

# A webmapping platform for publishing, sharing and managing EO-derived data for forest protection

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## ABSTRACT

Ecometrica, together with partners in the UK, Mexico and Brazil, have collaborated on a UK Space Agency international partnership space programme (IPSP) project to advance EO applications in forests. A key objective was to improve EO derived information management for forest protection. Ecometrica's cloud-based mapping platform was used to establish regional EO Labs within the partner organizations: ECOSUR (Mexico), INPE and FUNCATE (Brazil) and the University of Edinburgh (UK). The regional networks of EO Labs have provided a unified view of forestry-related data that is easy to access. In Mexico and Brazil the EO Labs enabled collaboration between research organisations and NGOs to develop applications for monitoring forest change in specified study areas and has enabled the compilation of previously unavailable regional EO and other spatial datasets into products that can be used by researchers, NGOs and state governments. Data on forest loss was linked to dynamic earth system models developed by the University of Edinburgh and INPE, utilising the EO Labs to provide an intuitive and powerful environment in which non-expert end-users can investigate the results from the huge datasets produced by multi-run model simulations. This paper demonstrates and discusses examples of mapping applications created on Ecometrica EO Labs by ECOSUR, INPE and the University of Edinburgh as part of this project, illustrating how cloud technology can enhance the field of forest protection.

**Keywords:** cloud-based, webmapping, EO Lab, Earth Observation, forest protection, deforestation, Amazon Basin

## 1. INTRODUCTION

Earth Observation (EO) offers an unrivalled approach to monitoring forests, especially for conservation, land use change, fires and forest health. Demand for improved forest observation has grown dramatically since 2007, when international agreement on the need to reduce emissions from deforestation and degradation and to increase atmospheric removals of CO<sub>2</sub> by reforestation or restoration (REDD+) was reached at COP13 of the UNFCCC. Further international collaborative efforts to promote and enforce the legality of the timber trade, and sustainability regulations on the import and use of bioenergy and biofuels have promoted growth in the demand for Earth Observation of forests.

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Nevertheless, despite the positive response of the Committee on Earth Observation Satellites (CEOS) and efforts of the GFOI, there remain barriers to effective and strategic use of EO in the forest sector. There has been limited understanding on the relative capabilities of different EO change detection products to detect different types of forest change, and spatial data sets (including EO derived content such as maps of vegetation, biomass, productivity, soil types, land suitability, water resources etc.) are often fragmented, mislaid or difficult to access by end users. Lack of integration between earth system models (ESMs), EO data and other spatial content means that model outputs are rarely used outside single research organisations, and their application in land use planning and management are limited.

## 2. INTERNATIONAL PARTNERSHIP SPACE PROGRAM

With funding from the International Partnership Space Programme (IPSP) of the UK Space Agency, this project lead by Ecometrica, has invested £3.2 million in research and development of digital infrastructure and content to advance the application of Earth Observation in forests. Collaborators included leading organisations in Brazil, Mexico and the UK with expertise in Earth Observation of forests and related aspects of forest monitoring, resource management, planning and policy making.

The project addressed various barriers to advancing EO applications in forests, of which this paper focuses on two. The main objective was to establish, controlled sharing and distribution of data products between collaborators and stakeholders by creating scalable cloud-based 'EO Labs' at collaborating institutions in Brazil, Mexico and the UK. Other objectives included the demonstration of the benefits of EO inputs to constrain Terrestrial Ecosystem Models (TEMs) to create advanced EO-derived data products, which were incorporated into the EO Labs for dissemination of modeling results.

Terrestrial ecosystem models (TEMs) simulate land-atmosphere fluxes of carbon, energy, water and nutrients in response to natural and/or anthropogenic boundary conditions. The University of Edinburgh has a powerful TEM known as CARDAMOM that models the terrestrial carbon cycle in a spatially-explicit way. CARDAMOM can use information from change detection to estimate the greenhouse gas impacts of land use change. INPE's Integrated Model of Land Surface Processes (INLAND) uses weather and climate data, and represents surface processes such as water and energy balance of canopy, soil physics, short and long term vegetation dynamics.

## 3. EO LABS

The EO Lab is a cloud-based, spatial data content management platform that gives organisations the capacity to develop multiple data sharing and communication applications. Data is stored within a secure cloud infrastructure and can be used by multiple applications, avoiding duplication - if a data layer is updated, all applications will automatically use the updated layer. As data is stored online on the cloud, multiple application managers in disparate locations can collaborate with the same data.

Application managers bring together data sets, areas of interest and narrative information for dissemination, discussion and learning with defined end users. The platform is standard, but each application can be set up as bespoke in order to answer a specific question relevant to a defined problem. The construction of pre-written queries into each application builds in the expert guidance required to query complex model data, which gives the data some value outside of single research institutions, and enables their application in land use management and planning. End users are able to interrogate the data to produce actionable reports, download results and receive alerts, without requiring specialist GIS or remote sensing expertise.

By providing access and analysis of expert spatial data layers, the platform can be used in various ways, for example by publishing or sharing research results with peers, and providing practical and insightful advice to non-specialist end users, industry groups and policy makers. Depending on how a mapping application has been customized, end-users can obtain quantitative and qualitative information about resources, measure impacts and opportunities, check compliance to environmental legislation, monitor changes to vegetation, water and other resources. Examples of such applications, set up by the partner institutions within their respective EO Labs, are given below.

### 3.1 INPE

The INPE EO Lab built on the Ecometrica Mapping platform displays maps of vegetation characteristics in South America, estimated with the Brazilian Integrated Model of Land-surface Processes (INLAND). The model builds on previous versions of the Integrated Biosphere Simulator<sup>[1],[2]</sup>, and simulates land-surface processes such as vegetation dynamics and terrestrial carbon cycle, based on dominant climate and soil properties, and offers the possibility of performing global and regional simulations from common input datasets, such as precipitation, temperature and soil texture.

INLAND is in development at the Center for Earth System Sciences (CCST) of the Brazilian Institute for Space Research (INPE) (<http://www.ccst.inpe.br/inland>), as part of a broad effort in Earth System modeling in Brazil. INLAND aims at global applications with an emphasis on enhanced performance for ecosystems in South America and Brazil, with funding and institutional support from CCST/INPE, Brazilian National Council for Scientific and Technological Development (CNPq), Rede Clima, CNPq/PIBIC Program at INPE, and the European Commission's FP7 projects COMBINE and AMAZALERT.

The INPE EO Lab currently displays INLAND results for surface properties for South America, including vegetation/surface type and biomass. Major classes of vegetation/surface types estimated by INLAND include polar, desert, tundra, shrubs, grassland, savanna, and forests (deciduous/evergreen boreal, temperate, and tropical) (Figure 1a). Maps of simulated biomass are shown separately for the two vegetation layers of upper (Figure 1b) and lower canopy (Figure 1c), in units of KgC/m<sup>2</sup>.

For some specific areas it is also possible to compare model results with remote-sensing information, generating reports that can be extracted as PDF files using the EO Lab functionality. At this point, two biomes in Brazil (Amazonia and Caatinga) were selected for displaying information on total and average upper and lower canopy biomass (Figure 1d). In addition to INLAND results, the application also displays information from Saatchi et al. (2011)<sup>[3]</sup> and Baccini et al. (2012)<sup>[4]</sup> for the same reported areas.

In addition to the visualization and comparison of INLAND outputs, the INPE EO Lab is also useful to facilitate discussions about Earth System modeling in Brazil and South America. Several research activities are under way to provide knowledge for new model implementations to represent relevant processes in the region, such as agriculture and disturbances from deforestation and fire. Future improved versions of INLAND and other surface models are planned for evaluations of the impacts of climate and land-use change on ecosystems in Brazil, and mapping platforms such as the one presented here can help in the process of publication and evaluation of modeling results.

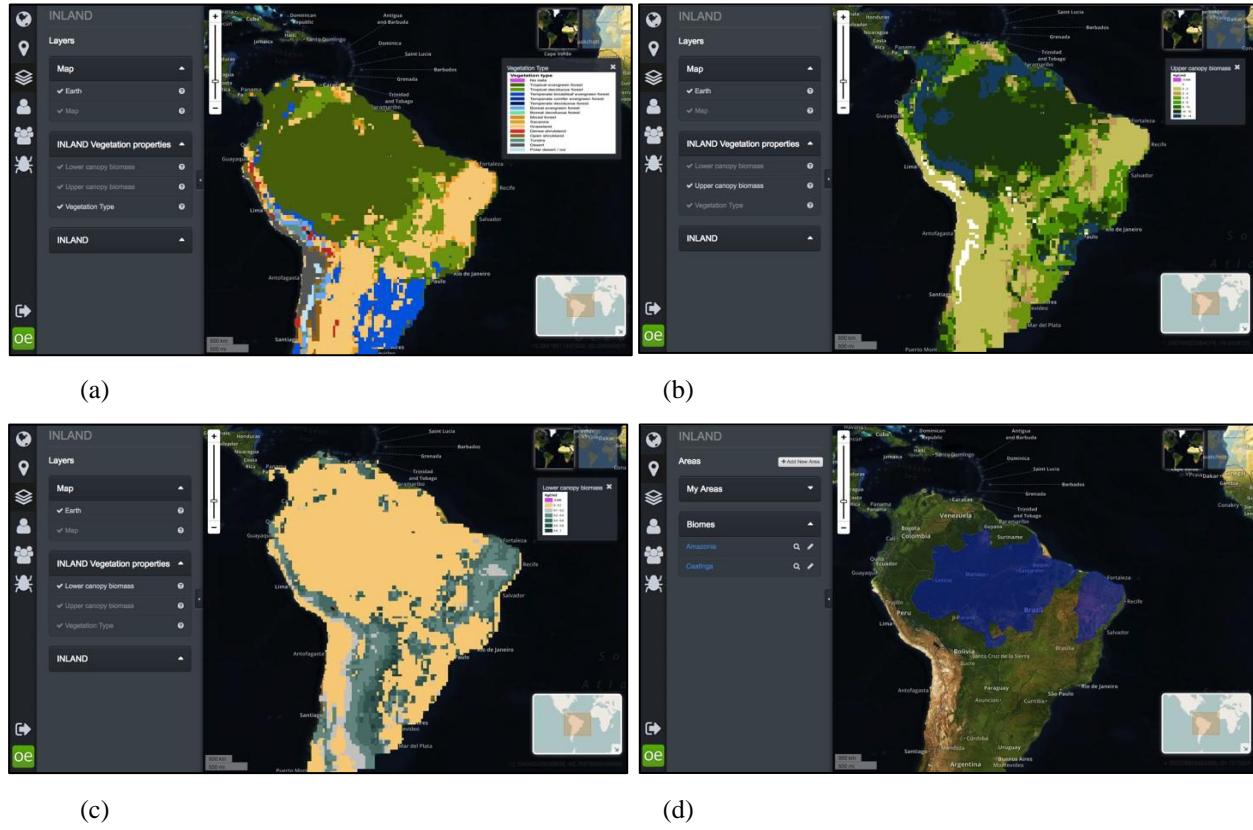


Figure 1. The INPE EO Lab displaying information on vegetation characteristics for South America, estimated with the Brazilian Integrated Model of Land-surface Processes (INLAND). The maps correspond to major classes of vegetation/surface types (a), biomass for the two simulated vegetation layers of upper (b) and lower (c) canopy ( $\text{KgC/m}^2$ ), and two specific areas in Brazil (biomes Amazonia and Caatinga) where it is also possible to compare model results with remote-sensing information (d).

### 3.2 ECOSUR

Often the availability of information about the spatial distribution of forests in a user-friendly format is restricted, particularly in tropical regions. We used Ecometrica's EO Lab to develop several applications including one focused on the monitoring of forests and deforestation in Chiapas, Mexico. The purpose of this application was to provide a tool that allows decision makers and other stakeholders to obtain information and statistics about current and historical distribution of forests within their specific areas of interest.

The application contains maps of the current and historical distribution of forests, a model of risk of deforestation, maps of forest carbon, as well as additional layers of environmental data. All of these data were collected from studies conducted independently, with differing scales and source years. In some cases it was necessary to generalize the classification system to enhance visualisation of maps and also to compare results between different data sources.

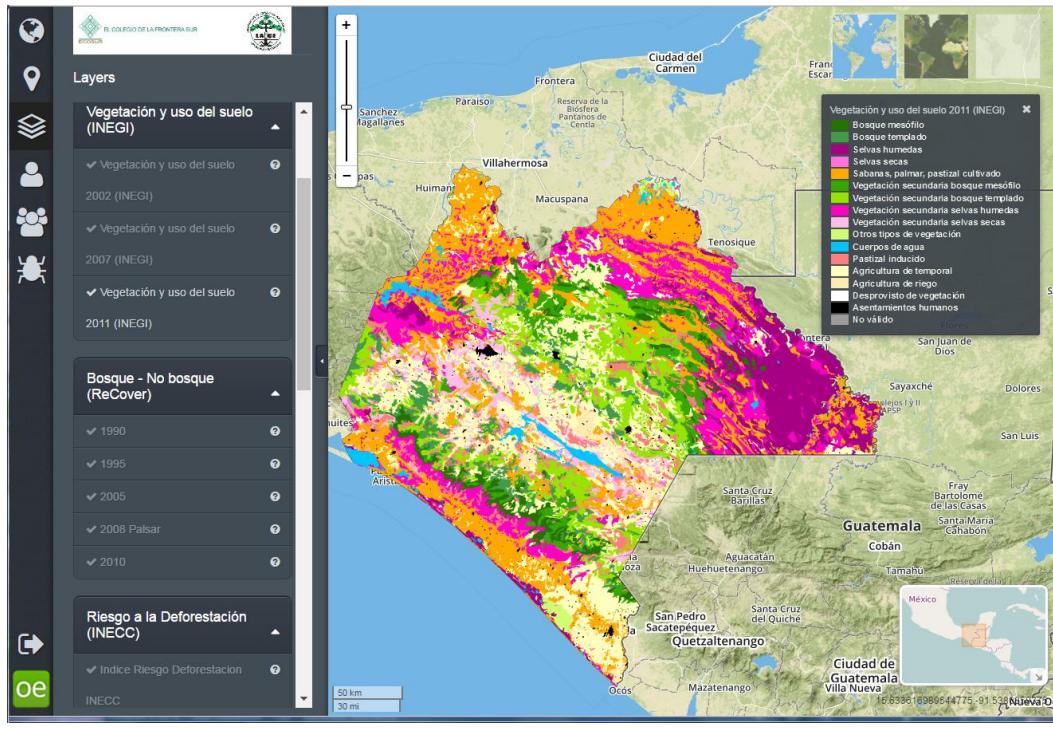


Figure 2. Land cover map of Chiapas for 2011.

Chiapas is one of the states that make up Mexico's southern border. It encompasses an area of approximately 7.36 million ha, and is considered one of the most biodiverse regions in Mexico (see Figure 2). In this region there remain very important fragments of tropical forests, coniferous and cloud forest as well as wetlands. Approximately 17% of state forests and wetlands are legally protected within nature reserves. Unfortunately, in the 1980s and 1990s deforestation rates in this state were very high (about 40,000 ha/year); although this trend has changed in recent years. This application is a valuable tool to monitor the effectiveness of conservation efforts of forest resources and levels of CO<sub>2</sub> emissions associated with deforestation.

The map data included in the application were classed into four groups:

a) Land-cover maps:

- Land-cover of the years 2002, 2007 and 2011 developed by the National Institute of Statistics and Geography of Mexico (INEGI)<sup>[5]</sup> by photo-interpretation of Landsat and SPOT satellite images.
- Forest Cover of the 1990, 1995, 2005, 2008 and 2010 prepared by the Technical Research Centre of Finland (VTT)<sup>[6]</sup> through automated processing of Landsat satellite images
- Deforestation of the periods 1990-2000 and 2000-2010 obtained from automated processing of Landsat images<sup>[7]</sup>.
- Loss of forest cover<sup>[8]</sup>.

b) Risk of deforestation:

- Model of deforestation risk developed by the Mexican National Institute of Ecology and Climate Change (INECC)<sup>[9]</sup>.
- Forests Carbon maps:
- Estimation of aboveground forest carbon using optical and radar data<sup>[10]</sup>.
- Estimation of aboveground forest carbon using MODIS products<sup>[11]</sup>.

d) Environmental variables: Elevation, slope, precipitation and temperature.

One of the advantages of the platform is the ability to obtain information and statistics for certain areas of interest. This application contains three types of pre-defined areas: municipalities, reserves, and socio-economic regions (see Figure

3). Once users have displayed and selected one of the areas of interest, a query for the area of interest will generate several tables and graphs showing statistics of land cover, deforestation and biomass. Figures 4 and 5 show an extract of a query report, which contains graphs and tables obtained for the selected area of interest. As an administrative user of the EO Lab, we were able to set up customised query reports in a format relevant to the specific data included.

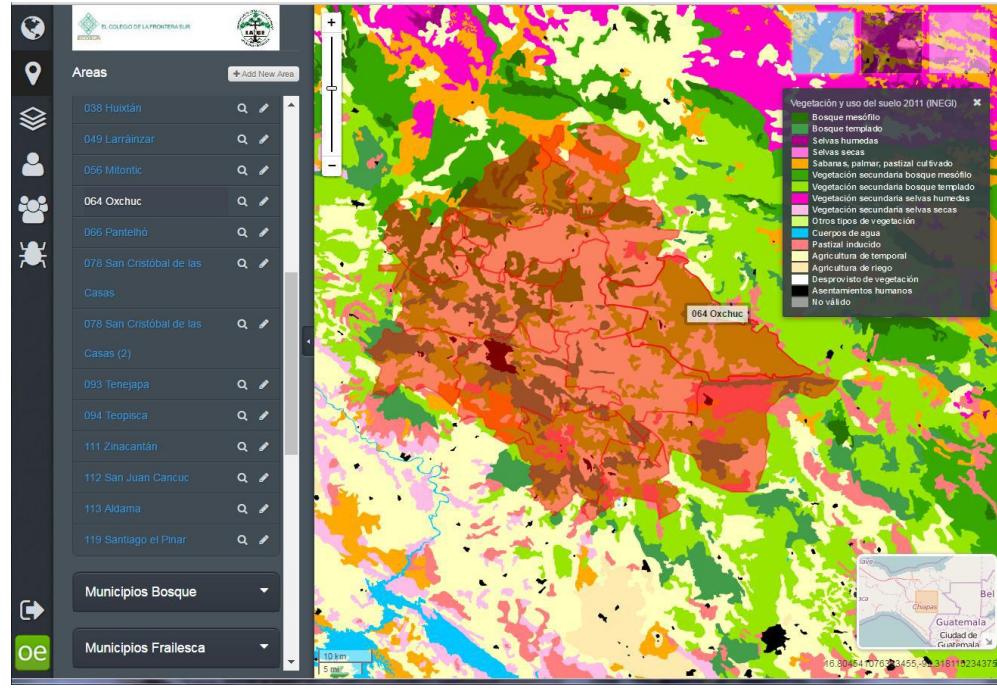


Figure 3. Example of selecting a predefined area of interest, Oxchuc Municipality.

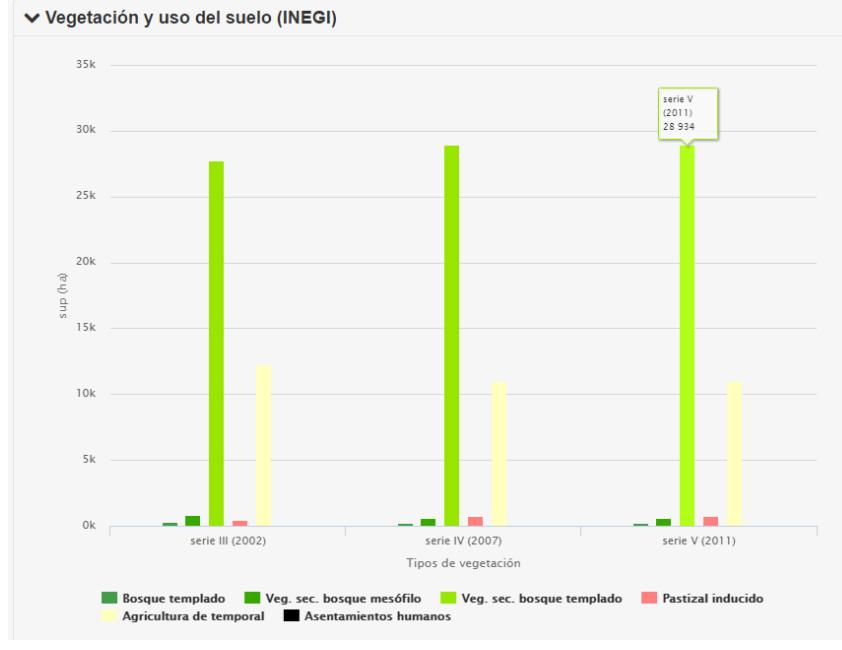


Figure 4. Extract from a query report showing an example of comparative graphs for land cover over time obtained for a selected area of interest, the municipality of Oxchuc.



Figure 5. Extract from a query report for the municipality of Oxchuc showing an example of change in forest/non-forest land cover over time in graph and table format.

### 3.3 The University of Edinburgh

Quantifying the state of the terrestrial carbon cycle represents a fundamental challenge, requiring an understanding of the links and feedbacks between the biosphere and changes in climate and land cover<sup>[12]</sup>. The dynamics of the terrestrial carbon cycle are determined by patterns of carbon allocation and turnover, parameters that typically lack robust constraints. The process of estimating ecosystem carbon stocks and their changes have only been well constrained in a few intensively studied sites<sup>[13][14][15]</sup>. Additionally, processes of carbon uptake and release vary greatly in space and time, so upscaling to landscape, national and global scales has large uncertainties. To overcome this scaling challenge, global datasets on leaf area index, biomass, soil carbon, and climate have been collated in the CARbon DAta MOdel fraMework (CARDAMOM)<sup>[14][16][17]</sup>. CARDAMOM is a model-data fusion framework that integrates a range of biophysical observations, including Earth Observation data from satellites, with a relatively simple model of the terrestrial carbon cycle, DALEC GSI<sup>[14][16]</sup>, to provide a robust estimate of plant and soil carbon pools, the fluxes between pools, and the exchange of carbon with the atmosphere.

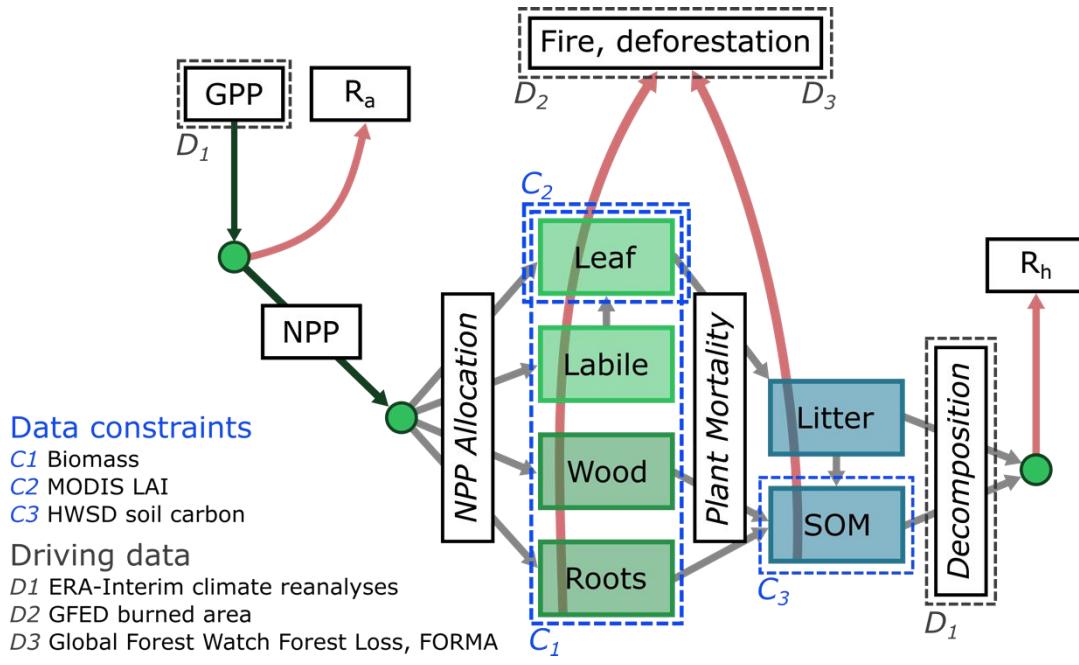


Figure 6. An overview of the CARDAMOM framework, redrawn and adapted from Bloom et al. [2016]. Carbon fluxes are represented by arrows, stocks by coloured boxes. GPP = Gross Primary Production, NPP = Net Primary Production,  $R_a$  = autotrophic respiration,  $R_h$  = heterotrophic respiration. The net ecosystem exchange of carbon from the atmosphere is calculated as  $NEE = -GPP + Ra + Rh$ .

Underlying the CARDAMOM framework is a relatively simple model of the terrestrial carbon cycle, DALEC (Figure 6)<sup>[14][16]</sup>. DALEC comprises a mass balance model that calculates the allocation and fluxes of carbon linking four live carbon pools (foliar, labile, wood and roots) and two soil carbon pools (litter and soil organic matter). The flow of C through this system is determined by 20 process parameters and 6 initial carbon stocks values. These parameters are retrieved based on a Bayesian inverse method that statistically minimises the difference between the model variables and the available observations, including Earth Observation data, while ensuring that the model behavior fits within the bounds imposed by a series of Ecological and Dynamical Constraints (“ecological common sense”; EDCs)<sup>for detailed description, see [16]</sup>.

The simplicity of DALEC presents the major advantage that it can be used with a Markov Chain Monte Carlo algorithm. Millions of simulations for every model pixel explore the parameter space constrained by the available observations using the CARDAMOM data assimilation framework. Rather than being limited to a particular set of parameter values prescribed a priori, this yields a distribution of possible parameter sets that are consistent with the available information on the state of the system. The variability exhibited by this ensemble of simulations informs the posterior uncertainty on the retrieved carbon cycle and the associated stocks and fluxes. Moreover, the assimilation of EO products into the CARDAMOM framework feeds through to reduce the posterior uncertainty and hence provide an improved analysis of the state of the carbon cycle<sup>[18][19]</sup>.

By providing a dynamically updating picture of the terrestrial carbon cycle that is consistent with all available data, CARDAMOM demonstrates great potential for quantifying the terrestrial carbon cycle driven by changes in climate and land use, and the implications of these changes with regards to the exchange of carbon between the biosphere and atmosphere. However, the large volume of information retrieved by CARDAMOM, particularly relating to uncertainties, presents a significant challenge with respect to the effective communication of results to stake-holders and project partners, particularly those working in a non-academic context or those without expertise in GIS.

To place this in context, for each pixel in the model domain, the CARDAMOM framework generates a hypercube of data that describes the distribution of parameter values for all model parameters and fluxes at every time-step for each iteration of the model. During the IPSP project, we used CARDAMOM to simulate the evolution of the carbon cycle in the Amazon Basin. In order to drive the model simulations, we utilised a range of EO products (Figure 6), including remotely sensed aboveground biomass<sup>[20]</sup>, deforestation<sup>[21][22]</sup>, MODIS LAI<sup>[23]</sup>, GFED burned area<sup>[24]</sup>, and ERA-Interim meteorological reanalyses<sup>[25]</sup>, in addition to the HWSD global soil carbon map<sup>[26]</sup>. In total, we ran  $3 \times 10^6$  simulations for a time period extending from January 2009 to December 2014 with a monthly timestep and quarter degree resolution. Of these runs, 1500 were sampled to represent the distribution of parameter values that are consistent with the available observational constraints. The resultant hypercube comprised the accepted distributions of the 26 parameters, with time series of carbon fluxes (32) and carbon stocks (six) over 72 timesteps for 7817 model pixels. Exploring and retrieving useful information from this CARDAMOM hypercube requires an environment in which it is possible to view and cross-query multiple geospatial data layers, and easily undertake queries and analyses based on spatial subsets of the model domain.

We developed an EO Lab to display the temporal evolution of the Amazon carbon cycle, specifically illustrating both the spatial patterns of carbon stocks and carbon exchange with the atmosphere and displaying time series showing how these varied through the modeling period. The aforementioned hypercube was condensed to a set of quantiles (median, 50% and 95% confidence intervals) for the stocks and a subset of the fluxes that together describe the primary pathways of biosphere-atmosphere carbon exchange. These were uploaded to the EO Lab, and a set of queries constructed to produce a suite of time series illustrating the variation in median and interquartile range (representative of the distribution of stocks/fluxes produced by the simulations) of carbon stocks and fluxes through time for a given spatial subset. In addition, a suite of display layers were prepared for visualisation, including maps displaying the time-average carbon fluxes, initial and final carbon stocks and the total change in carbon. Accompanying the time series plots that are produced during a query, we created short excerpts of text to accompany the figures that briefly explain how to interpret the results, thus the expert guidance is provided not only in the spatial analysis built into each query, but also to deliver understanding of the model results and limitations. The resultant application succinctly describes the state and evolution of the Amazon carbon cycle, as viewed through CARDAMOM (Figure 7). For future applications more detailed analyses of carbon cycle dynamics could be added, for example exploring carbon use efficiency, residence times and the interconnections between leaf life span and leaf mass per unit area<sup>[17]</sup>. Where previously investigating these results would require proficiency in both GIS and computer programming, the EO Lab interface allows a non-expert user to quickly probe the data, whether aggregated to the scale of the full basin, state level or even for individual pixels.

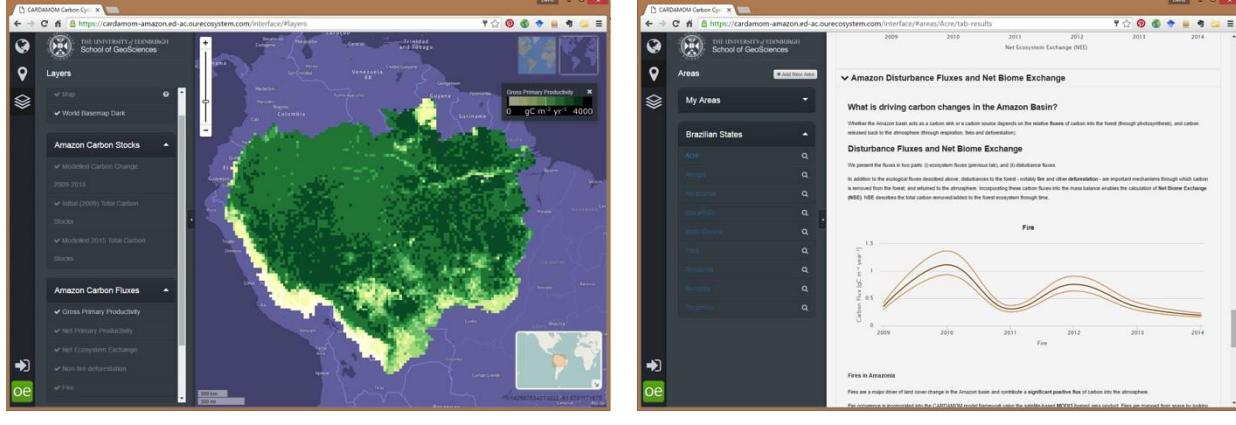


Figure 7. An illustration of the EO Lab application built to display the results of a CARDAMOM-DALEC analysis of the Amazon basin carbon cycle, including the graphical map display (left), and a sample of the automatically generated reports on spatial subsets of the data (right).

To conclude, the EO Lab built on the Ecometrica Mapping platform has proven to be exceptionally useful for disseminating the output of our CARDAMOM simulations, providing a means through which to present a subset of the resultant data hypercube in such a way that a non-expert can be guided through quite complex model data. In effect, by designing an EO Lab, we are able to impart our expert guidance to application users, enabling them to interactively

interrogate the results with the flexibility to focus in on spatial subsets that are of particular interest to a given user. Thus, while CARDAMOM creates value from disparate EO products by combining them into an integrated carbon cycle model, EO Labs open up this added value to a much greater potential audience by providing a pathway through which useful information can be readily extracted from the complex resultant datasets. With this in mind, we intend to continue to develop EO Labs to accompany future publications that are underpinned by similar complex spatial datasets and modeling results. Finally we note that the output from CARDAMOM (and other models) is information rich, and therefore, a subset of results are predefined by the application manager to be used as the data layers within the application. Consequently consideration of the target audience – including effective dialogue with relevant stakeholders – during the development phase is important in order to maximize the value of nascent applications.

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