Geosci. Model Dev. Discuss., 8, 429–462, 2015
www.geosci-model-dev-discuss.net/8/429/2015/
doi:10.5194/gmdd-8-429-2015

Geoscientific Model Development Discussions
Open Access

Plant functional type classification for Earth System Models: results from the European Space Agency's Land Cover Climate Change Initiative

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Received: 22 November 2014 – Accepted: 29 December 2014 – Published: 21 January 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Global land cover is a key variable in the earth system with feedbacks on climate, biodiversity and natural resources. However, global land-cover datasets presently fall short of user needs in providing detailed spatial and thematic information that is consistently mapped over time and easily transferable to the requirements of earth system models. In 2009, the European Space Agency launched the Climate Change Initiative (CCI), with land cover (LC_CCI) as one of thirteen Essential Climate Variables targeted for research development. The LC_CCI was implemented in three phases, first responding to a survey of user needs, then developing a global, moderate resolution, land-cover dataset for three time periods, or epochs, 2000, 2005, and 2010, and the last phase resulting in a user-tool for converting land cover to plant functional type equivalents. Here we present the results of the LC_CCI project with a focus on the mapping approach used to convert the United Nations Land Cover Classification System to plant functional types (PFT). The translation was performed as part of consultative process among map producers and users and resulted in an open-source conversion tool. A comparison with existing PFT maps used by three-earth system modeling teams shows significant differences between the LC_CCI PFT dataset and those currently used in earth system models with likely consequences for modeling terrestrial biogeochemistry and land–atmosphere interactions. The LC_CCI tool is flexible for users to modify land cover to PFT conversions and will evolve as Phase 2 of the European Space Agency CCI program continues.

1 Introduction

Terrestrial ecosystems are characterized by a wide variety of biomes covering arctic to tropical vegetation and extending over almost 150 million square kilometers (Mkm^2), about 30 % of the earth's surface (Olson et al., 2001). Land surface features associated with terrestrial ecosystems vary greatly across the earth due to climate, soil

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and disturbance conditions. Some of these features, like leaf area index (LAI), surface roughness and albedo exert a strong control on the exchange of biogeochemical fluxes, including carbon, water and nutrients, as well as energy fluxes between vegetation and the atmosphere (Bonan, 2008). These fluxes have an influence on multiple atmospheric processes that function over various temporal and spatial scales (Sellers et al., 1996). Because of the importance of land-cover feedbacks on climate, a detailed and accurate description of global vegetation types and their patterns is thus a key component in dynamic global vegetation models (DGVM) and earth system models (ESM), with relevance for both weather and climate prediction. Presently, there are several global datasets of land cover available for modeling purposes, including MODIS-based land cover (Friedl et al., 2010), GLC2000 (Bartholome and Belward, 2005), and GLOBCOVER (Arino et al., 2008). However, the current generation of global land-cover datasets provides little consistency in terms of time period of observations, spatial resolution, thematic resolution and accuracy standards. This presents various challenges for earth system modeling applications that require recent and consistent time series of land-cover and particular thematic information regarding land-cover categories (Giri et al., 2005; Herold et al., 2008; Neumann et al., 2007; Poulter et al., 2011; Wullschleger et al., 2014).

To address these challenges, the European Space Agency established the Land Cover component of the Climate Change Initiative (LC_CCI) and surveyed the land-surface modeling community to define user requirements for developing a new global land-cover dataset (Bontemps et al., 2012; Herold et al., 2011; Hollmann et al., 2013). The LC_CCI addressed these data needs by implementing an improved approach for mapping moderate-resolution global land cover consistently through time using surface-reflectance from the MERIS and VEGETATION 1 and 2 sensors aboard ENVISAT and SPOT 4 and 5, respectively. The final LC_CCI product resulted in the development of three global land-cover datasets, one for each of three epochs (1998–2002, 2003–2007 and 2008–2012) using a spectral classification approach derived from that of GLOBCOVER (Arino et al., 2008), yet with improved algorithms (Radoux et al.,

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2014). Most importantly, its implementation to multi-year and multi-sensor time series ensured temporal consistency across epochs (Bontemps et al., 2012). The LC_CCI land-cover maps depict the permanent features of the land surface by providing information on land-cover classes defined by the United Nations Land Cover Classification System (UNLCCS). It also delivers land surface seasonality products in response to the needs of the ESM and DGVM communities for dynamic information about land-surface processes (Bontemps et al., 2012). Land surface seasonality products provide for each pixel the climatology describing, on a weekly basis, seasonal dynamics of snow cover, vegetation "greenness" based on the normalized difference vegetation index and burned area. Of particular relevance to the needs of the ESM modeling community, the LC_CCI developed a framework to convert the categorical land-cover classes to the fractional area of plant functional types, available at various spatial scales relevant to the respective ESMs.

Plant functional types, or PFTs, are a key feature of current generation ESMs and represent groupings of plant species that share similar structural, phenological, and physiological traits, and can be further distinguished by climate zone (Bonan et al., 2002). Typically, 5–15 PFTs are included in an earth system model simulation (Table 1), including natural and managed grasses with either C3 or C4 photosynthetic pathways, broadleaf or needleleaf trees with deciduous, evergreen or "raingreen" phenology, and shrubs (Alton, 2011; Krinner et al., 2005; Sitch et al., 2003). The PFT concept was originally proposed as a non-phylogenetic classification system partly to reduce computational complexity of ESMs but also to maintain a feasible framework for hypothesis testing. For example, interpreting the outcome of interactions for 5–15 PFTs following a model simulation is much more tractable than interpreting interactions among the thousands of plant species found throughout the world. The PFT concept also provides a practical solution to the problem that many of the plant traits required to parameterize a model at a species level are difficult to obtain (Ustin and Gamon, 2010). Second generation DGVMs are currently addressing some of the limitations posed by the PFT concept as plant trait data become more widely available (Kattge et al., 2011),

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as model structure becomes more computationally efficient (Fisher et al., 2010), or as modeling concepts move toward adaptive trait rather than "fixed" values (Pavlick et al., 2013; Scheiter and Higgins, 2009).

This paper describes the LC_CCI land-cover classification and presents a conversion scheme that "cross-walks" the categorical UNLCCS land-cover classes to their PFT fractional equivalent. This work is one of several LC_CCI publications that have previously described the need for consistent land-cover mapping (Bontemps et al., 2012), the user-requirements (Tsendbazar et al., 2015), and the processing of remote sensing data (Radoux et al., 2014). Land-cover to PFT conversion is a complex task and until the mapping of plant functional traits at global scale becomes possible (i.e., via "optical types", Ustin and Gamon, 2010), the cross-walking approach remains a viable alternative for generating vegetation requirements for ESM and DGVM modeling approaches (Bonan et al., 2002; Faroux et al., 2013; Gotangco Castillo et al., 2013; Jung et al., 2006; Lawrence et al., 2011; Lawrence and Chase, 2007; Poulter et al., 2011; Verant et al., 2004; Wullschleger et al., 2014). The LC_CCI conversion scheme described here provides users with a transparent methodology as well as the flexibility to modify the cross-walking approach to fit the needs of their study region. The conversion scheme has been derived as part of a consultative process among experts involved in deriving the land cover map data and three ESM modeling groups as part of Phase 1 of the project. With consensus for the thematic translation scheme, a conversion tool has been designed to spatially resample PFT fractions to various model grid formats common to the climate modeling community. The cross-walking table is expected to be periodically updated by the LC_CCI team, i.e., Phase 2 of LC_CCI began in 2014, and will be revised to include modifications and improvements related to the classification scheme and mapping procedure.

2 Methods

2.1 LC_CCI land cover mapping scheme

The LC_CCI combined spectral data from 300 m full and 1000 m reduced resolution MERIS surface reflectance (and SPOT-VEGETATION for the pre-MERIS era) to classify land cover into 22 Level 1 classes and 14 Level 2 sub-classes following the UN LCCS legend (Di Gregorio and Jansen, 2000). The whole archive of full and reduced resolution MERIS data, 2003–2012, is first pre-processed in a series of steps that include radiometric and geometric correction, cloud screening and atmospheric correction with aerosol retrieval before being merged to 7 day composites. An automated classification process, combining supervised and unsupervised algorithms, is then applied to the full time series to serve as a baseline to derive land-cover maps that are representative of three 5 year periods, referred to as epochs, for 2000 (1998–2002), 2005 (2003–2007) and 2010 (2008–2012). It is achieved through back- and up-dating methods using the full resolution SPOT-VEGETATION and MERIS time series. The three global land-cover maps described all the terrestrial areas by 22 land cover classes explicitly defined by a set of classifiers according to the UNLCCS, each classifier referring to vegetation life form, leaf type and leaf longevity, flooding regime, non-vegetated cover types and artificiality. Inland open water bodies and coastlines were mapped using Wide Swath Mode, Image Mode at Medium-resolution (150 m) and Global Monitoring Image Mode (1 km) acquired by the Advanced Synthetic Aperture Radar (ASAR) sensor aboard ENVISAT satellite for a single period (2005–2010).

In addition to the land cover classification, the land surface seasonality products describe, for 1 km^2 rather than 300 m resolution, the average behavior and the inter-annual variability of the seasonal normalized difference vegetation index (NDVI), the burned area, and the snow occurrence, computed over the 1998–2012 period. These seasonality products are spatially coherent with the land cover classification and are provided at weekly intervals averaged over this 15 year period and are based on existing independent products: SPOT-VEGETATION NDVI daily time series, MODIS burned area (MCD64A1), and MODIS snow cover (MOD10A2). All products are provided to users in NetCDF and geotiff file format referenced to Plate Carrée projection using the World Geodetic System (WGS 84) and are available from http://maps.elie.ucl.ac.be/CCI/viewer/. Detailed descriptions of each component in the processing chain can be found on the European Space Agency Land Cover Climate Change Initiative web site http://www.esa-landcover-cci.org.

2.2 Cross-walking land cover to PFTs

In consultation with the three climate modeling teams engaged in the LC_CCI project, Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Met Office Hadley Centre (MOHC) and Max Planck Institute for Meteorology (MPI), 10 PFT groups were defined based on their phenology (needleleaf or broadleaf, evergreen or deciduous), physiognomy (tree, shrub, or grass), and grassland management status (natural or managed). Three additional non-PFT classes were added for bare soil, water and snow/ice. The cross-walking methodology assumed that each UNLCCS category could be split into one or more PFT classes according to the class description at the per pixel level (Table 2). For example, the "cropland" UNLCCS land cover class was assigned as 100 % managed grass, whereas the UNLCCS "tree cover, needleleaved evergreen, open (15–30 %)" class was assigned to 30 % needleleaved evergreen, 5 % broadleaved deciduous shrub, 5 % needleleaved evergreen shrub, and 15 % natural grass. Of note, wet tropical forest vegetation, mainly the UNLCCS class "tree cover, broadleaved evergreen, closed to open (> 15 %)", was assigned to the PFT categories of "broadleaf evergreen" tree (90 %) and deciduous (5 %), evergreen shrub (5 %) following observations that moist tropical forests tend to have indeterminate phenology rather than distinct periods of onset and offset (Borchert et al., 2002; Fontes et al., 1995; Reich and Borchert, 1984). The derivation of Table 2 is the result of consultative process among the producers of the land cover map and the three modeling groups that have resulted in a consensus on the PFT fractions for each LCCS-defined land cover class.

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2.3 The LC_CCI conversion tool

The LC_CCI land cover and seasonality products are initially downloaded in full spatial resolution, i.e., 300 m grid cells for land cover, and 1 km grid cells for the seasonality products, at global extent in Plate Carrée projection. In order to fulfil a range of ESM requirements, the LC_CCI project team developed the LC_CCI user tool to allow users to adjust parameters of the LC products in a way that is suitable to their model set-up, including modifying the spatial resolution and converting the LC_CCI classes to fractional PFT area. The BEAM Earth Observation Toolbox and Development Platform, designed for visualization and analysis of ENVISAT products, was selected to provide the basis of the conversion software. A list of resampling resolution and coordinate system options are provided in Table 3. The coordinate re-projection and aggregation of the LC_CCI data uses slightly different resampling algorithms depending on whether the tool is used on the land-cover or seasonality products. The tool converts the original LC_CCI geotiff file to target files produced in NetCDF-4 format and following CF (Climate and Forecast) conventions, more commonly used in numerical modelling. The open-source BEAM tool (source code at https://github.com/bcdev) can be run independently using either Windows or Unix-based operating systems and the compiled operational tool can be downloaded from http://maps.elie.ucl.ac.be/CCI/viewer/download.php.

2.4 Re-sampling algorithm for LC_CCI land cover

For the land cover classes, the resampling algorithm produces an aggregated LC_CCI dataset that in addition to the fractional area of each PFT, also includes the fractional area of each LC_CCI UNLCCS class, the majority LC_CCI UNLCCS class, and the overall accuracy of the aggregated classification. The majority class n is defined as the LC_CCI class which has the rank n of sorted list of LC_CCI classes by fractional area in the target cell (see Fig. 1). The number of majority classes computed is a parameter, which can be defined by user, so that the full number of LCCS classes can be reduced to a user-defined subset, i.e., the top 3. Each original, valid land, water, snow or ice pixel contributes to the final target cell according to its area percentage contribution. The accuracy is calculated by the median of the land cover classification probability values weighted by the fractional area.

2.5 Re-sampling algorithm for LC_CCI seasonality products

The aggregation of LC_CCI seasonality products is specific for NDVI (i.e., greenness), burned areas, and snow cover. In the case of the LC_CCI NDVI condition, the mean NDVI over all valid NDVI observations are included in the aggregated product. The burned area and snow cover LC_CCI products also contain 3 different layers: the proportion of area (in %) covered by burned or snow area, the average frequency of the burned area or snow area detected over the aggregated zone and the sum of all valid observations of burned or snow area. Similar to aggregation rules for land-cover, each original pixel contributes to the target cell according to its area percentage but the value of a pixel will only be considered if its value falls within its valid range, i.e., zero to one for NDVI.

2.6 Extension to specific model needs

The LC_CCI tool provides users with a zero-order classification, that is, the PFT classes are defined as broadly as possible so that users can continue to aggregate to the requirements of their model (Fig. 2). For example, models that do not include shrub PFTs can merge shrub and tree categories together to create a single woody PFT category. Modeling groups that require climatic distinctions for PFTs, for example, temperate vs. tropical vs. boreal types can use their own climate or biome datasets such as Koeppen–Geiger or Trewartha ecological zones (Baker et al., 2010; Kottek, 2006; Peel et al., 2007) and define classification rules based on temperature thresholds for example (Poulter et al., 2011). Most models also require a distinction between the C3 and C4 photosynthetic pathways for different grass species, where C4 is more common in warm and dry climates (Edwards et al., 2010; Still et al., 2003). The photosynthetic biochemistry of C4 grasses is very different to C3 grasses, with important consequences on the global carbon cycle, and various attempts have been made to map their distribution using climate (Poulter et al., 2011) or some combination of remote sensing and modeling (Still et al., 2003). The LC_CCI managed grasslands PFT category represents all non-irrigated, irrigated and pasture lands and so, drawing finer thematic distinctions between these must come from country or sub-country statistics similar to downscaling work made by Hurtt et al. (2006), Klein Goldewijck (1997) and others (Monfreda et al., 2008; Ramankutty and Foley, 1998).

2.7 Analysis and comparison to PFT maps

For analysis and demonstration of the tool, we compare the LC_CCI PFTs with the original PFTs used by the Land Surface Model (LSM) components of the ESMs from the three modeling centers developing ORCHIDEE at LSCE (Krinner et al., 2005), JULES at MOHC (Clark et al., 2011; Cox et al., 2000; Pacifico et al., 2011), and JSBACH at MPI (Knorr, 2000; Pongratz et al., 2009; Reick et al., 2013). The original ORCHIDEE PFT map, based on 12 PFTs plus bare soil, has its origins in the Olson land cover dataset from the 1980's (Olson et al., 1983) and the International Geosphere Biosphere Program (IGBP) DISCover dataset for the period 1992–1993 (Loveland and Belward, 1997). This was implemented within ORCHIDEE using a look-up table approach to estimate PFT fractions (Verant et al., 2004). The JULES model also uses PFT distributions derived from the IGBP DISCover dataset to estimate fractional coverage of 5 PFTs and 4 non-vegetated surfaces (water, urban, snow/ice and bare soil). JSBACH uses original data from Wilson and Henderson Sellers (1985) and continuous tree fractions from Defries (1999) to represent the distribution and abundance of 12 PFTs. The LC_CCI Epoch 2008–2012 was converted to 0.5° resolution using the LC_CCI user tool and compared with the individual default model PFT maps to illustrate regional differences and biases between products and to provide a baseline of how the LC_CCI products may improve land surface model performance.

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3 Results

3.1 Global summary of LC_CCI

The global land areas covered by the aggregated 0.5° LC_CCI PFT equivalents (Fig. 3) are dominated by barren and bare soil (39 M km^2), followed by forests (30 M km^2), managed grasslands, croplands and pasture (25 M km^2), natural grasslands (18 M km^2), and shrublands (14 M km^2). For comparison, MODIS Collection 5 land cover developed by Friedl et al. (2010), report for barren area 18 M km^2, forest and savanna at 49 M km^2, a shrubland area of 22, and 12 M km^2 for croplands. With reference to the Food and Agriculture Organization (FAO) statistics, forest area is reported as 38 M km^2 (FAO and JRC, 2012), cropland area as approximately 15 M km^2 (Monfreda et al., 2008) and pasture lands of 28 M km^2 (Ramankutty et al., 2008). While part of the areal differences are explained by the spatial resolution between the moderate-resolution MODIS data (500 m) in comparison to the 0.5° LC_CCI data, thematic differences introducing uncertainty in aggregating to forest, grassland, etc. classes, and factors stemming from different definitions of forest cover thresholds used to categorize forest land between the UNLCCS approach (10 % cover) and the IGBP (60 %) approach used for MODIS. In addition, the UNLCCS to PFT conversion approach considers assumptions related to plant community level variability, and so a bare soil fraction is introduced during the conversion (see Table 3) increasing its global area and explaining the difference with MODIS land cover.

3.2 Comparison with original PFT maps

Differences between the LC_CCI PFT datasets and the original PFT datasets were specific for each ESM (Fig. 4) because the original reference data were different per group. In addition, different PFT classification schemes were used for each model (Table 1), introducing further aggregation uncertainties in the comparison between LC_CCI and the original PFT data.

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For all models, grasslands PFT distributions showed the largest changes, with large reductions in northern latitudes for ORCHIDEE and JULES (Fig. 6). For ORCHIDEE, the grass PFT reductions were associated with an increase in bare soil, together with a shift from C3 grasses to (boreal) forest in the mid-to-high latitudes (Fig. 5). Agricultural PFTs, not included in JULES, were similar for the original ORCHIDEE and LC_CCI inputs at regional scales, but showed increases in tropical regions where deforestation activities were high, e.g., the Brazilian arc of deforestation region. JSBACH generally had a reduction in cropland area, especially over North America and the North African arid regions.

Over arid regions, in comparison to the original PFT map, JULES was affected by a decrease of C4 grasses over Australia, with an increase in the fractional cover of shrubs and bare soil. In the Sahel, apparent differences in the definition of natural and managed C4 grass account for differences found between ORCHIDEE and JSBACH. The inclusion of the LC_CCI product resulted in a strong increase in the C4 grass fraction over the Sahel in ORCHIDEE, whereas no significant change in the C4 grass fraction has been found over these areas for JSBACH. Instead, an increase in C4 crops was found over the Sahel for JSBACH. Since the JSBACH conversion also accounts for pasture, this difference may be well the result of the pasture definition, which is a weighted part of all herbaceous PFTs. This is also the reason why the JSBACH C4 Pasture PFT decreases exactly in the same areas where the C4 crops increase due to the use of the LC_CCI data. In JULES, the C4 types over Sahel shift to bare soil.

In the tropics, reductions in broadleaved tropical tree cover were largely consistent across all 3 ESMs, although increases in broadleaf forest area were found for some parts of African Congo Basin for JULES (Fig. 6). Needleleaved forest area increased compared to the reference dataset for both JULES and JSBACH for boreal Europe and Australia (shrubland PFTs). The increase in needleleaved PFTs in boreal Europe was partially associated with a decrease in broadleaves (Fig. 6a and b) for all three models, but also a decrease in natural grassland cover.

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4 Discussion

4.1 Advantages of the LC_CCI for ESM modeling

The LC_CCI approach provides the ESM modeling community with a flexible tool for using up-to-date land-cover information consistently provided over time. Following the requests of the user survey, the land-cover dataset is available across multiple spatial domains, conforms to standard file formats used in numerical models, and includes information on classification confidence levels for the land cover classes and resulting PFT fractions. The standardized conversion tool provides users with a consistent documented approach for aggregating land cover classes and thus overcomes limitations associated with consensus approaches, for example (Tuanmu and Jetz, 2014). Of particular importance is that the multi-temporal LC_CCI mapping approach facilitated more accurate mapping leading to improved remote sensing observations of deforested areas in the tropics, the treeline-tundra boundary in the high latitudes, and better distinctions between managed and non-managed grasslands in Africa. Additionally, the SAR-based water bodies and coastline delineation helped to standardize the physical boundaries between terrestrial and water systems for all models. Using this standardized PFT mapping approach for ESMs can be expected to reduce model ensemble uncertainty as attempted by recent inter-model comparison efforts (Huntzinger et al., 2013).

4.2 Opportunities for Phase 2

During Phase 1 of the LC_CCI project (2011–2014) several limitations of the conversion scheme and tool were recognized and targeted for improvement in Phase 2 where improvements to the land cover classes and conversion scheme will be made. In the high latitudes, a reduction in grassland fractional cover was noted with the LC_CCI product for all models, and on further investigation, it was recognized that a better representation of lichens and moss vegetation (Class 140, Table 3) would be an improvement for the Sparse Vegetation category (Class 150), especially in the high latitudes. Mapping of high-latitude vegetation to PFT equivalents has been a challenge in several recent regional studies (Ottlé et al., 2013; Wullschleger et al., 2014) where discriminating spectrally between shrubs and trees, or grass and non-vascular plant species, is difficult. Accurate mapping of high-latitude vegetation can be particularly important for modeling wildfire (Yue et al., 2014) where the spread of tundra fire is sensitive to fuel loading. In the tropics, the seasonal cycle of forest canopies continues to be a contentious issue (Morton et al., 2014; Myneni et al., 2007; Poulter and Cramer, 2009; Ryan et al., 2014) with the binary distinction between evergreen and deciduous phenology proving to be overly-simplistic where semi-deciduous traits are perhaps more appropriate (Borchert et al., 2002). More specifically, Phase 2 will target (i) improved thematic accuracy with a specific focus on transition areas (e.g. grassland-sparse vegetation-bare soil, tree-shrub-grassland) and the distinction between C3 and C4 grasses, (ii) create a historical land cover time series to cover the 1990s using 1 km AVHRR NDVI surface reflectances, (iii) include more detailed change detection, with more classes, i.e., IPCC land categories (forests, agriculture, grassland, settlement, wetland, other land) as targets, and (iv) deliver an albedo and/or LAI seasonality product.

Physiological traits such as nitrogen fixation and different photosynthetic pathways, C3, C4 or Crassulacean Acid Metabolism (CAM), are presently not detectable from surface reflectance values, and so broad climate-based assumptions must be made to split into these groups. These assumptions can lead to large uncertainties that can impact a chain of ecosystem processes and land surface properties. While the LC_CCI dataset provides updated information on inland water bodies, the seasonality of water bodies and wetlands is yet to be represented and only considered in radar based surveys (Schroeder et al., 2015). Finally, the existing 22 UNLCCS land-cover classes currently don't include pastures while the importance of grazing on biogeochemical cycles is becoming increasingly recognized. Instead, pastures are currently mapped as croplands or grasslands according to their degree of management. Better thematic dis-

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crimination between these 3 classes would clearly improve the carbon cycle modeling as agriculture, in the broadest sense, is a significant contributor to land degradation and anthropogenic global greenhouse gas emissions (Haberl et al., 2007). Nevertheless, remote sensing of land management categories remains a challenging task since existing classification approaches have yet to demonstrate an ability to capture the whole range of rangelands and crops diversity at global scale.

4.3 Modeling challenges

Updating PFT datasets used in ESMs will clearly lead to improvements in the realism of the patterns of biogeography and have important feedbacks on simulating ecosystem processes and interactions with the atmosphere. Available PFT datasets used in ESMs remain outdated, using land cover information from the 1980s mainly because of a lack of tools available for cross-walking land cover to PFTs. The LC_CCI scheme and tool fills a critical data need for improving the representation of carbon, water and energy cycles being developed by the modeling community, however, extensive model benchmarking and calibration activities may now be necessary before the new PFT datasets result in model improvement. For example, model processes may be calibrated to some extent to produce performance metrics under outdated land cover information, and thus a range of benchmarks should be considered when transitioning to new PFT information.

4.4 Summary

The LC_CCI has made significant progress in responding to the ESM community data needs (Tsendbazar et al., 2015). These include:

- New land-cover classifications for 3 Epochs using consistent algorithms and based on the UNLCCS system.

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– A user-friendly tool that can map the UNLCCS classes into user-defined PFT classes and at most grid resolutions used by the ESM community.

– Seasonality products describing average weekly conditions for burned area, NDVI and snow cover.

– Confidence information for each of the UNLCCS classes and a median estimate for the converted PFT legend.

The UNLCCS-PFT conversion tool and the land cover products will continue to be improved during Phase 2 of the LC_CCI with updates made periodically and described at http://www.esa-landcover-cci.org.

Acknowledgements. The LC_CCI project was funded by the European Space Agency Climate Change Initiative Phase 1. The authors appreciate the support and comments from Frank Martin Seifert, Vasileos Kalogirou and Fabrizio Ramoino.

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Table 1. Plant functional types used by three Earth system models and mapped by the LC_CCI Initiative.

ORCHIDEE	JSBACH	JULES	ESA LC_CCI
Tropical broadleaf evergreen	Tropical broadleaf evergreen	Broadleaf trees	Broadleaf evergreen tree
Tropical broadleaf deciduous	Tropical broadleaf deciduous	Needleleaf trees	Broadleaf deciduous tree
Temperate needleleaf evergreen	Extra-tropical evergreen	C3 grass	Needleleaf evergreen tree
Temperate broadleaf deciduous	Extra-tropical deciduous	C4 grass	Needleleaf deciduous tree
Temperate broadleaf summergreen	Rain-green shrubs	Shrubs	Broadleaf evergreen shrub
Boreal needleleaf evergreen	Deciduous shrubs		Broadleaf deciduous shrub
Boreal broadleaf summergreen	Tundra		Needleleaf evergreen shrub
Boreal needleleaf summergreen	Swamp		Needleleaf deciduous shrub
C3 grass	C3 grass		Natural grass
C4 grass	C4 grass		Managed grass
C3 crops	C3 crops		
C4 crops	C4 crops		

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Table 2. Default land cover to plant functional type cross-walking table provided by the conversion tool with the 22 Level 1 UNLCCS classes and 14 Level 2 UNLCCS subclasses in bold. The units are % coverage of each PFT per UNLCCS class.

	UNLCCS Land Cover Class Description	Tree				Shrub				Grass		Non-vegetated		
LCCS Class		BrEv	BrDc	NeEv	NeDe	BrEv	BrDc	NeEv	NeDe	Nat. Grass	Man. Grass	Bare soil	Water	Snow/ Ice
10	Cropland, rainfe										100			
11	Herbaceous cover										100			
12	Tree or shrub cove						50				50			
20	Cropland, irrigated or post-floodin										100			
30	Mosaic cropland (> 50 %)	5	5			5	5	5		15	60			
40	Mosaic nat. veg. (tree, shrub, herb.) (> 50 %)	5	5			7.5	10	7.5		25	40			
50	Tree cover, broadleaved, evergreen, closed to open (> 15 %)	90				5	5							
60	Tree cover, broadleaved, deciduous, closed to open (> 15 %)		70				15			15				
61	Tree cover, broadleaved, deciduous, closed (> 40 %)		70				15			15				
62	Tree cover, broadleaved, deciduous, open (15–40 %)		30				25			35		10		
70	Tree cover, needleleaved, evergreen, closed to open (> 15 %)			70		5	5	5		15				
71	Tree cover, needleleaved, evergreen, closed (> 40 %)			70		5	5	5		15				
72	Tree cover, needleleaved, evergreen, open (15–40 %)			30			5	5		30		30		
80	Tree cover, needleleaved, deciduous, closed to open (> 15 %)				70	5	5	5		15				
81	Tree cover, needleleaved, deciduous, closed (> 40 %)				70	5	5	5		15				
82	Tree cover, needleleaved, deciduous, open (15–40 %)				30		5	5		30		30		
90	Tree cover, mixed leaf type (broadleaved and needleleaved)		30	20	10	5	5	5		15		10		
100	Mosaic tree and shrub (> 50 %)	10	20	5	5	5	10	5		40				
110	Mosaic herbaceous cover (> 50 %)	5	10	5		5	10	5		60				
120	Shrublan					20	20	20		20		20		
121	Shrubland evergree					30		30		20		20		
122	Shrubland deciduou						60			20		20		
130	Grasslan									60		40		
140	Lichens and mosses									60		40		
150	Sparse vegetation (tree, shrub, herbaceous cover) (< 15 %)	1	3	1		1	3	1		5		85		
152	Sparse shrub (< 15 %)					2	6	2		5		85		
153	Sparse herbaceous cover (< 15 %)									15		85		
160	Tree cover, flooded, fresh or brackish water	30	30							20			20	
170	Tree cover, flooded, saline wate	60				20							20	
180	Shrub/herbaceous cover, flooded, fresh/saline/brackish water		5	10			10	5		40			30	
190	Urban area		2.5	2.5						15		75	5	
200	Bare areas											100		
201	Consolidated bare area											100		
202	Unconsolidated bare area											100		
210	Water bodies												100	
220	Permanent snow and ice													100

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Table 3. Minimum set of projections and spatial resolutions included in the re-projection, aggregation, subset and conversion tool developed by the LC_CCI project–LC_CCI user tool.

Regional subset ID	Predefined regional subset
	Free specification of regional subset (4 corner coordinates)
Spatial resolution	Original resolution
	0.25°
	0.5°
	1°
	1.875°
	1.875 × 1.25°
	3.75 × 2.5°
Projection	Original projection (Plate-Carrée)
	Gaussian grid,
	Rotated lat/lon grid
Conversion of LC_CCI classes to PFT	LC_CCI standard cross table
	User defined cross table

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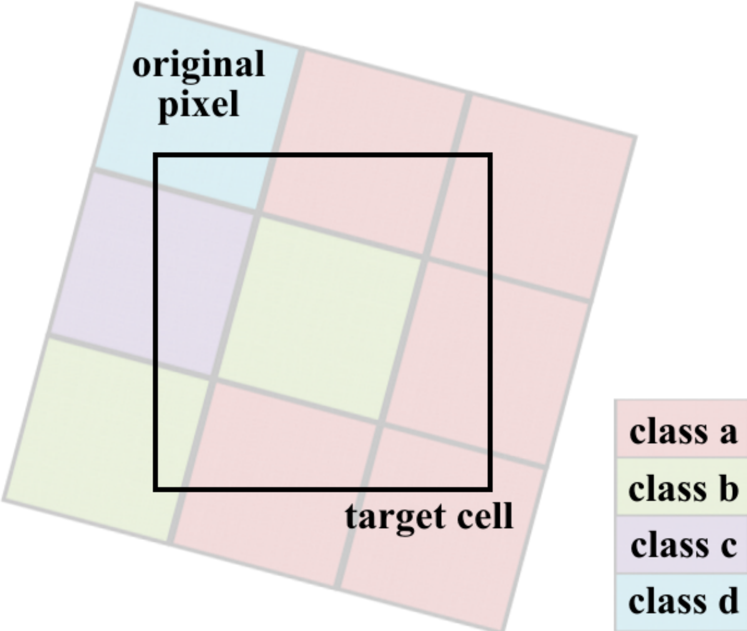

	Area	Majority class
class a	~ 8/16	1
class b	~ 5/16	2
class c	~ 2/16	3
class d	~ 1/16	4

Figure 1. Visualization of the pixel aggregation from the spatial resolution of original LC_CCI map product into the user-defined spatial resolution of the aggregated LC_CCI map product.

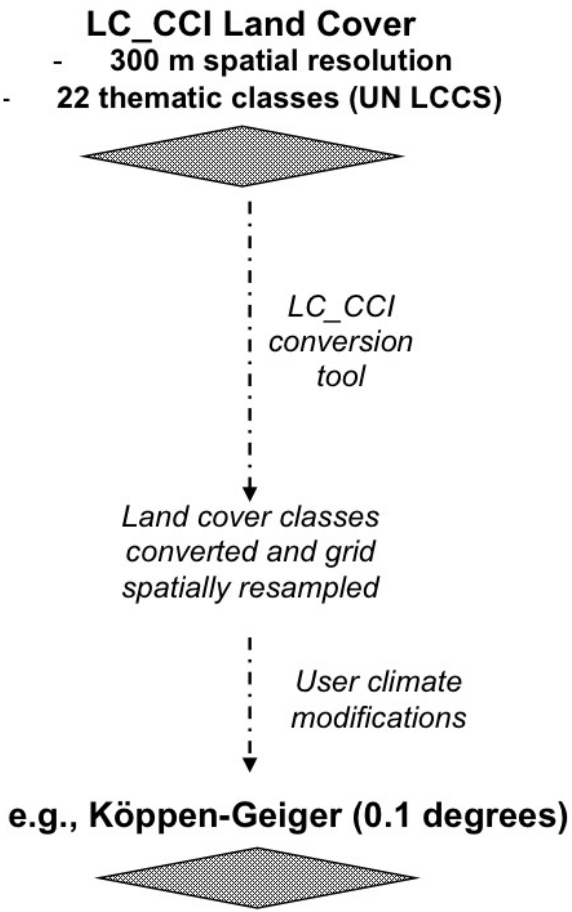

Figure 2. The LC_CCI land cover conversion tool processing chain requires converting the thematic legend and resampling the grid resolution to user defined PFT and coordinate system. Independent of the LC_CCI tool, users can append climate classes to the PFT aggregation.

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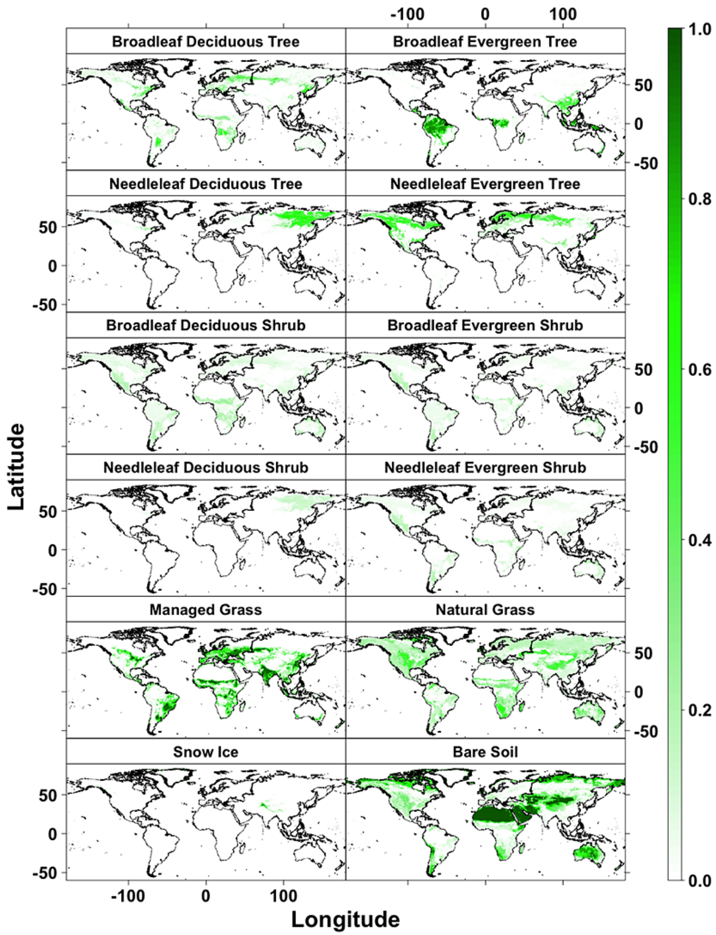

Figure 3. Fractional coverage of plant functional types, at 0.5° spatial resolution, calculated from original 300 m LC_CCI dataset, epoch 2008–2012, using the LC_CCI conversion tool.

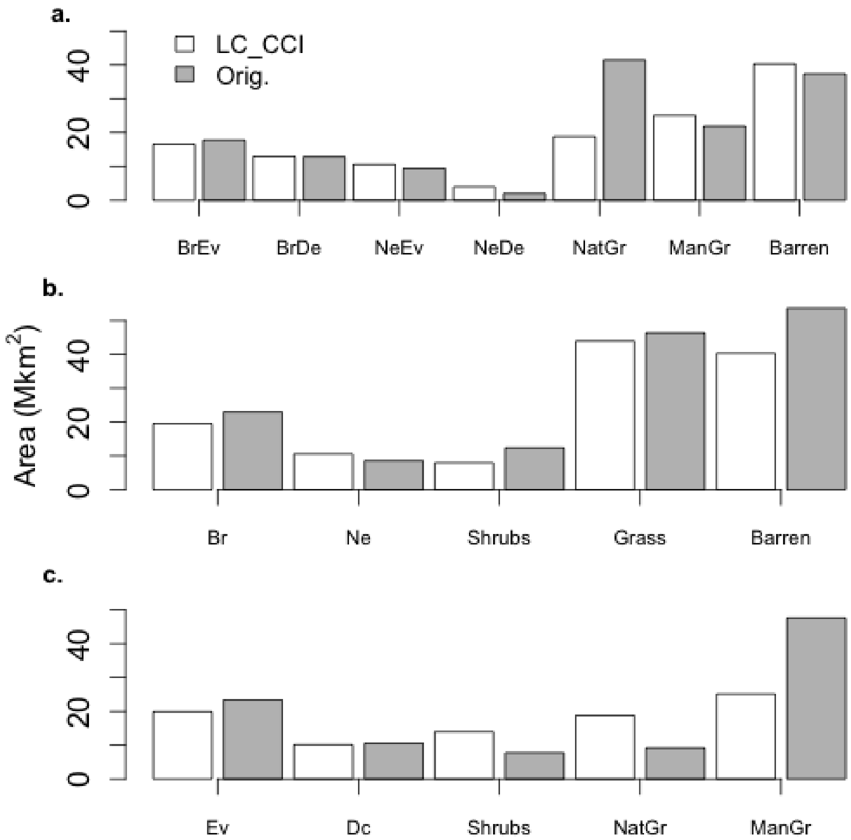

Figure 4. Global PFT coverage comparing the LC_CCI and original datasets for **(a)** ORCHIDEE, **(b)** JULES, and **(c)** JSBACH. Where "Br" is broadleaf, "Ne" is needleleaf, "Ev" is evergreen, "De" is deciduous, "ManGr" is managed grassland, "NatGr" is natural grassland, and "barren" includes bare soil or ice. Note JSBACH has no bare soil category.

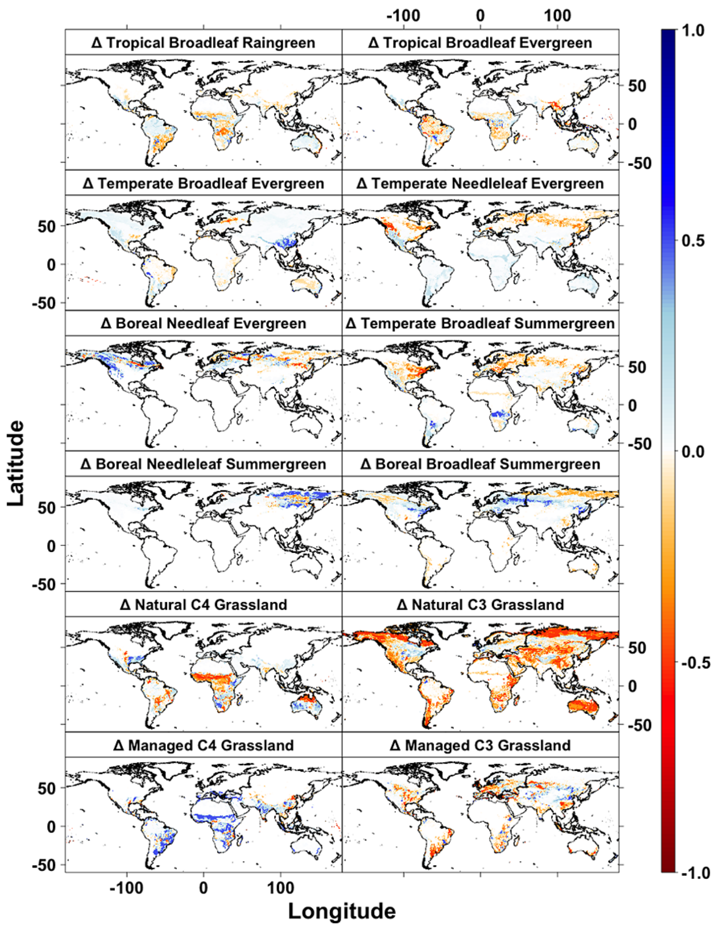

Figure 5. Difference in fractional coverage between the LC_CCI (epoch 2008–2012) and original ORCHIDEE PFT dataset, based on Olson et al. (1983).

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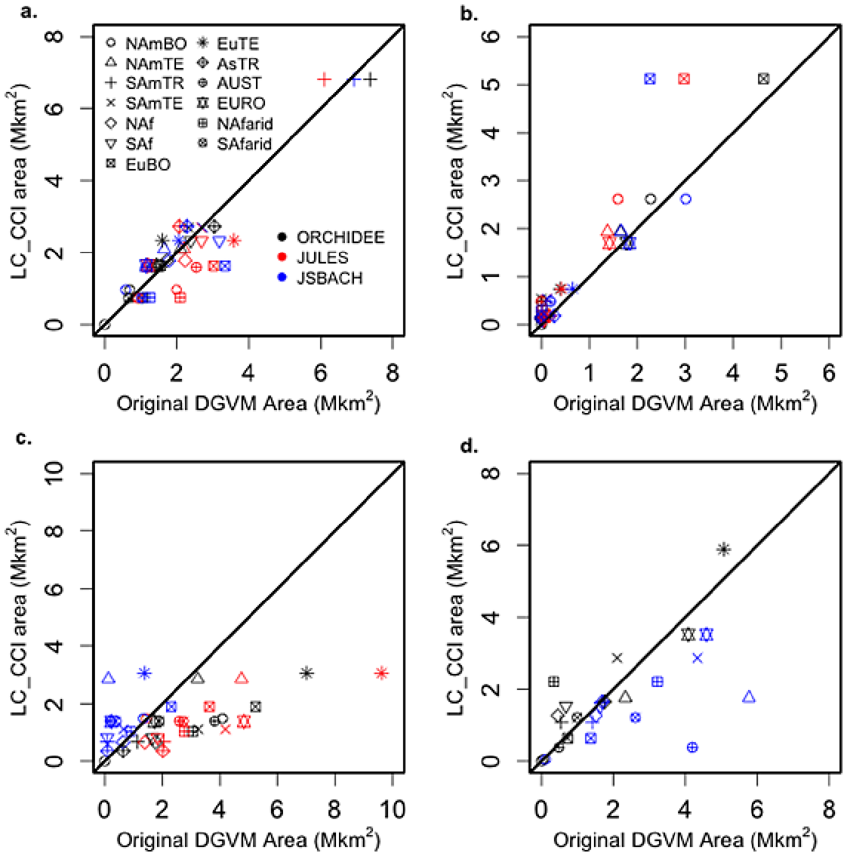

Figure 6. Regional correlations between the original ESM PFT coverage and the LC_CCI, epoch 2008–2012, coverage for **(a)** broadleaved trees, **(b)** needleleaved trees, **(c)** natural grasslands, and **(d)** managed grasslands. The regions follow the TRANSCOM biome boundaries, which partition terrestrial ecosystems into 13 areas (see Fig. A1).

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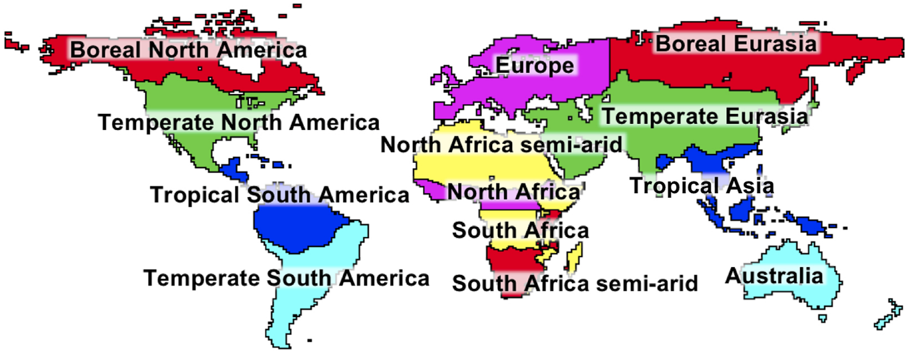

Figure A1. TRANSCOM experiment biome boundaries from Gurney et al. (2002). The codes from Fig. 6 are Boreal North America (NAmBO), Temperate North America (NAmTE), Tropical South America (SAmTR), Temperate South America (SAmTE), North Africa (NAf), South Africa (SAf), Boreal Eurasia (EuBO), Temperate Eurasia (EuTE), Tropical Asia (AsTR), Australia (AUST), Europe (EURO), Arid North Africa (NAfarid), Arid South Africa (SAfarid).

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