Remote Sensing of Environment xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Uncertainty in plant functional type distributions and its impact on land surface models

A.J. Hartley[a,*], N. MacBean[b], G. Georgievski[c,d], S. Bontemps[e]

[a] Met Office Hadley Centre, FitzRoy Road, Exeter, EX1 3PB, United Kingdom
[b] Max Planck Institute for Meteorology, Bundesstrasse 53, 20146 Hamburg, Germany
[c] Laboratoire des Sciences du Climat et de l'Environnement, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
[d] School of Natural Resources and the Environment, University of Arizona, 1064 E Lowell St, Tucson, AZ 85721, USA
[e] Université catholique de Louvain, Place de l'Université 1, 1348 Louvain-la-Neuve, Belgium

ARTICLE INFO

Keywords:
Land cover
Plant functional type
Uncertainty
Vegetation distribution
Land surface model
Terrestrial biosphere
Biogeochemical cycles
Carbon cycle
Hydrological cycle
Energy budget

ABSTRACT

The spatial distribution and fractional cover of plant functional types (PFTs) is a key uncertainty in land surface models (LSMs) that is closely linked to uncertainties in global carbon, hydrology and energy budgets. Land cover is considered to be an Essential Climate Variable because changes in it can result in local, regional or global scale impacts on climate. In LSMs, land cover (LC) class maps are converted to PFT fractional maps using a cross-walking (CW) table by prescribing the fraction of each PFT that occurs within each LC class. In this study we assess the largest plausible range of PFT uncertainty derived from remotely sensed LC maps produced under the European Space Agency Land Cover Climate Change Initiative on simulations of land surface fluxes using 3 leading LSMs. We evaluate the impact of uncertainty due to both LC classification algorithms, and CW procedure, on energy, moisture and carbon fluxes in LSMs. We investigate the maximum plausible range of uncertainty deriving from both LC and CW within the context of a potential biomass scale (bare ground-grass-shrub-tree), representing a gradient from low to high biomass PFTs. More specifically, plausible alternative land cover maps and associated PFT fractional distributions were produced to prioritise low or high biomass vegetation in the LC classification (uncertainty in LC), and subsequently in the assignment of PFT fractions for each LC class (uncertainty in CW), relative to a reference PFT distribution.

We examined the impact of PFT uncertainty on 3 key variables in the carbon, water and energy cycles (gross primary production (GPP), evapo-transpiration (ET), and albedo), for 3 LSMs (JSBACH, JULES and ORCHIDEE) at global scale. Results showed a greater uncertainty in PFT fraction due to CW as opposed to LC uncertainty, for all three variables. CW uncertainty in tree fraction was found to be particularly important in the northern boreal forests for simulated LSM albedo. Uncertainty in the balance between grass and bare soil fraction in arid parts of Africa, central Asia, and central Australia was also found to influence albedo and ET in all models. The spread due to PFT uncertainty for albedo was between 30 and 105% of inter-model uncertainty, for GPP between 20 and 90%, and for ET 0–30%. Each model had a different sensitivity to PFT uncertainty, for example, GPP in JSBACH was found to have a much higher sensitivity to PFT uncertainty in the tropics than JULES and ORCHIDEE, whereas the inverse was true for ET.

These results show that inter-model uncertainty for key variables in LSMs can be reduced by more accurate representation of PFT distributions. Future efforts in land cover mapping should therefore be focused on reducing CW uncertainty through better understanding of the fractional cover of PFTs within a land cover class. Efforts to reduce LC uncertainty should particularly be focused on more accurate mapping of grass and bare soil fractions in arid areas. In the context of Land Surface Models, these results demonstrate that prescribed vegetation distribution in models is a key source of uncertainty that is comparable to the spread between models for key model state variables.

* Corresponding author.
E-mail address: andrew.hartley@metoffice.gov.uk (A.J. Hartley).

http://dx.doi.org/10.1016/j.rse.2017.07.037
Received 3 October 2016; Received in revised form 10 July 2017; Accepted 31 July 2017
0034-4257/

1. Introduction

Land cover (LC) is considered by the Global Climate Observing System (GCOS) as an Essential Climate Variable that is used to monitor natural and anthropogenic changes to the land surface. It is a key component of the earth system that influences carbon, moisture, energy and momentum exchanges between the land surface and the atmosphere (Jung et al., 2007; Poulter et al., 2011; Sterling et al., 2013).

Land Surface Models (LSMs) are the land component of numerical weather prediction, climate and Earth System Models. Most LSMs assign fixed vegetation, derived from global land cover maps (e.g. (Loveland and Belward, 1997; Wilson and Henderson-Sellers, 1985)), while some also simulate dynamic vegetation that responds to and interacts with climate, anthropogenic land use, carbon dioxide, hydrology and other aspects of the earth system (e.g. (Cox, 2001; Cramer et al., 2001; Prentice et al., 1992; Sitch et al., 2003)). Commonly, LSMs represent global vegetation in terms of a small set of Plant Functional Types (PFTs; the exact number of which differ between LSMs) and need as input the spatial coverage of each PFT in each model grid cell, expressed as a grid cell fraction. The LSMs that can simulate dynamic vegetation can also be configured with fixed vegetation. LSMs represent processes in the earth system (such as photosynthesis and transpiration) via equations that are common for all PFTs which have fixed parameter values that differ according to PFT (e.g. the relationship between leaf stomatal closure and vapour pressure deficit). LC information is commonly used by LSM modelling groups to determine the spatial distribution of PFTs via a cross-walking(CW) procedure (described in more detail in Section 1.2) that assigns PFT fractions for each LC class. While mapping the global fractional coverage of PFTs directly from satellite radiances would be preferable (because the uncertain CW procedure would become unnecessary), this approach is not currently used by any LSM modelling group because of difficulties to distinguish the spectral properties of different functional types and mixing of different functional types within a pixel (see Section 4 for further discussion). However, different groups have constructed their own PFT maps, based on the unique set of PFTs required by each model and on different underlying land cover map products, potentially leading to inconsistencies between LSMs.

The spatial distribution of PFTs is associated with uncertainties in three important aspects of LSMs: budgets of carbon (Ballantyne et al., 2015), moisture (Boisier et al., 2014) and energy (Hoffmann and Jackson, 2000; Mahmood et al., 2014). Annual reporting of the global carbon budget by (Le Quéré et al., 2015) using both a book keeping method and LSMs has shown that uncertainty in the amount of carbon released by land use change was 0.5 PgC/year (1σ) in 2014, with the land carbon uptake varying by an additional 0.9 PgC/year. These ranges are influenced by uncertainties in the reporting or detection of land use change, and by uncertainties in the vegetation type and carbon stored in the vegetation before the change occurred (Anav et al., 2013; Houghton et al., 2012). Furthermore, uncertainties in the global land carbon uptake are related to PFT distributions via uncertainties in the rate of primary production (Quaife et al., 2008), soil and vegetation carbon storage (Anav et al., 2013; Brovkin et al., 2013), and plant and soil CO_2 respiration.

Moisture budgets are also sensitive to uncertainties in PFT distribution. For example, (Boisier et al., 2014) showed that LSM simulations of evapotranspiration (ET) are poorly constrained by observations, and concluded that reductions in historical simulated ET uncertainty can be made by improving historical land cover reconstructions. In global terms, changes in land-atmosphere moisture fluxes are governed by two competing anthropogenic processes. Firstly, the location and magnitude of forest conversion to agriculture reduces global ET as a result of reducing leaf area and increases surface runoff due to reduced interception of water by vegetation (Findell et al., 2007; Gordon et al., 2005; Sterling et al., 2013). Secondly, the global expansion of irrigated agriculture during the 20th Century has been shown to increase the amount of ET, due to greater moisture availability for photosynthesis and surface evaporation (Gordon et al., 2005; Puma and Cook, 2010). Regionally, it has also been shown in land-atmosphere coupled simulations that these human-induced changes to the moisture budget may have an impact on the variability (Zeng, 1999), location (Hartley et al., 2016; Knox et al., 2011), and strength (Feddema et al., 2005b) of tropical monsoon systems in South America, Africa and South East Asia.

Energy budgets can also be directly influenced by the spatial distribution of PFTs. Forests, in comparison to cropland and grasslands, tend to exert a cooling effect on regional climate in the tropics and temperate regions through evaporative cooling, whereas boreal forests tend to exert a warming effect due to lower surface albedo (Bonan, 2008; Luyssaert et al., 2014; Zeng and Neelin, 1999). This has been shown by studies that have used both satellite observations (Alkama et al., 2016) and coupled land-atmosphere models (Berbet and Costa, 2003; Betts, 2001; Boisier et al., 2012) to show the strong local positive radiative effects of replacing forest cover with cropland or pasture. Conversely, (Betts, 2000) showed that boreal afforestation reduced surface albedo by 0.1 to 0.3, leading to a positive radiative forcing of 10–20 Wm^{-2}, which is higher than the equivalent radiative cooling due to increasing carbon sequestration. Despite a clear biogeophysical sensitivity of LSMs to LULCC at regional scales, very little work exists on the impact of uncertainty in present-day PFT distributions on the land surfaces fluxes of energy, moisture and carbon in LSMs. One exception to this is the work by (Feddema et al., 2005a) who show that while average global temperature model sensitivity to present day vegetation uncertainty is only 0.21 K, a much larger uncertainty range of up to 5 K can be found at regional scales.

The accuracy of PFT fractional coverage in each model grid cell is therefore an important component of LSMs that can have a significant impact on simulations of carbon, water, and energy fluxes. Understanding and reducing the uncertainty in land cover-derived PFT spatial distributions should lead to more confident predictions of how ecosystem services have responded, and will respond in the future, to the combined impacts of climate change and land use and land cover changes (LULCC).

A principle aim of the European Space Agency (ESA) Land Cover Climate Change Initiative (LC_CCI) is to reduce LSM uncertainty through the use of spatially and temporally consistent LC maps that are created from satellite-derived surface reflectance and ground-truth observations. Part of this initiative has involved interaction between land surface modellers and LC mapping experts in the earth observation community in order to provide PFT maps for each individual LSM, based on the same underlying LC data. This process of expert interaction concluded that while it is currently not possible to accurately map PFTs directly from satellite observations, the approach of deriving PFT fractions from LC maps via a LC-to-PFT conversion ("cross-walking") table was a viable approach. In the process of creating PFT fractions for use in LSMs, there are two key sources of uncertainty, explained in detail below.

1.1. Land cover mapping uncertainty

In the context of LSMs, the requirements of LC maps are very precisely defined and sometimes are not consistent with other applications for LC maps. LSMs usually consider only 1 vegetation level, with no understory vegetation, meaning that the PFT fraction refers to the crown cover of each PFT at the point in the season when maximum leaf area occurs. This is because LSMs commonly use either seasonally varying leaf area information or a phenological model to define vegetation seasonality, therefore, for climate applications, it is not necessary to incorporate this temporal information into land cover classes. This ambiguity and lack of communication between climate and LC scientists can lead to considerable errors and uncertainties in land cover-derived PFT fractions.