the USA offer a plethora of LC products for multiple reference years especially during the decade 2000–2010. Asia and Africa do not have a complete regional product solely developed for these regions. East Africa is only covered from Africover and Asia is covered sparsely by national efforts.

after 2001. An LC change product also exists for 1992–2001 called Retrofit, but it is recommended for regional rather than local use (Fry et al. 2009).

Land Cover Trends (LCT) is a project created by the USGS offering LC change information for the following intervals: 1973–1980, 1980–1986, 1986–1992, 1992–2000, and for the entire study period (1973–2000) at a spatial resolution of 60 m (Loveland et al. 1999, 2002). The data set was created using a statistical sampling approach based on the manual interpretation of Landsat images.

4.2. Canada

The LC map of Canada (LCC85-05) is a time-series product spanning from 1985 to 2005 at a five year step from 1 km AVHRR data and has been developed to fully cover Canada (Latifovic and Pouliot 2005). Classification took place based on three LC legends: (1) 31 classes; (2) aggregated versions of the 31 classes to 12 classes; and (3) the 16 IGBP classes. The overall accuracy of the 12 classes was 62%. An LC product was also developed for 2005 named Land Cover Map of Canada (LCC05) at 250 m spatial resolution with improved accuracy reaching 70% based on MODIS data (Latifovic, Pouliot, and Olthof 2009). The 39 classes were derived from the Federal Geographic Data Committee/Vegetation Classification Standard (FGDC/NVCS) modified for use in Canada and the IGBP LC legends. A 250 m LC time series based on annual MODIS data from 2000 to 2011 with an accuracy of 70% at the 19-class thematic resolution was recently released (Pouliot et al. 2014). This product allows for change estimation in space and time at this temporal frequency and spatial extent for Canada for the first time (Pouliot et al. 2014). Still, the above-mentioned products lack the spatial detail required in most of today's applications. A 20 m LC product of Canada (forested regions – south of treeline) based on SPOT satellite data with 16 classes for the period 2005–2010 was released in early 2015 with an overall accuracy of 71% (Olthof, Latifovic, and Pouliot 2015). This product was then merged with a 30 m circa-2000 LC covering northern

Canada (north of treeline) (Olthof, Latifovic, and Pouliot 2009). This led to updated LC information for Canada with 20 classes with improved spatial resolution (Olthof, Latifovic, and Pouliot 2015).

4.3. Brazil

The Instituto Brazileiro de Geografia e Estatistica (IBGE) creates and updates the classification of land use and cover for the nation at 1:250.000 and 1:100.000 scales, respectively. LC maps are produced by interpreting satellite images and analysing information from field works, agricultural typology, and available ancillary documents and data (IBGE 2013). Currently available is the third edition of LC mapping for Brazil using five classes at the first level. Another product maps LULC of Brazil for 2000 and 2010 at 250 m spatial resolution (Macedo et al. 2013).

4.4. India

The National Remote Sensing Centre (NRSC, former National Remote Sensing Agency) of India has developed a rich LULC database for the entire nation. A yearly product starting from 2004–2005 is offered on a 1:250.000 scale using multi-temporal Advanced Wide Field Sensor (AWiFS) data sets having completed to date nine cycles until the year 2012–2013 (NRSA 2006; NRSC 2013). Two other products at a larger scale exist (1:50.000) for the years 2005–2006 and 2011–2012, also created by NRSC (NRSC 2006, 2013). Data are provided per region and the overall accuracy of different LULC classes spans from 79% to 97%.

4.5. Australia

The Dynamic Land Cover Dataset version 1 (DLCDv1) product provides LC information as well as trends and changes in LC across Australia for the period 2000–2008 (Lymburner et al. 2011). DLCDv1 is a 250 m spatial resolution product and is the first nationally consistent and accurate LC data set (Lymburner et al. 2011). The accuracy of the product was determined by the relative similarity score for all 25.817 field survey points. Almost 65% of these sampled points were exact or were a very similar match. A second version of the product covering the period 2000–2012 is under way (Lymburner et al. 2013).

4.6. China

China is the only country having various products at a 30 m spatial resolution available for change detection. For example, the National LC database of China (NLUD-C) product at a 30 m spatial resolution covers five different periods from 1987 to 2008. It is updated roughly every three to five years, allowing the ability for change detection analysis at a very detailed level with an overall accuracy ranging from 92.9% to 97.6% (Deng and Liu 2012). An update for 2010 based on the 2008 LC map is also available (Zhang et al. 2014). The most recent LC product for China at 30 m spatial resolution was published in 2014 using the CBEST clustering algorithm; it reached an overall accuracy of 71.7% (Hu et al. 2014). Comparisons between the two global LC products (FORM-GLC and GlobCover 2009) indicate better results in both classification and land-type area estimation.

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

4.7. *Russia*

Russia covers almost one-sixth of the world's land area. The Hybrid Land Cover of Russia (HLCR) is an LC data set for Russia, at 1 km spatial resolution based on the CLC 2000 data set (Schepaschenko et al. 2011). The product is based on the integration of all relevant information to explore synergies in different LC inventories and *in situ* observations. The product is updated for the reference year 2009. Russian Land Cover (RLC) is another LC product for Russia (Former Soviet Union) at 15 km spatial resolution with 14 LC classes and is useful mainly for stratification into general subregions along with using higher-resolution satellite data (Stone, Houghton, and Schlesinger 2000).

5. Discussion and future trends

This review illustrates the wide range of current LC products along with a lack of consensus in LC mapping from the operational point of view, especially at the global scale. Whereas the value for LC information is widely acknowledged, there are several limitations in current GLC and regional LC products: use of moderate to coarse spatial resolutions imagery, use of different acquisition input data, inconsistencies in the classification schemes, location-dependent accuracy performance, lack of independent and reliable validation data sets, and limited ability to compare LC products (Table 5).

The use of 30 m resolution imagery has only recently led to the release of two GLC products (GlobeLand30 and FROM-GLC, Table 1). Other GLC products have a spatial resolution starting at 250 m. At the regional level only the USA, Canada, China, South America, and East Africa contain 30 m LC products. Although for some applications spatial resolutions lower than 250 m would work, numerous applications require higher-resolution products. For example, moderate to coarse spatial resolution imagery for the classification of tree species is normally inappropriate (Foody, Warner, and Nellis 2009). Similarly, urban expansion patches or new roads development may be missed in large pixel sizes.

In addition, a significant limitation of the existing products lies in the different acquisition of the input data leading to products with different timestamps. The lack of multi-temporal consistency and the single-year usage of LC data may prove problematic for some LC types (Broxton et al. 2014). The accuracy differences that result from different types of data used are sometimes larger compared with the accuracy differences due to algorithmic selection and classification methods (Yu, Liang, et al. 2014).

One of the most intriguing inconsistencies lies in the classification schemas. Different schemas, stemming from the particular needs for each product, translate into different definitions of class boundaries. This problem is exacerbated in transitional zones where landscape heterogeneity exists. Yu, Liang, et al. (2014), after a thorough meta-analysis of 6771 peer-reviewed papers related to LC mapping and classification, concluded that the complexity of a classification system decreases its mapping accuracy. Problems also arise in the representation of a category in a classification scheme and semantics and ontologies should be further developed to address category heterogeneity (Kavouras, Kokla, and Tomai 2005). Semantics interoperability is crucial considering the fact that LC data sets are used for multidisciplinary research activities from different users/applications.

Another limitation of existing LC products is the low overall accuracies achieved and their high variability over different areas. For example, GLC overall accuracies rarely reach 80%. It is not unusual for overall accuracy estimates to get significantly smaller when these data sets are independently validated, reaching accuracies ranging from 10%

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

to 50% (Zhao et al. 2014; Gong 2009; Strahler et al. 2006). These low accuracies make change detection analysis problematic and comparison between different LC products difficult (Congalton et al. 2014; Bai et al. 2014; Giri et al. 2011; Herold et al. 2008; Jung et al. 2006; Defourny et al. 2012; Herold et al. 2008). Still, there is a limited data set of independent well-distributed validation and reference data sets (Tsendbazar, Bruin, and Herold 2015; Zhao et al. 2014).

One of the main challenges in the development of GLC products is to be locally relevant and at the same time globally consistent (Hansen et al. 2014). Still, the existing GLC and regional LC product uncertainties may result in considerable differences in external modelling outcomes (Mora et al. 2014). The choice of GLC product may influence model results by as much as 45% (Benitez et al. 2004). For example, the comparison between GlobCover 2005 and GlobCover 2009 and the comparison between GlobCorine 2005 and GlobCorine 2009 revealed disagreements between products (Defourny et al. 2012). As a result, from the user perspective it is not always clear which product should be used and why (Herold et al. 2008).

In response to the above needs, several international programmes and panels, such as the International Geosphere Biosphere Program (IGBP), the Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD), the Committee on Earth Observations Satellites (CEOS), the Group on Earth Observations (GEO), the UN Global Land Cover Network (GLCN), and the Land Cover Land Use Change (LCLUC) from US National Aeronautics and Space Administration (NASA), highlight the need for more consistent LC information, and activities are driven by harmonization initiatives. Harmonization is the procedure taken to improve the consistency, comparability, and compatibility of LC products by identifying and reducing differences on the one hand and enhancing similarities in land characterization definitions on the other.

Based on our review we present the following harmonization recommendations (Table 5).

(1) Development of products in finer spatial and temporal resolution. To better manage the increased accuracy and higher relevance/immediacy needs, research should move to annual products at resolutions between 250 m and 1 km, and products between 10 m and 30 m at least every five years, *in situ* observations for LC validation (Townshend et al. 2011; Lunetta et al. 2006). Using fine-resolution data sets will also help in better LC characterization in heterogeneous and mixed areas, which is now a significant problem in accurate classification results and in spatial agreements' comparison among different LC products (Herold et al. 2008). Currently, only three GLC products provide LC change data sets (CCI-LC, FROM-GLC, and GlobeLand30).

(2) Consistent definition of classification schemes. LC products should also use universally accepted LC classification systems (Townshend et al. 2011). According to Congalton et al. (2014) the selection of the classification scheme should be done in the beginning of each project and should take into consideration previous schemes if products already exist and determine clear class definitions. The FAO of the United Nations has developed the only universally applicable classification system called LC classification system – LCCS (Di Gregorio and Jansen 2005). This system allows the dynamic creation of classes and is independent of the mapping scale (Mora et al. 2014).

(3) Improved collection of validation data sets. Proper selection of validation data sets could lead to high-quality reference data sets (Manakos and Lavender 2014)

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Table 5. Summarizing the basic limitations of existing LC products along with the problems they infer from the technical and policy perspective.

Basic limitations of existing LC products	Problems	Suggestions	Basic benefits	Major efforts currently made
Technical Level				
Moderate to coarse resolution	Misclassifications, change detection not accurate	Develop LC in finer spatial resolution	More detailed analysis, e.g. urban expansion more easily detected	CCI-LC, FROM-GLC, GlobeLand30 all at 30 m spatial resolution
Different classification schemes	Makes direct comparison extremely difficult	Use universally accepted land-cover classification systems. Select scheme in the beginning	Flexible use at different scales and purposes. Comparison of LC classes can be made regardless of data source	FAO LCCS v3
Poor validation data sets	Low overall accuracies. Change detection problematic	Develop/use independent proper validation data sets. Use very-high-resolution images and or volunteered GIS. Increase reusability	Increase accuracy in world representation. Guide users to the most appropriate data set	CEOS, GOFC-GOLD, Boston University, GEO-Wiki
Policy Level				
Limited harmonization	Low consistency and comparability. Technical details not always open	Produce thematic layers in a standardized and homogenized way. Offer open and free data	Increase in interoperability and inter-comparability. Increase in usability from non-experts	GEO, GOFC-GOLD
Ensure continuity in LC monitoring	Gaps in Earth observation monitoring	Initiatives must be taken	Secure Earth observation data supply flow for the years to come	Landsat data continuity mission (LDCM, Kopernicus, SPOT)
Low frequency on revisit time period	Limited abilities for day-to-day observation for LC monitoring	Satellites for consistent coverage carrying multiple sensors. Interoperability among data sources from different sensors	Day-by-day monitoring, imagery in many different spatial resolutions. Increased capacity for time series analysis	ESA-Sentinel ORFEO-Pleiades NASA USGS-Landsat

Note: Suggestions, benefits as well as current major efforts from international programmes and organizations are also provided.

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

and the adoption of validation protocols is more than essential (Hansen and Loveland 2012). There is a need for further international coordination to increase publically available reference data sets and make easier their reusability by guiding users to the most appropriate data set according to their specific needs (Tsendbazar, Bruin, and Herold 2015). LC validation should be based on *in situ* observations and ancillary data should be used to improve accuracy assessments (Congalton et al. 2014; Townshend et al. 2011). LC validation can also benefit from volunteered geographic information and the use of crowd sourcing through web validation tools (Fritz et al. 2009). With the advent of very-high-resolution images, publicly available (e.g. Google Earth) or even acquired by the public (e.g. using inexpensive drones), traditional approaches can be supplemented and take advantage of the eagerness of citizens to participate in geographically related projects and thus offer up-to-date information for LC analysis.

(4) Improved communication of product limitations. It is typical that accuracy assessment is provided in aggregated summaries, such as an error matrix. Although such assessments provide a basic step towards understanding product limitations, their lack of spatial specificity constrains applicability and/or creates improper use by non-experts. There is an inherent obligation of the remote-sensing community to develop pixel-based accuracy metrics, especially for large heterogeneous landscapes. Furthermore, it is essential to communicate not only accuracy metrics but also their confidence, in other words how trustworthy are the accuracy metrics produced. An early approach has been proposed that complements accuracy metrics with confidence metrics by considering similarity in the classification input space of validation and to-be-classified data sets (Mountrakis and Xi 2013).

Future LC projects are currently under way. Researchers from NASA, USGS EROS (Earth Resources Observation and Science), University of Maryland, State University of New York, and other collaborators embraced the US GEO Global Land Cover Initiative announced during the Beijing GEO summit in 2010 to: (1) develop a 30 m GLC for the 2000–2010 period based on Landsat data; (2) update this LC product every 1, 2, and 5 years and create LCC products for these periods; (3) improve 30 m availability data; and (4) develop LCC time-series since 1970 (Giri et al. 2013). This project will lead to the first product at very high resolution with an up-to-date LCC database, offering the means for reliable LCC analysis starting from the early 1970s. Furthermore, the Joint Research Centre of the European Commission is finalizing the Global Human Settlement Layer (GHSL) using Landsat data that would support comparison from the years of 1975, 1990, 2000, and 2014. The NASA MODIS science team is planning the release of its 6th version (C6) of the yearly GLC product within 2015. In addition, NASA also supports the Land Cover/Land Use Change (LCLUC) Program, which addresses societal linkages with land processes. LCLUC is also supporting research to create an automated GLC mapping from calibrated satellite data (Gutman, Justice, and King 2012). European Environmental Protection Agency is due to publish Corine LC for the year 2012 and Corine LC changes since 2006 for 39 European countries, in 2015. In the North America region, NALCMS is currently preparing an annual 250 m LCC, with prospects for products being offered at the 30 m scale.

Efforts should also be directed towards strategic missions of satellites for consistent coverage, with long-term planning, carrying multiple sensors and producing finer-scale images (Mora et al. 2014). For example, ESA is developing Sentinel-2 mission (first satellite launched in 2014) that will provide imagery in 10 m, 20 m, and 60 m spatial resolution for the next generation of LC maps and land-change detection maps. The French-Italian ORFEO programme (Optical & Radar Federated Earth Observation) has recently launched the Pleiades constellation (launched in 2012 and 2013) providing very-high-resolution images and daily revisits to any point on the globe. The integration of existing Earth observation systems with new sensors on constellations ordinance will offer much richer information. In addition, taking into account the expected rich time series data repository that will be created from new satellite constellations along with older ones such as Landsat, change detection at the global and regional scales will be more easily facilitated. According to Giri et al. (2013), currently the challenge is to extract useful information from vast volumes of satellite and ancillary data along with the technology to easily handle and process them.

To conclude, we suggest that a protocol for systematic development, updating, and assessment of future LC products should be prioritized on the scientific agenda through international collaboration. As remote-sensing data are becoming cheaper and easier to use, LC products will increase in value to the scientific community and the broader society, prompting more researchers to use LC maps for a wide variety of purposes. Remote sensing is often the only technology available to understand large-scale environmental dynamics; satellite images not only increase our current understanding but also allow the creation of a permanent record for a wide range of future applications. It is an investment with very high return.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the State Scholarships Foundation of Greece (IKY) under Grant [SR 22032/13], IKY Fellowships of excellence for postgraduate studies in Greece-Siemens Program. Dr Mountrakis' research was partially supported by the National Aeronautics and Space Administration through a New Investigator Award [# NNX08AR11G].

References

Arino, O., P. Bicheron, F. Achard, J. Latham, R. Witt, and J. L. Weber. 2008. "GLOBCOVER the Most Detailed Portrait of Earth." *ESA Bulletin-European Space Agency* 136: 24−31.

Bai, Y., M. Feng, H. Jiang, J. Wang, Y. Zhu, and Y. Liu. 2014. "Assessing Consistency of Five Global Land Cover Data Sets in China." *Remote Sensing* 6: 8739–8759, doi:10.3390/rs6098739.

Bartholomé, E., and A. S. Belward. 2005. "GLC2000: A New Approach to Global Land Cover Mapping from Earth Observation Data." *International Journal of Remote Sensing* 26: 1959–1977. doi:10.1080/01431160412331291297.

Benitez, P., I. McCallum, M. Obersteiner, and Y. Yamagata. 2004. "Global Supply for Carbon Sequestration: Identifying Least-Cost Afforestation Sites under Country Risk Consideration." *IIASA Interim Report*. Austria. Accessed June 20, 2014. http://webarchive.iiasa.ac.at/Admin/PUB/Documents/IR-04-022.pdf

Bicheron, P., P. Defourny, C. Brockmann, L. Schouten, C. Vancutsem, M. Huc, S. Bontemps, M. Leroy, F. Achard, M. Herold, F. Ranera, and O. Arino. 2008. *Globcover. Products Description and Validation Report*. Accessed February 20, 2014. http://due.esrin.esa.int/globcover/LandCover_V2.2/GLOBCOVER_Products_Description_Validation_Report_I2.1.pdf

Blanco, P. D., R. R. Colditz, L. G. Saldaña, L. A. Hardtke, R. M. Llamas, N. A. Mari, A. Fischer, C. Caride, P. G. Aceñolaza, H. F. Del Valle, M. Lillo-Saavedra, F. Coronato, S. A. Opazo, F.

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Morelli, J. A. Anaya, W. F. Sione, P. Zamboni, and V. B. Arroyo 2013. "A Land Cover Map of Latin America and the Caribbean in the Framework of the SERENA Project." *Remote Sensing of Environment* 132: 13–31. doi:10.1016/j.rse.2012.12.025.

Bliss, N. 2013. *LBA-ECO LC-08 Soil, Vegetation, and Land Cover Maps for Brazil and South America*. Data set available online (http://daac.ornl.gov) from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge. http://dx.doi.org/10.3334/ORNLDAAC/1155.

Bontemps, S., P. Defourny, E. Bogaert, O. Arino, V. Kalogirou, and J. Perez. 2011. *Globcover 2009. Products Description and Validation Reports*. Accessed February 20, 2014. http://due.esrin.esa.int/globcover/LandCover2009/GLOBCOVER2009_Validation_Report_ 2.2.pdf

Broxton, P., X. Zeng, D. Sulla-Menashe, and P. Troch. 2014. "A Global Land Cover Climatology Using MODIS Data." *Journal Applications Meteor Climatology* 53: 1593–1605. doi:10.1175/JAMC-D-13-0270.1.

Buttner, G., et al. 1998. "The European CORINE Land Cover Database." In *Proceedings of ISPRS Commission VII Symposium*, Budapest, September 1–4, 633–638.

Buttner, G., G. Feranec, and G. Jaffrain. 2002. *Corine landcover update 2000, Technical guidelines*. EEA Technical report No 89. Accessed February 20, 2014. http://reports.eea.europa.eu/technical_report_2002_89/en

Buttner, G., J. Feranec, G. Jaffrain, L. Mari, G. Maucha, and T. Soukup. 2004. "The CORINE Land Cover 2000 Project." In *eProceedings of EARSeL*, March 3 2004, 331–346. http://las.physik.uni-oldenburg.de/eProceedings/

Buttner, G., B. Kosztra, G. Maucha, and R. Pataki. 2012a. "Implementation and achievements of CLC2006." *Report of European Environment Agency*. Accessed February 25, 2014. http://www.eea.europa.eu/data-and-maps/data/corine-land-cover#tab-documents

Buttner, G., and B. Kosztra. 2012b. *CLC2012 Addendum to CLC2006 Technical Guidelines*. Accessed September 25, 2014. http://gamta.lt/files/Addendum_finaldraft.pdf

Chen, J., J. Chen, A. Liao, X. Cao, L. Chen, X. Chen, C. He, G. Han, S. Peng, M. Lu, W. Zhang, X. Tong, and J. Mills. 2015. "Global Land Cover Mapping at 30 M Resolution: A Pok-Based Operational Approach." *ISPRS Journal of Photogrammetry and Remote Sensing* 103: 7–27. doi:10.1016/j.isprsjprs.2014.09.002.

Congalton, G. R., J. Gu, K. Yadav, P. Thenkabail, and M. Ozdogan. 2014. "Global Land Cover Mapping: A Review and Uncertainty Analysis." *Remote Sensing* 6: 12070–12093, doi:10.3390/rs61212070.

Defourny, P., S. Bontemps, E. Bogaert, J. Weber, W. Luis, and T. Soukup. 2010a. *GlobCorine validation report*. Accessed February 20, 2014. http://due.esrin.esa.int/files/p114/GLOBCORINE_VR_2.1_20100406.pdf

Defourny, P., S. Bontemps, E. Bogaert, J. Weber, C. Steenmans, and L. Brodsky.2010b. *GlobCorine 2009. Description and validation report*. Accessed February 20, 2014. http://due.esrin.esa.int/files/p114/GLOBCORINE2009_DVR_2.1.pdf

Defourny, P., P. Mayaux, M. Herold, and S. Bontemps. 2012. "Global Land Cover Map Validation Experiences: Toward the Characterization of Uncertainty." In *Remote Sensing of Land Use and Land Cover: Principles and Applications*, edited by C. P. Giri, vol. 8, 207–223. Boca Raton, FL: CRC Press.

DeFries, R. S., G. P. Asner, and R. A. Houghton. (eds) 2004. *Ecosystems and Land Use Change. Geophysical Monograph 153*. Washington, DC: American Geophysical Union.

Deng, X., and J. Liu. 2012. "Mapping Land Cover and Land Use Changes in China." In *Remote Sensing of Land Use and Land Cover: Principles and Applications*, edited by C. P. Giri, vol. 8, 339–349. Boca Raton, FL: CRC Press.

Di Georgio, A., and L. J. M. Jansen. 1996. "Part I: Technical documentation on the Africover Land Cover Classification Scheme (pp. 4–33, 63–76), in FAO (1997). Africover Land Cover Classification.

Di Gregorio, A., and L. Jansen. 2005. *Land Cover Classification System*. Report. Accessed June 12, 2014. http://www.glcn.org/downs/pub/docs/manuals/lccs/LCCS2-manual_en.pdf

EEA-European Environment Agency. 2007. "CLC2006 Technical Guidelines." *EEA Technical Report No. 17/2007 ISSN 1725–2237*. Accessed February 20, 2014. http://www.eea.europa.eu/publications/technical_report_2007_17

EEA-European Environmental Agency. 2013. *Changes in the European Land Cover Form 2000 to 2006*. Accessed February 25, 2014. http://www.eea.europa.eu/data-and-maps/figures/land-cover-2006-and-changes-1

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Ellis, E., and R. Pontius. 2007. "Land-Use and Land-Cover Change." In *Encyclopedia of Earth*, edited by C. J. Cleveland. Washington, DC: Environmental Information Coalition, National Council for Science and the Environment. Accessed September 28, 2014. http://www.eoearth.org/article/Land-use_and_land-cover_change.

ESA. 2014. *CCI-LC Product User Guide v2.4*. Accessed October 10, 2014. http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-PUG-v2.4.pdf

Feddema, J. J. 2005. "The Importance of Land-Cover Change in Simulating Future Climates." *Science* 310: 1674–1678. doi:10.1126/science.1118160.

Feranec, J., G. Hazeu, S. Christensen, and G. Jaffrain. 2007. "Corine Land Cover Change Detection in Europe (Case Studies of the Netherlands and Slovakia)." *Land Use Policy* 24: 234–247. doi:10.1016/j.landusepol.2006.02.002.

Foody, M. G., A. T. Warner, and M. D. Nellis. 2009. "A Look to the Future." In *The SAGE Handbook of Remote Sensing*, edited by M. G. Foody, A. T. Warner, and M. D. Nellis, 475–481. London: Sage.

Friedl, M. A., and D. Sulla-Menashe. 2011. *Note To Users of Modis Land Cover* (MCD12Q1) *Products*. Report. Accessed March 2, 2014. http://landweb.nascom.nasa.gov/QA_WWW/forPage/C51_LC.pdf

Friedl, M. A., D. Sulla-Menashe, B. Tan, A. Schneider, N. Ramankutty, A. Sibley, and X. M. Huang. 2010. "MODIS Collection 5 Global Land Cover: Algorithm Refinements and Characterization of New Datasets." *Remote Sensing of Environment* 114 (1): 168–182 doi:10.1016/j.rse.2009.08.016.

Fritz, S., I. McCallum, C. Schill, C. Perger, R. Grillmayer, F. Achard, F. Kraxner, and M. Obersteiner. 2009. "Geo-Wiki.Org: The Use of Crowdsourcing to Improve Global Land Cover." *Remote Sensing* 1: 345–354, doi:10.3390/rs1030345.

Fritz, S., I. McCallum, C. Schill, C. Perger, L. See, D. Schepaschenko, M. Velde, F. Kraxner, and M. Obersteiner. 2012. "Geo-Wiki: An Online Platform for Improving Global Land Cover." *Environmental Modelling and Software* 31: 110–123. doi:10.1016/j.envsoft.2011.11.015.

Fry, J. A., M. J. Coan, C. Homer, D. K. Meyer, and J. D. Wickham. 2009. *Completion of the National Land Cover Database* (NLCD) *1992–2001 Land Cover Change Retrofit product: U.S. Geological Survey Open-File Report 2008-1379*, 18 p. Accessed June 20, 2014. http://pubs.usgs.gov/of/2008/1379/

Fry, J. A., G. Xian, S. Jin, J. Dewitz, C. Homer, L. Yang, C. Barnes, N. Herold, and J. Wickham. 2011. "Completion of the 2006 National Land Cover Database for the Conterminous United States." *Pe&Rs* 77(9): 858–864.

Gascon, L. H., H. D. Eva, N. Gobron, D. Simonetti, and S. Fritz. 2012. "The Application of Medium-Resolution MERIS Satellite Data for Continental Land-Cover Mapping over South America: Results and Caveats." In *Remote Sensing of Land Use and Land Cover: Principles and Applications*, edited by C. P. Giri, vol. 8, 325–337. Boca Raton, FL: CRC Press.

Giri, C., and J. Long 2014. "Land Cover Characterization and Mapping of South America for the Year 2010 Using Landsat 30 m Satellite Data." *Remote Sensing* 6 (10): 9494–9510. doi:10.3390/rs6109494.

Giri, C., B. Pengra, J. Long, and T. R. Loveland. 2013. "Next Generation of Global Land Cover Characterization, Mapping, and Monitoring." *International Journal of Applied Earth Observation and Geoinformation* 25: 30–37. doi:10.1016/j.jag.2013.03.005.

Giri, C. P. 2012. "Brief Overview of Remote Sensing of Land Cover." In *Remote Sensing of Land Use and Land Cover: Principles and Applications*, edited by C. P. Giri, vol. 8, p. 1. Boca Raton, FL: CRC Press.

Giri, C. P., E. Ochieng, L. L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. 2011. "Status and Distribution of Mangrove Forests of the World Using Earth Observation Satellite Data." *Global Ecology and Biogeography* 20: 154–159. doi:10.1111/geb.2011.20.issue-1.

Gong, P. 2009. "Some Frontier Questions in Remote Sensing Science and Technology." *Journal of Remote Sensing* 13 (1): 16–28.

Gong, P., J. Wang, L. Yu, Y. Zhao, Y. Zhao, L. Liang, Z. Niu, X. Huang, H. Fu, S. Liu, C. Li, X. Li, W. Fu, C. Liu, Y. Xu, X. Wang, Q. Cheng, L. Hu, W. Yao, H. Zhang, P. Zhu, Z. Zhao, H. Zhang, Y. Zheng, L. Ji, Y. Zhang, H. Chen, A. Yan, J. Guo, L. Yu, L. Wang, X. Liu, T. Shi, M. Zhu, Y. Chen, G. Yang, P. Tang, B. Xu, C. Giri, N. Clinton, Z. Zhu, J. Chen, and J. Chen 2013. "Finer Resolution Observation and Monitoring of Global Land Cover: First Mapping Results with

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Landsat TM and ETM+ Data." *International Journal of Remote Sensing* 34: 2607–2654. doi:10.1080/01431161.2012.748992.

Grekousis, G., and G. Mountrakis 2015. "Sustainable Development under Population Pressure: Lessons from Developed Land Consumption in the Conterminous US." *PLoS ONE* 10(3): e0119675. doi:10.1371/journal.pone.0119675.

Grekousis, G., M. Kavouras, and G. Mountrakis 2015. "Land Cover Dynamics and Accounts for European Union 2011-2011." Third International Conference on Remote Sensing and Geoinformation (RSCy2015). Proceedings of SPIE, Vol. 9535, 953507, doi:10.1117/12.2192554.

Gutman, G., C. Justice, and L. King. 2012. "The NASA Land Cover and Land-Use Program Research Agenda and Progress (2005–2011)." In *Remote Sensing of Land Use and Land Cover: Principles and Applications*, edited by C. P. Giri, vol. 8, 379–396. Boca Raton, FL: CRC Press.

Hansen, M., R. DeFries, J. Townshend, and R. Sohlberg. 2000. "Global Land Cover Classification at 1 km Spatial Resolution Using a Classification Tree Approach." *International Journal of Remote Sensing* 21: 1331–1364. doi:10.1080/014311600210209.

Hansen, M. C., A. Egorov, P. V. Potapov, S. V. Stehman, A. Tyukavina, S. A. Turubanova, D. P. Roy, S. J. Goetz, T. R. Loveland, J. Ju, A. Kommareddy, V. Kovalskyy, C. Forsyth, and T. Bents 2014. "Monitoring Conterminous United States (CONUS) Land Cover Change with Web-Enabled Landsat Data (WELD)." *Remote Sensing of Environment* 140: 466–484. doi:10.1016/j.rse.2013.08.014.

Hansen, M. C., and T. Loveland. 2012. "A Review of Large Area Monitoring of Land Cover Change Using Landsat Data." *Remote Sensing of Environment* 122: 66–74. doi:10.1016/j.rse.2011.08.024.

Herold, M., P. Mayaux, C. Woodcock, A. Baccini, and C. Schmullius. 2008. "Some Challenges in Global Land Cover Mapping: An Assessment of Agreement and Accuracy in Existing 1 km Datasets." *Remote Sensing of Environment*. 112: 2538–2556. doi:10.1016/j.rse.2007.11.013.

Homer, C., J. Dewitz, J. Fry, M. Coan, M. N. Hossain, C. Larson, N. Herold, A. McKerrow, J. VanDriel, and J. Wickham. 2007. Completion of the 2001 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering and Remote Sensing* 73: 337–341.

Hu, L. Y., Y. L. Chen, Y. Xu, Y. Zhao, L. Yu, J. Wang, and P. Gong. 2014. "A 30 meter Land Cover Mapping of China with an Efficient Clustering Algorithm CBEST." *Science China: Earth Sciences* 57: 2293–2304. doi:10.1007/s11430-014-4917-1.

IBGE. 2013. *Technical Manual of Land Use*. Rio de Janeiro: IBGE. Accessed January 30, 2015. ftp://geoftp.ibge.gov.br/documentos/recursos_naturais/manuais_tecnicos/manual_uso_da_terra.pdf

Jarnagin, S. T. 2004. "Regional and Global Patterns of Population, Land Use, and Land Cover Change: An Overview of Stressors and Impacts." *GIScience & Remote Sensing* 41(3): 207–227. doi:10.2747/1548-1603.41.3.207.

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. 2013. "A Comprehensive Change Detection Method for Updating the National Land Cover Database to Circa 2011." *Remote Sensing of Environment* 132: 159–175.

Jung, M., K. Henkel, M. Herold, and G. Churkina. 2006. "Exploiting Synergies of Global Land Cover Products for Carbon Cycle Modeling." *Remote Sensing of Environment*. 101(4): 534–553. doi:10.1016/j.rse.2006.01.020.

Kavouras, M., M. Kokla, and E. Tomai. 2005. "Comparing Categories among Geographic Ontologies." *Computers & Geosciences* 31(2): 145–154. doi:10.1016/j.cageo.2004.07.010.

Lambin, E. F., and H. J. Geist (Eds). 2010. *Land-Use and Land-Cover Change. Local processes and Global Impacts*. The IGBP Series. Berlin: Springer-Verlag, 222 pp. (A synthesis of LUCC science).

Latham, J., R. Cumani, I. Rosati, and M. Bloise. 2014. *Global Land Cover SHARE* (GLC-SHARE) *database Beta-Release Version 1.0*. Rome: FAO. Accessed March 27. http://www.glcn.org/downs/prj/glcshare/GLC_SHARE_beta_v1.0_2014.pdf

Latifovic, R., C. Homer, R. Ressel, D. Pouliot, N. Hossain, R. Colditz, I. Olthof, C. Giri, and A. Victoria. 2012. "North American Land Change Monitoring System." In *Remote Sensing of Land Use and Land Cover: Principles and Applications*, edited by C. P. Giri, vol. 8, 303–324. Boca Raton, FL: CRC Press.

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

Latifovic, R., and D. Pouliot. 2005. “Multi-Temporal Land Cover Mapping for Canada: Methodology and Products.” *Canadian Journal of Remote Sensing* 31: 347–363. doi:10.5589/m05-019.

Latifovic, R., D. Pouliot, and I. Olthof. 2009. “North America Land Change Monitoring System: Canadian perspective.” *30th Canadian Symposium on Remote Sensing*, 22–25 June 2009: Lethbridge.

Loveland, T., J. Brown, D. Ohlen, B. Reed, Z. Zhu, L. Yang, and S. Howard. 2009. “ISLSCP II IGBP DISCover and SiB Land Cover, 1992–1993.” In *ISLSCP Initiative II Collection*, edited by F. Hall, G. G. Collatz, B. Meeson, S. Los, E. Brown De Colstoun, and D. Landis. “Data set.” Available online [http://daac.ornl.gov/]. Oak Ridge: Oak Ridge National Laboratory Distributed Active Archive Center. doi:10.3334/ORNLDAAC/930.

Loveland, T., B. Reed, J. Brown, D. Ohlen, J. Zhu, L. Yang, and J. Merchant. 2000. “Development of a Global Land Cover Characteristics Database and IGBP DISCover from 1-km AVHRR Data.” *International Journal of Remote Sensing* 21: 1303–1330. doi:10.1080/014311600210191.

Loveland, T., T. Sohl, K. Sayler, A. Gallant, J. Dwyer, J. Vogelmann, and G. Zylstra.1999. *Land Cover Trends: Rates, Causes, and Consequences of Late-Twentieth Century U.S. Land Cover Change*. EPA report. Accessed May 8, 2014. http://www.epa.gov/esd/land-sci/trends/pdf/trends_research_plan.pdf

Loveland, T., T. Sohl, S. Stehman, A. Gallant, K. Sayler, and D. Napton. 2002. “A Strategy for Estimating the Rates of Recent United States Land Cover Changes.” *Photogrammetric Engineering and Remote Sensing* 68 (10): 1091–1099.

LUCAS. 2009. *Technical Reference Document C-3: Landuse and Land Cover: Nomenclature*. Accessed May 8, 2014. http://epp.eurostat.ec.europa.eu/portal/page/portal/lucas/documents/LUCAS2009_C3-Classification_20121004.pdf

LUCAS. 2013. *Technical Reference Documentc-3 Land Use and Land Cover Classification* (Revised). Accessed May 8, 2014. http://epp.eurostat.ec.europa.eu/portal/page/portal/lucas/documents/LUCAS2012_C3-Classification_20131004_0.pdf

Lunetta, R., J. Knight, J. Ediriwickrema, J. Lyon, and L. Worthy. 2006. “Land-Cover Change Detection Using Multi-Temporal MODIS NDVI Data.” *Remote Sensing of Environment* 105: 142–154. doi:10.1016/j.rse.2006.06.018.

Lymburner, L., P. Tan, A. McIntyre, A. Lewis, and M. Thankappan. 2013. “Dynamic Land Cover Dataset Version 2: 2001-Now…A Land Cover Odyssey.” *Geoscience and Remote Sensing Symposium* (IGARSS). IEEE International, doi:10.1109/IGARSS.2013.6723532.

Lymburner, L., P. Tan, N. Mueller, R. Thackway, and M. Thankappan. 2011. *The National Dynamic Land Cover Dataset - Technical report. Record 2011/031*. Canberra: Geoscience Australia. Accessed January 28, 2015. http://www.ga.gov.au/corporate_data/71069/Rec2011_031.pdf

Macedo, R., M. Moreira, E. Domingues, A. Gama, F. Sanson, F. Teixeira, F. Dias, F. Yamaguchi, and L. Jacintho. 2013. “LUCC (Land Use and Cover Change) and the Environmental-Economic Accounts System in Brazil.” *Journal of Earth Science and Engineering* 3(12): 840–844.

Manakos, I., and S. Lavender. 2014. “Remote Sensing in Support of the Geoinformation in Europe.” In *Land Use and Land Cover Mapping in Europe: Practices and Trends. Remote Sensing and Digital Image Processing*, edited by I. Manakos and M. Braun, 3–10. Dordrecht: Springer.

Martino, L., and M. Fritz. 2008. *New Insights into Land Cover and Land Use in Europe*. Statistics in Focus 33/2008. Accessed February 20, 2014. http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-SF-08-033/EN/KS-SF-08-033-EN.PDF

Meyer, W. B., and B. Turner. 1994. *Changes in Land Use and Land Cover: A Global Perspective*. Cambridge: Cambridge University Press.

Mora, B., N. Tsendbazar, M. Herold, and O. Arino. 2014. “Global Land Cover Mapping: Current Status and Future Trends.” In *Land Use and Land Cover Mapping in Europe: Practices and Trends. Remote Sensing and Digital Image Processing*, edited by I. Manakos and M. Braun, 11–27. Dordrecht: Springer.

Mountrakis, G., and B. Xi. 2013. Assessing Reference Dataset Representativeness through Confidence Metrics based on Information Density. *ISPRS Journal of Photogrammetry and Remote Sensing* 78: 129–147. doi:10.1016/j.isprsjprs.2013.01.011.

Mucher, S., K. Steinnocher, J. Champeaux, S. Griguolo, K. Wester, K. Heunks, and V. Katwijk. 2000. “Establishment of a 1-km Pane European Land Cover Database for Environmental Monitoring.” In *Proceedings of the Geoinformation for all XIXth congress of the*

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015

International society for photogrammetry and remote sensing, edited by K. J. Beek and M. Molenaar, 702–709. Amsterdam: GITC.

NRSA. 2006. *National Land Use and Land Cover Mapping Using Multitemporal AWiFS Data*. Project Report. Accessed January 14, 2015. http://bhuvan.nrsc.gov.in/gis/thematic/tools/document/LULC250/0405.pdf

NRSC. 2006. *Land Use/Land Cover Database on 1:50,000 Scale*. Natural Resources Census Project. LUCMD, LRUMG, RS & GIS AA, National Remote Sensing Centre, ISRO, Hyderabad. Accessed January 14, 2015. http://bhuvan.nrsc.gov.in/gis/thematic/tools/document/LULC/AN.pdf

NRSC. 2013. *National Land Use Land Cover Mapping Using Multitemporal AWiFS Dat* (LULC-AWiFS), *Ninth Cycle 2012–2013)*. Project Report. Accessed January 14, 2015. http://bhuvan.nrsc.gov.in/gis/thematic/tools/document/LULC250/1213.pdf

NRSC. 2014. *Land Use/Land Cover Database on 1:50,000 Scale*. Natural Resources Census Project. LUCMD, LRUMG, RSAA, National Remote Sensing Centre, ISRO, Hyderabad. Accessed January 14, 2015. http://bhuvan.nrsc.gov.in/gis/thematic/tools/document/2LULC/lulc1112.pdf

Olthof, I., R. Latifovic, and D. Pouliot. 2009. “Development of a Circa 2000 Land Cover Map of Northern Canada at 30 M Resolution from Landsat.” *Canadian Journal of Remote Sensing* 35: 152–165. doi:10.5589/m09-007.

Olthof, I., R. Latifovic, and D. Pouliot. 2015. “Medium Resolution Land Cover Mapping of Canada from SPOT 4/5 Data.” *Technical Report, Geomatics Canada, 2015*. Open File 4, 37 p. doi:10.4095/295751.

Pouliot, D., R. Latifovic, N. Zabcic, L. Guindon, and I. Olthof. 2014. “Development and Assessment of a 250 M Spatial Resolution MODIS Annual Land Cover Time Series (2000–2011) for the Forest Region of Canada Derived from Change-Based Updating.” *Remote Sensing of Environment* 140: 731–743. doi:10.1016/j.rse.2013.10.004.

Scepan, J. 1999. “Thematic Validation of High-Resolution Global Land-Cover Data Sets.” *Photogrammetric Engineering and Remote Sensing* 65(9): 1051–1060.

Schepaschenko, D., I. McCallum, A. Shvidenko, S. Fritz, S. Kraxner, and M. Obersteiner. 2011. “A New Hybrid Land Cover Dataset for Russia: A Methodology for Integrating Statistics, Remote Sensing and In Situ Information.” *Journal of Land Use Science* 6,4: 245–259. doi:10.1080/1747423X.2010.511681.

See, L., D. Schepaschenko, M. Lesiv, I. McCallum, S. Fritz, A. Comber, C. Perger, C. Schill, Y. Zhao, V. Maus, M. A. Siraj, F. Albrecht, A. Cipriani, M. Vakolyuk, A. Garcia, A. H. Rabia, K. Singha, A. A. Marcarini, T. Kattenborn, R. Hazarika, M. Schepaschenko, M. Van Der Velde, F. Kraxner, and M. Obersteiner 2015. Building a Hybrid Land Cover Map with Crowdsourcing and Geographically Weighted Regression.” *ISPRS Journal of Photogrammetry and Remote Sensing* 103: 48–56 doi:10.1016/j.isprsjprs.2014.06.016.

Stone, T., R. Houghton, and P. Schlesinger. 2000. “Map of the Former Soviet Union Based Upon a Time Series of 15 km Resolution NOAA AVHRR Data.” In *Disturbance in Boreal Forest Ecosystems: Human Impacts and Natural Processes*. USDA Gen. Technical Report NC-209. Duluth: International Boreal Forest Research Association 1997. Symposium Proceedings, pp. 67–80.

Stone, T. A., P. Schlesinger, G. Woodwell, and R. A. Houghton, 1994. A Map of the Vegetation of South America Based on Satellite Imagery. *Photogrammetric Engineering and Remote Sensing* 60 (5): 541–551.

Strahler, A., G. Boschetti, M. Foody, M. Fiedl, M. Hansen, P. Herold, P. Mayaux, J. Morisette, S. Stehman, and C. Woodcock. 2006. *Global Land Cover Validation: Recommendations for Evaluation and Accuracy Assessment of Global Land Cover Maps*. Report of Committee of Earth Observation Satellites (CEOS) – Working Group on Calibration and Validation (WGCV). Luxembourg: Office for Official Publications of the European Communities.

Tateishi, R., D. Bayaera, M. Ghara, H. Al-Bilbisia, J. Tsendayusha, A. Shalaby, A. Kasimu, N. Hoan, T. Kobayashi, B. Alsaaideh, M. Rahman, E. Tsevengee, Y. Yamada, and S. Kajikawa. 2008. “A New Global Land Cover Map, GLCNMO.” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXVII: Part B7.

Tateishi, R., N. Hoan, T. Kobayashi, B. Alsaaideh, G. Tana, and D. Phong. 2014. “Production of Global Land Cover Data - GLCNMO2008.” *Journal of Geography and Geology* 6 (3): 99–122. doi:10.5539/jgg.v6n3p99.

Tateishi, R., B. Uriyangqai, H. Bilbisi, M. Ghar, J. Ayush, T. Kobayashi, A. Kasimu, N. T. Hoan, A. Shalaby, B. Alsaaideh, T. G. Enkhzaya, and H. P. Sato 2011. "Production of Global Land Cover Data-Glcnmo." *International Journal of Digital Earth* 4 (1): 22–49. doi:10.1080/17538941003777521.

Tchuente, A., J. Roujean, and S. Jong. 2011. "Comparison and Relative Quality Assessment of the GLC2000, GLOBCOVER, MODIS and ECOCLIMAP Land Cover Data Sets at the African Continental Scale." *International Journal of Applied Earth Observation and Geoinformation* 13: 207–219. doi:10.1016/j.jag.2010.11.005.

Townshend, J., J. Latham, C. Justice, A. Janetos, R. Conant, and O. Arino. 2011. "International Coordination of Satellite Land Observations: Integrated Observations of the Land." In *Land Remote Sensing and Global Environmental Change*, edited by B. Ramachandran, C. Justice, and M. Abrams, 835–856. New York: Springer Science.

Tsendbazar, N., S. Bruin, and M. Herold 2015. "Assessing Global Land Cover Reference Datasets for Different User Communities." *ISPRS Journal of Photogrammetry and Remote Sensing* 103: 93–114 doi:10.1016/j.isprsjprs.2014.02.008.

Turner, B. L.II 2006. "Land Change as a Forcing Function in Global Environmental Change." In *Our Earth's Changing Land: An Encyclopedia of Land-Use and Land-Cover Change*, vol. 1 (A–K), edited by H. J. Geist, xxv–xxxii. Westport: Greenwood Press.

UN (United Nations). 2012a. *Report of the United Nations Conference on Sustainable Development*. Rio de Janeiro, Brazil, 20–22 June. Accessed March 15, 2012. http://www.uncsd2012.org/content/ documents /814UNCSD%20REPORT%20final%20revs.pdf

UN (United Nations). 2012b. *The Future We Want*. Rio de Janeiro, Brazil 20–22 June. Accessed February 21, 2014. http://daccess-dds-ny.un.org/doc/UNDOC/GEN/N11/476/10/PDF/N1147610.pdf?OpenElement

UNSD. 2007. *Environmental Indicators. Land Use. Total Surface Area as of 19 January 2007*. Accessed January 25, 2015. http://unstats.un.org/unsd/environment/totalarea.htm

Vogelmann, J. E., S. Howard, L. Yang, C. Larson, B. Wylie, and J. Van Driel. 2001. "Completion of the 1990's National Land Cover Data Set for the conterminous United States." *Photogrammetric Engineering and Remote Sensing* 67: 650–662.

Wang, J., Y. Zhao, C. Li, L. Yu, D. Liu, and P. Gong. 2015. "Mapping Global Land Cover in 2001 and 2010 with Spatial-Temporal Consistency at 250 M Resolution." *ISPRS Journal of Photogrammetry and Remote Sensing* 103: 38–47. doi:10.1016/j.isprsjprs.2014.03.007.

Wickham, J. D., S. V. Stehman, L. Gass, J. Dewitz, J. A. Fry, and T. G. Wade. 2013. "Accuracy Assessment of NLCD 2006 Land Cover and Impervious Surface." *Remote Sensing of Environment* 130: 294–304. doi:10.1016/j.rse.2012.12.001.

Yan, W. Y., A. Shaker, and N. E. Ashmawy. 2015. "Urban Land Cover Classification Using Airborne Lidar Data: A Review." *Remote Sensing of Environment* 158: 295–310. doi:10.1016/j.rse.2014.11.001.

Yu, L., J. Wang, and P. Gong. 2013. "Improving 30 M Global Land-Cover Map FROM-GLC with Time Series MODIS and Auxiliary Data Sets: A Segmentation-Based Approach." *International Journal of Remote Sensing* 34 (16): 5851–5867. doi:10.1080/01431161.2013.798055.

Yu, L., J. Wang, X. C. Li, C. C. Li, and P. Gong. 2014. "A Multi-Resolution Global Land Cover Dataset through Multisource Data Aggregation." *Science China Earth Sciences* 57 (10): 2317–2329. doi:10.1007/s11430-014-4919-z.

Yu, L., L. Liang, J. Wang, Y. Y. Zhao, Q. Cheng, L. Y. Hu, S. Liu, L. Yu, X. Wang, P. Zhu, X. Li, Y. Xu, C. Li, W. Fu, X. Li, W. Li, C. Liu, N. Cong, H. Zhang, F. Sun, X. Bi, Q. Xin, D. Li, D. Yan, Z. Zhu, M. F. Goodchild, and P. Gong. 2014. "Meta-Discoveries from a Synthesis of Satellite-Based Land Cover Mapping Research." *International Journal of Remote Sensing* 35 (13): 4573–4588. doi:10.1080/01431161.2014.930206.

Zhang, Z., X. Wang, X. Zhao, B. Liu, L. Yi, L. Zuo, Q. Wen, F. Liu, J. Xu, and S. Hu. 2014. "A 2010 Update of National Land Use/Cover Database of China at 1:100000 Scale Using Medium Spatial Resolution Satellite Images." *Remote Sensing of Environment* 149: 142–154.

Zhao, Y. Y., P. Gong, L. Yu, L. Hu, X. Y. Li, C. C. Li, H. Zhang, Y. Zheng, J. Wang, Y. Zhao, Q. Cheng, C. Liu, S. Liu, and X. Wang. 2014. "Towards a Common Validation Sample Set for Global Land-Cover Mapping." *International Journal of Remote Sensing* 35 (13): 4795–4814.

Downloaded by [SUNY College of Environmental Science and Forestry] at 13:19 17 November 2015