

Dear Dr. Thonicke,

Thank you very much for your comments and your suggestions for improving the article.

We have included in the new version the corrections suggested by the reviewers, and more information as you have suggested. Our answers to your Editor comments can be found below.

Reviewer 1 comment:

Plants live or dead and their residues are the combustible materials that fuel wildland fires. The diversity of plants or even of vegetation types prompted the need of reducing them to a number of sizable classes, i.e. fuel types, that could be manageable for a number of practical uses in relation to fire modelling. Pettinari and Chuvieco present here a world classification of fuels using the Fuel Characteristics Classification System. The approach is not novel, and has been previously applied to other areas, including a full continent, by various authors including those of this paper.

Your reply:

Please note that the main author of the other paper was the same person, as both articles are part of the same research. The Pettinari et al. (2014) article was a first attempt to derive a global product using FCCS, taking a continent as a study case, and it allowed us to test the method and include several improvements for this global product that are specified in the manuscript in Section 4.1.

Editor comment:

Please make sure the added value of this study in comparison to your earlier paper is clearly stated in the introduction, e.g. what is the new objective to make clear it is not repetitive and what methodological challenges arise with scaling up your product to the global scale.

Reply:

We have included some more information at the end of the Introduction mentioning some of the most important changes in this article with respect of the previous one, but the detailed description of the changes is included in the Discussion section 4.1.

Reviewer 1 comment:

As a validation exercise, the authors related their product for one of the variables they computed (e.g. biomass) using other products independently derived. While their results are more or less comparable, this cannot be considered as a true validation. Actually, some of the papers they cite did such a validation against true ground data and highlighted the differences between the various products and the true ground data. Having a global fuels map is something very much needed, but the basis of such map need to be firm, and to achieve that, real validations are needed. Without that, being this exercise a notable one, it falls short of the rigor that it is needed to be accepted as a true progress in this field. I can but encourage the authors to use existing database to test their results against field data, at a minimum in a number of representative sites and, at a minimum as well, for at least one of the main purposes for which this product is supposed to be used. After this is made the paper may be subject to critical review.

Your reply:

The comparison of our results with the biomass products was not a validation, but a first assessment of our results, which we consider to be acceptable at this stage. Any global dataset requires a generalization of the parameters, and that will make it unfeasible to validate the results in local sites.

Regarding the test of the results for some of the main purposes of the product, we are currently working on another article using this fuelbed map, along with climatic information, to obtain fire behaviour parameters such as reaction intensity and compare them with other related information (fire radiative power) that could improve the assessment of our product. The description of the inputs used, the methodology and the results entail the writing of another article, though, due to the extent of the information to be provided.

Editor comment:

Your product requires a decent and clear validation, avoiding circularity or comparing modelled variables against data used for parameterization for example. Please revise your manuscript accordingly, where you describe the source of data used to validate which variable of your product and at which spatial scale this was done. If site or plot data are not representative, because they do not match conceptually, or global data of the required variables are not provided then use other source of data. Explore and explain how products such as Carvalhais et al. (Nature 2014) for biomass, litter and soil carbon data can be used. Either way, the validation procedure should be clearly described in the revised manuscript and data demand on what needs to be done to allow for a validation at the global scale which is obviously a huge data gap. This information is very important to put the quality of the product into the right context.

Reply:

We have included new information in Section 2.3 to better explain how the biomass of our product is obtained. There is no circularity on our assessment, as the biomass products used for the comparison were not used to create our fuelbeds. As we have included in the text, the biomass of the fuelbeds is calculated using the fuelbed parameters and several biomass equations from different authors (which were not cited in the text for brevity, but only the reference to the Pritchard article where they are all described). The biomass information is an output of the FCCS run of our fuelbeds, and not an input.

The text already indicates the spatial scale of the comparison: “For our product, once the biomass values were computed at the raw resolution of the database (300 m), they were aggregated into 0.5 x 0.5 degree cells.”

Regarding the Carvalhais article, the authors used some of the same inputs for biomass that we have used for our comparison. They derived the total vegetation carbon from the Thurner et al. (2014) Northern Hemisphere biomass, and the Saatchi et al. (2011) pan-tropical biomass. They used that information, with the inclusion of soil carbon data, to create a biomass map that allowed them to calculate the carbon return time in the ecosystems and analyse its correlation with climatic variables. They included soil information from the Harmonized World Soil Database and the Northern Circumpolar Soil Carbon Database to the total biomass pool, which we did not include in our analysis. We have included in the text, at the end of Section 4.2, the possibility of including this information for the assessment for future work.

Reviewer 1 comment:

P11 19-20: A critical point here is to determine the validity of the RS methods to assess biomass. The paper cited indicates that there are large discrepancies between RS (you use both approaches used in that comparison) and ground-based methods. It is unclear how these discrepancies so fundamental can be reconciled.

Your reply:

The two biomass maps described in the cited paper were derived from both RS and ground-based information (Mitchard et al., 2013). The authors of both maps used field plot data to obtain relationships between the field AGB information and GLAS footprints in order to extrapolate that AGB to the GLAS covered area. In that sense, the authors do not see the differences between the two sources of information as discrepancies, but as complementary data that can very well be used together.

We also believe that approach to be useful, being one of the main advantages of the use of RS for different applications: the possibility to extrapolate field plot information into large areas using the data provided by RS, always acknowledging the limitations of these approaches, which are being reduced as more research is done in this field.

Editor comment:

Please include this explanation in the manuscript text.

Reply:

Most of the information on the Baccini and Saatchi methods commented here was already in the text, at the end of Section 3.2. We have made some corrections to that paragraph to clarify the use of both RS and ground-based information.

Reviewer 2 comment:

The application of the results of this study for fire behaviour prediction is justified if local more detailed data are not available. The Authors should nevertheless explain how this downscaling can be performed for a smaller area if a more detailed fuel map is required.

Your reply

As we have stated in the other comments and in the text (P17 L21-24), the objective of this map is for global and regional applications, and is not intended to be used for local fire behaviour prediction. The global fuelbed parameters were created using mean information of canopy cover and height globally, as well as several representative existing fuelbeds of Photo Series. To obtain a local fuelbed map, we would suggest creating a custom map with the same methodology for the creation of the global map, using the same data sources (or even better, local sources of information if available). In that way, if mean values need to be obtained they would only include local variation and would better describe local conditions. Part of our current analysis of automation will tackle this issue.

Editor comment:

Please include this explanation in the manuscript text.

Reply:

Two new paragraphs at the end of Section 4.3 were added to address this point.

Reviewer 2 comment:

Remarks to other comments: Regarding the comment of P. Fernandes that the fact that the authors used the FCCS approach to select and present their fuel bed parameters is a limitation of the work and of its applications. I understand that the parameters that are provided are basic ones and can be used by other fire behaviour models rather than Rothermel. For example the assessment of crown fires requires parameters that are available in this database and not present in common databases. I recommend that the Authors justify better their option of selecting FCCS and explain if it is or not a limitation of the work.

Your reply

We appreciate your comment. We have included some more information on the reasons for using FCCS in the answer to Dr. Fernandes (below), which could also be included in the text.

Editor comment:

Please include this explanation in the manuscript text.

Reply:

New information at the beginning of Section 2 was added to address this point.

Editor comment to your reply to the interactive comment by P. Fernandez:

Your explanation of the validity and conceptual limitation of your product in reply to the interactive comment by P.Fernandez is very important. Please integrate these points in your manuscript.

Reply:

This information was added to Section 4.3 within the two new paragraphs.

1 Generation of a global fuel dataset using the Fuel 2 Characteristic Classification System

3
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7 8 Abstract

9 This study presents the methods for the generation of the first global fuel dataset, containing
10 all the parameters required to be input in the Fuel Characteristic Classification System
11 (FCCS). The dataset was developed from different spatial variables, both based on satellite
12 Earth observation products and fuel databases, and is comprised by a global fuelbed map and
13 a database that includes the parameters of each fuelbed that affect fire behavior and effects. A
14 total of 274 fuelbeds were created and parameterized, and can be input into FCCS to obtain
15 fire potentials, surface fire behavior and carbon biomass for each fuelbed.

16 We present a first assessment of the fuel dataset by comparing the carbon biomass obtained
17 from our FCCS fuelbeds with the average biome values of ~~was used to~~
18 ~~calculate the carbon biomass of each fuelbed, and the results were compared to the values~~
19 ~~obtained for~~ four other regional or global biomass products. The results showed reasonable a
20 good agreement both in terms of geographical distribution and biomass loads when compared
21 to other biomass data, with the best results found for Tropical and Boreal forests (Spearman's
22 coefficient of 0.79 and 0.77).

23 This global fuel dataset ~~could~~ may be used for a varied range of applications, including fire
24 danger assessment, fire behavior estimations, fuel consumption calculations and emissions
25 inventories.

26 1 Introduction

27 Fire is an important process in the Earth system, ~~affecting more than 30% of the earth's land~~
28 ~~area (Chuvieco et al., 2008)~~ with a global burned area of 3.0 to 3.8 million km² (Giglio et al.,
29 2013; Alonso-Canas and Chuvieco, 2015), and ~~having~~ multiple biophysical, and ~~and~~ ecological

1 | and socioeconomic consequences. It has shaped the Earth's vegetation through its natural
2 | history, altering vegetation composition by preventing the growth of succession by damaging
3 | some plant types while promoting others, thus creating flammable ecosystems where other
4 | vegetation would exist based solely on climate or soil (Pausas and Keeley, 2009). Fire is also
5 | an important source of atmospheric gases and aerosol particles, including greenhouse-gasses
6 | such as CO₂, CO and CH₄ (Schultz et al., 2008).

7 | The characteristics of the vegetation and the environmental conditions ~~of affecting~~ the fuels
8 | are considered the primary factors in fire initiation, behavior and effects (Rothermel, 1983).
9 | Variables such as fuel loading, fuel depth, stand structure, fuel moisture, etc., will determine
10 | fire behavior parameters such as rate of spread, fire intensity, or fuel consumption, amongst
11 | others (Cohen and Deeming, 1985). ~~These Fuel variables allow associating different~~
12 | ~~vegetation groups into~~ are commonly grouped in fuel types, following different classification
13 | systems. based on their fuel elements. Fuel types are frequently created to account for the
14 | vegetation characteristics of a particular region, such as the case of the fuels created for
15 | South-East Asia (Dymond et al., 2004), or for the Mediterranean ecosystems (Prometheus,
16 | 1999; Riaño et al., 2002). ~~In other cases, When the~~ fuel types are used as input to fire behavior
17 | models they are converted to developed around the concept of fuel models, ~~that is, they~~ which
18 | include the ~~fuel properties~~ specific parameters necessary to run ~~specific fire models~~ fire
19 | simulation programs. Such is the case of the 13 fuel models of ~~Behave the Northern Forest~~
20 | Fire Laboratory (NFFL) ~~(Anderson, 1982)~~ (Rothermel, 1972), the 20 fuel models of the
21 | National Fire Danger Rating System (NFDRS) (Cohen and Deeming, 1985), or the ~~16-17~~ fuel
22 | types of the Canadian Fire Behavior Prediction System (FBP) (Stocks et al., 1989). Other fuel
23 | type classifications were created with a broader scope. The Fuel Characteristic Classification
24 | System (FCCS) (Ottmar et al., 2007), for example, uses the concept of fuelbed to represent a
25 | relatively homogeneous unit in the landscape with a distinct combustion environment
26 | (Riccardi et al., 2007), and includes information on physical and biological variables that
27 | allow for both fuel-fire behavior (through an adaptation of the Rothermels' equations) and
28 | effects (emissions) calculations, which can be used for fuel management at different scales
29 | (McKenzie et al., 2007).

30 | Maps including information on fuel types are a necessary input for fire risk and fire effects
31 | assessment. At local or regional scale, fuel maps are useful for spatial modeling of fire risk
32 | assessment (Finney et al., 2011; Chuvieco et al., 2014) and real-time analysis of fire behavior

1 (Dymond et al., 2004; McKenzie et al., 2007). Continental or global fuel maps, meanwhile,
2 are usually used for carbon-cycle or air-quality modeling (Keane et al., 2001; McKenzie et al.,
3 2007; San Miguel-Ayanz et al., 2012), and they can also be used for the estimation of
4 continental to global fire danger (Sebastián-Lopez et al., 2001; Pettinari et al., 2014).

5 Different approaches can be used to create fuel maps. Field surveys have been used to provide
6 detailed information on fuel characteristics, but they are costly to implement, and thus are
7 only useful for small areas (Keane et al., 2001; Rollins et al., 2004; McKenzie et al., 2007).
8 Ecological modeling employs environmental gradients such as climate and topography, as
9 well as ecosystem dynamic models, to create vegetation and fuel maps (Keane et al., 2001;
10 Rollins et al., 2004). Remote sensing approaches are sound alternatives to fuel type mapping,
11 as they provide updated spatial coverage and are sensitive to some of the critical variables for
12 fuel type definition: fuel loads, horizontal and vertical continuity, fuel moisture, etc.,
13 particularly when using LiDAR observations (Riaño et al., 2004).

14 Previous fuel maps created at continental scales have relied ~~in~~on the use of remote sensing
15 information, usually reclassified to land cover classes, and ancillary data from other sources,
16 such as potential vegetation, canopy cover, etc. Some examples of continental or sub-
17 continental fuel maps are the National Fuel-type map for Canada (Nadeau et al., 2005), the
18 LANDFIRE fuel maps for the United States, which include several fuel type classifications
19 (<http://www.landfire.gov/>, accessed January 2016) and the European fuel map used by the
20 European Forest Fire Information System (EFFIS) (San Miguel-Ayanz et al., 2012).

21 The objective of this paper is presenting the methods to generate a global fuel map based on
22 the FCCS approach. Our goal was to deliver a global product to the international community
23 interested in improving the modeling of fire danger and fire effects assessment. To our
24 knowledge, global fuel maps are not yet available, thus this paper is a first attempt to generate
25 a planetary fuel dataset that is based on consistent inputs. In addition, since the FCCS is the
26 base for the fuel typology, quantitative estimations of fire risk and behavior parameters can be
27 generated from the final product. In a previous study, we created a fuel map for South
28 America using the FCCS methodology (Pettinari et al., 2014). In this study, we have extended
29 ~~the~~that methodology to create a global fuel dataset using FCCS, which required the inclusion
30 of new sources of data to reflect the characteristics of biomes and ecosystems not present in
31 South America. Also, the methodology was expanded~~based on our previous experience,~~
32 adding more spatial variability to the fuelbeds and updating some sources of information,

~~amongst other improvements. In addition, we have undertaken a first assessment of our product by comparing the biomass estimations provided by the FCCS outputs of our fuelbeds with existing regional or global biomass products, and have calculated the fuelbeds biomass to compare it with other existing biomass products. We have also built on the experience gained during the development of the South American fuel map, including some improvements to the methodology.~~

2 Methods

The development of the global fuelbed dataset is based on the Fuel Characteristic Classification System (FCCS), which is both a conceptual framework and a software tool for quantifying fuels (Ottmar et al., 2007). The fuel characteristics are organized into six strata including trees, shrubs, grasses, woody surface fuels, litter and soil organic matter (duff), and are referred to as fuelbeds. We have used version 3.0 of the FCCS software, which is integrated into the Fuel and Fire Tools (FFT, available at <http://www.fs.fed.us/pnw/fera/fft/index.shtml>, accessed September 2015). FFT is a software application that integrates different fire characteristics, behavior and effects tools developed by the Fire and Environmental Research Applications Team (FERA) of the United States Forest Service (USFS).

FCCS was selected to develop the fuel dataset because it has the advantage that it includes a wide set of physical characteristics of the fuels, and not only the ones required by a particular fire model ~~such as NFFL or NFDRS. The NFFL models were developed for uniform continuous fuels and for the severe period of the fire season~~ (Anderson, 1982; Rothermel, 1983), ~~and they do not describe fuels with higher live fuel moisture or that burn well at high humidity~~ (Scott and Burgan, 2005). ~~FCCS, meanwhile, allows creating fuelbeds for environments not contemplated by other models, such as moist ecosystems that are found in several parts of the world. Also, the parameters included in the FCCS fuelbeds also provide information on the crown and ground fuels, not included in most models only developed for surface fuels~~ (Cohen and Deeming, 1985; Scott and Burgan, 2005). This extends its use to other applications beyond fire behavior estimations, allowing also estimating crown fire potentials, the amount of available fuel, or predicting fuel consumption.

The fuelbeds to create our global fuel type dataset were developed in two stages: first land cover products and a biome map were used to identify fuelbed categories, along with their geographic location, creating a fuelbed map. Then, each fuelbed was given a set of parameters

1 that determine their fire behavior and effects. The fuelbed parameters ~~allow running can be~~
2 input in the FCCS software, and the results can be mapped joining the results to the fuelbed
3 map (Fig. 1). An example is given on estimated biomass, which is compared with external
4 databases.

5 **2.1 Generation of the fuelbeds**

6 The first stage of the development of the fuel map comprises the delineation of the fuelbeds,
7 and the creation of the map itself. A flow chart summarizing the steps to obtain fuelbeds is
8 included in Fig. 2.

9 The land cover information was extracted primarily from the GlobCover 2005 V2.2 product
10 (Bicheron et al., 2008), developed from a temporal series of MERIS (Medium-Resolution
11 Imaging Spectrometer) images acquired between December 2004 and June 2006. This
12 product has a spatial resolution of 10 arc seconds (~300 m at the Equator) and its legend was
13 defined using the Land-cover Classification System (LCCS) of the United Nations' Food and
14 Agricultural Organization (Di Gregorio, 2005). The GlobCover V2.2 has both global and
15 regional maps. The global map uses the Level 1 of LCCS, which consists of 22 classes, 18 of
16 which include vegetation. In addition to the global Globcover 2005 product, other land cover
17 products were used to solve some problems or limitations that we found in this map. For
18 instance, the Global GlobCover product did not include a specific class for needleleaved
19 deciduous forests (ND), which was mixed with the needleleaved evergreen (NE) forests.
20 Since both categories have distinct fire behavior, the regional GlobCover V2.2 maps
21 (Bicheron et al., 2008) corresponding to Eastern Europe and Central Asia were used, as they
22 discriminate between NE and ND. For our map, the pixels from the global map were
23 reclassified into those two categories following the regional GlobCover maps classification.

24 Another important adaptation of the global land cover map was linked to the Australian
25 eucalyptus class, which was included in the standard Globcover with the broadleaved
26 evergreen or semi-deciduous (BE) forests. However, it is well known that *Eucalyptus sp.* is
27 much more flammable than other major broadleaved evergreen species due to their high
28 concentration of volatile compounds (Kesselmeier and Staudt, 1999) and the production and
29 accumulation of large amounts of flammable litter from the leaves and bark (Agee et al.,
30 1973). Since these species are one of the primary tree species in the Australian continent,
31 specific fuelbeds were created for that region. The GlobCover product assigned vast regions

1 of Australia as broadleaved deciduous (BD) forests, which was in disagreement with other
2 sources of Australian vegetation information (Department of the Environment and Water
3 Resources, 2007). In order to account for this, the map of Major Vegetation Groups in
4 Australia V3.0 ([http://www.environment.gov.au/resource/major-vegetation-groups-](http://www.environment.gov.au/resource/major-vegetation-groups-australia#map)
5 [australia#map](http://www.environment.gov.au/resource/major-vegetation-groups-australia#map), accessed September 2014) was used to reclassify the pixels from BD to BE
6 (mainly eucalyptus and acacias) when the Australian map showed a majority of this type of
7 vegetation. A new land cover class was created to represent this type of vegetation.

8 Regarding the crops, even though the GlobCover V2.2 product only distinguishes between
9 rainfed and irrigated croplands, fuel conditions and biomass are very different in some of the
10 most extended crops. To assign individual crops species to the cropland classes the
11 ‘Harvested Area and Yield of 175 crops’ map was used
12 (<http://www.geog.mcgill.ca/landuse/pub/Data/Agland2000/>, accessed September 2014). This
13 map shows the global distribution of 175 different crops according to crop areas, yields,
14 physiological types and primary production in the year 2000, based on satellite data sets and
15 national and regional agricultural statistics (Monfreda et al., 2008). Only the 15 crops with the
16 highest global harvested area were considered, and these data were extracted from the
17 FAOSTAT’s crops production database (Food and Agriculture Organization of the United
18 Nations, Statistics Division, <http://faostat3.fao.org/faostat-gateway/go/to/download/Q/QC/E>,
19 accessed September 2014). The land cover classes that include croplands were subdivided
20 according to the world countries’ first order administrative divisions (extracted from the ESRI
21 World Administrative Division Map,
22 <http://www.arcgis.com/home/item.html?id=d86e32ea12a64727b9e94d6f820123a2>, accessed
23 September 2014). For each land cover and administrative division, the crop with the highest
24 harvested area from the 15 crops considered was identified, and assigned to that land cover
25 class and region. For the countries with no information in the crop’s map, the crop was
26 assigned based on the FAOSTAT statistics.

27 Once the global land cover classes were complemented with the ancillary information, some
28 of the classes were combined. Both rainfed and irrigated were grouped when they
29 corresponded to the same crop, because they did not represent a difference in vegetation
30 characteristics for the objective of the fuelbed classification. Also, the classes that differed
31 only in their vegetation density (close or open) were merged.

1 The biomes description was extracted from the Map of Terrestrial Ecoregions (Olson et al.,
2 2001), as it is widely used by different international organizations, including the World
3 Wildlife Fund (WWF). The description includes 14 global vegetated biomes and more than
4 800 ecoregions. In order to decrease the total number of fuelbeds, we considered that it was
5 possible to eliminate biomes 9 (Flooded Grasslands and Shrublands) and 10 (Montane
6 Grasslands and Shrublands), as they shared many vegetation characteristics with other
7 fuelbeds in nearby biomes. The different patches of these two biomes were reclassified to the
8 biomes that limited with them. As a result, a total of 12 vegetated biomes were considered for
9 the combination with the land cover classes.

10 The intersection of the land cover classes and the biomes was performed at the spatial
11 resolution of the land cover map. An area map was developed to represent the area of each
12 10- arc-second pixel of the GlobCover map, and it was used to calculate the total area of each
13 possible combination of land cover class and biome. The combinations with low
14 representation (<0.01% of global land area: 14,900 km²) were reclassified into other similar
15 categories. With this step, the final fuelbed map was generated, with the delineation and the
16 geographic location of the global fuelbeds.

17 **2.2 Parameterization of the fuelbeds**

18 Once the spatial distribution of the fuelbeds was defined, a set of parameters that affect fire
19 behavior and effects was assigned to each fuel stratum (tree, shrubs, grasses, woody surface
20 fuels, litter and ground fuels). These parameters are listed in Table 1. A flow chart of the steps
21 followed is shown in Fig. 3.

22 Percentage cover of trees was extracted from the MODIS Vegetation Continuous Field
23 (VCF), Collection 5 (DiMiceli et al., 2011) corresponding to the year 2005, to be coetaneous
24 with the base land cover product. This product has a spatial resolution of 250 m (Carroll et al.,
25 2011) and describes the percent of a pixel which is covered by tree canopy (>5 m high). The
26 map was resampled to the land cover spatial resolution. In order to include more variability in
27 canopy cover (CC) than in previous studies (Pettinari et al., 2014), the percentage of CC was
28 subdivided into 3 classes: 0-40% (named class A), 40-70% (class B) and 70-90% (class C) as
29 shown in (Fig. 4). The value of 40% was assigned because that is the threshold used in FCCS
30 to decide if canopy fire spread can occur (Prichard et al., 2013). The 70% threshold was
31 assigned to divide the rest of the existing canopy percentage in two equal parts. No valid

1 values above 90% appeared in the resampled map. The area of each fuelbed corresponding to
2 each CC class was calculated. If a fuelbed included two or three CC classes with an area
3 higher than 0.01% of global land area, it was subdivided into as many sub-fuelbeds as
4 complied with the minimum area criterion. Otherwise, it remained as a single fuelbed. After
5 this step, the canopy cover mean value was calculated for each fuelbed or sub-fuelbed, and
6 assigned to it.

7 Canopy height was extracted from the global canopy height map developed by Simard et al.
8 (2011), which was created using LiDAR data and ancillary data corresponding to slope,
9 climate and vegetation characteristics. The LiDAR data was acquired in 2005 by the
10 Geoscience Laser Altimeter System (GLAS) on board the ICESat mission ([http://nsidc.org/
11 data/icesat/index.html](http://nsidc.org/data/icesat/index.html), accessed May 2015). The canopy height database had a spatial
12 resolution of 1 km, and was resampled to the land cover map resolution using nearest
13 neighbor interpolation. As in the case of the canopy cover, the mean value of the canopy
14 height was calculated for each fuelbed or sub-fuelbed, and assigned as one of the required
15 parameters of the fuelbeds.

16 To assign the main species of trees, shrubs and grasses to each fuelbed, the representative
17 plant species for each biome were extracted from the description of the Terrestrial Ecoregions
18 of the World Wildlife Fund (WWF) ([http://www.worldwildlife.org/biome-categories/terrestrial-
19 ecoregions](http://www.worldwildlife.org/biome-categories/terrestrial-ecoregions), accessed September 2014). One or two representative species of each type of
20 vegetation were assigned to each individual fuelbed from the list available within FCCS,
21 considering the vegetation form and foliage type most characteristic within every fuelbed. In
22 the case of the crop fuelbeds, the 15 crops considered were grouped to 10 categories,
23 according to their characteristics, and they were assigned the most similar agricultural fuelbed
24 from the ones developed by French et al. (2013).

25 The remaining variables for each fuelbed (Table 1) were assigned based on information from
26 existing fuelbeds in the FCCS database or from the Natural Fuels Photo Series from Mexico
27 (Morfín-Ríos et al., 2008) and Brazil (Ottmar et al., 2001). The existing FCCS database,
28 which includes fuelbeds in most biomes, from the Alaskan Tundra to the Tropical forests of
29 Florida and Hawaii, was used if possible, because its fuelbeds have all the necessary
30 parameters required to calculate the fire potentials. For each global fuelbed, the existing
31 similar FCCS fuelbeds were selected based on the biome in which they appear and their
32 vegetation form, foliage type and plant species, and the mean values of their parameters were

1 used to populate the global fuelbed variables, with some adjustments in the tree layer if
2 necessary due to the differences in canopy cover and/or height. The Natural Fuels Photo
3 Series were used primarily for the tropical fuelbeds because they most accurately represent
4 the vegetation found in those biomes. Some variables were ~~populated~~assigned based on
5 expert opinion whenever there was no other information available.

6 **2.3 Fuel map assessment**

7 ~~It is not possible to~~ Strict validation of our product was not feasible as it would imply a huge
8 groundwork effort, particularly to obtain average fuel parameters. Comparison with other fuel
9 products was also problematic, as regional fuel types use ~~e directly the results of the fuelbed~~
10 ~~map created in this study, because there is no other global product available with the same~~
11 ~~characteristics, and regional products use~~ many different classification systems (Rollins,
12 2009; San Miguel-Ayanz et al., 2012). For these reasons, as a first assessment of the fuelbed
13 dataset we decided to compare estimations produced by FCCS with existing databases.
14 ~~Therefore, we decided instead to compare variables estimated from our global fuelbed product~~
15 ~~with the same variables obtained from different modeling approaches.~~ We selected the carbon
16 biomass ~~value obtained from FCCS,~~ since ~~as~~ this variable has been modeled at global and
17 regional scales by different research groups.

18 FCCS estimates the amount of total biomass and carbon load per stratum based on the
19 parameters assigned to each strata and a set of biomass equations for different types of
20 vegetation (Prichard et al., 2013), ~~as~~ This biomass is used for the calculation of the
21 available fuel potential and biomass consumption in the Consume Module inside FFT
22 (<http://www.fs.fed.us/pnw/fera/fft/consumemodule.shtml>, accessed ~~December 2014~~January
23 2016). For our product, once the biomass values were computed at the raw resolution of the
24 database (~300-9 ham), they were aggregated into 0.5 x 0.5 degree cells. Cells with
25 homogeneous land cover types (>80% of the cell) were selected for the comparison exercise
26 ~~with other sources of biomass estimation~~. The following biomass products were compared
27 with our estimations:

- 28 • Global biomass from the Orchidee Dynamic Global Vegetation Model (DGVM) (Krinner
29 et al., 2005), as estimated from Yue et al. (2015). The biomass was obtained from a
30 vegetation distribution map classified into 13 plant functional types based on the IGBP
31 vegetation map (Loveland et al., 2000).

- 1 • Northern boreal and temperate above ground biomass (AGB) from the carbon stock and
2 density map developed by Thurner et al. (2014). This map is based on the growing stock
3 volume (GSV) estimates obtained with the Biomasar-H algorithm (Santoro et al., 2011)
4 using ENVISAT ASAR images.
- 5 • Tropical biomass from the aboveground live woody vegetation carbon density map
6 developed by Baccini et al. (2012).
- 7 • Tropical biomass from the forest carbon stocks map developed by Saatchi et al. (2011).

8 Both of these tropical biomass datasets (from now on referred as the Baccini and Saatchi
9 maps) use similar ~~input data layers~~remote sensing inputs, mainly the LiDAR data from the
10 ICESat GLAS, but they use different ground-based datasets and modeling methods to extend
11 the GLAS footprints to full-coverage AGB maps. The differences between the two maps are
12 described in Mitchard et al. (2013).

13 **3 Results**

14 **3.1 Global fuelbed map**

15 The final fuelbed map contains 274 main fuelbeds. As some of them were subdivided
16 considering their canopy cover, the value increased to 359 when the sub-fuelbeds were
17 considered. The resulting fuelbed map is shown in Fig. 5. Each fuelbed is identified by a
18 number where the first two digits correspond to the biome, and the following three identify
19 the land cover type associated with a pixel. For example, fuelbed 13140 is in the Desert and
20 Xeric Shrublands biome (13) and associated with grassland vegetation (140).

21 The inclusion of the regional Globcover maps of Eastern Europe and Central Asia resulted in
22 the creation of 30 dedicated ND fuelbeds or sub-fuelbeds in biomes 11 (Tundra), 8
23 (Temperate Grasslands, Savannas and Shrublands), 6 (Boreal Forest/Taiga), 5 (Temperate
24 Coniferous Forests) and 4 (Temperate Broadleaf and mixed Forests). Similarly, 25 fuelbeds or
25 sub-fuelbeds were created specifically for Australia, in biomes 4, 8, 7 (Tropical and
26 Subtropical Grasslands, Savannas and Shrublands), 12 (Mediterranean Forests, Woodlands
27 and Scrub) and 13 (Desert and Xeric Shrublands). The fuelbed with the largest area is 1040
28 (Broadleaved evergreen or semi-deciduous forest vegetation in a Tropical/Subtropical moist
29 broadleaf forest biome), with 10.4 million km², which is subdivided in 3 sub-fuelbeds: 1040a
30 (1-40% canopy cover) with 1.7 million km², 1040b (41-70% CC) with 2.9 million km², and

1 1040c (71-90% CC) with 5.8 million km². The second largest area, with 4.3 million km²,
2 belongs to both the Sparse Vegetation in the Tundra biome (fuelbed 11150), and the
3 Needleleaved Evergreen Forest in the Boreal Forest/Taiga Biome (fuelbed 6091), which is
4 subdivided into two sub-fuelbeds: 6091a (1.8 million km²) and 6091b (2.5 million km²).

5 **3.2 Carbon Biomass**

6 Fig. 6 shows ~~the map with the the FCCS estimations of~~ carbon biomass values
7 estimated/computed from our product ~~the global fuelbed dataset aggregated at 0.5 x 0.5 degree~~
8 pixels. There were 11 fuelbeds with biomass higher than 200 MgC ha⁻¹. All of these fuelbeds
9 represent forests with high canopy cover (sub-fuelbeds b or c). In 5 of those fuelbeds the main
10 sources of biomass were the trees; these were the sub-fuelbeds 12091b, 5100c, 12061b, 4091c
11 and 4043c, which correspond to Temperate and Mediterranean forests. In the remaining 6
12 fuelbeds with highest biomass, the main source of carbon biomass was located in the ground
13 fuel stratum, corresponding to the duff. These sub-fuelbeds were located in the Mangrove
14 (14170c), in Temperate ND (4092b), in Boreal (6091c, 6092c, 6102b), and in Tundra
15 (11091b) forests.

16 The comparison between the biomass results in this study and the other products used for our
17 comparison exercise (also aggregated at 0.5 x 0.5 degree resolution) is shown in Table 2. This
18 table shows mean and standard deviation values for different biomes, as computed from
19 homogeneous land cover cells. It also includes the Spearman's rho correlation coefficient
20 between the different products and the results from our study. Fig. 7 shows the biomass
21 distribution of the different products in the form of box plots.

22 The tropical forest carbon biomass shows the highest consistency between our estimations
23 and the external products used for comparison, with a Spearman's coefficient of 0.79 between
24 this study and the Baccini product. Only the Orchidee estimations are clearly above the others
25 (by 40%). The box plot distribution (Fig. 7(a)) also show a similar biomass distribution
26 amongst the fuelbeds and the Baccini and Saatchi map, with the Orchidee one having the
27 biggest discrepancies.

28 Regarding the boreal forests fuelbeds, the values obtained in this study for total carbon
29 biomass are 3.5 to 3.7 times higher than the other biomass products, which is easily
30 appreciable in Fig. 7(b). As described earlier in this section, in some of the fuelbeds with
31 highest biomass located in boreal, tundra or temperate biomes, a significant proportion of

1 | biomass for these regions is stored in the ground fuel stratum. The BiomasarH product
2 | includes above ground biomass (AGB) and root biomass, but does not have a duff component.
3 | For this reason, the values of carbon biomass corresponding only to the tree stratum of the
4 | fuelbeds were used for comparison. In that case, the tree carbon biomass from this study was
5 | similar to the BiomasarH for the boreal forest (only 5% lower). The Spearman's coefficient
6 | ($\rho_s=0.77$) also shows a significant correlation between the results obtained for this study and
7 | the BiomasarH data. Finally, taking into account only the tree biomass of the temperate
8 | forests obtained for the fuelbeds, the mean and median values obtained is higher than the
9 | values obtained for the Orchidee and BiomasarH products (see Table 2 and Fig. 7(d)). The
10 | correlation coefficients are also low to moderate ($\rho_s = 0.39$ and 0.42 , respectively).

11 | The mean biomass of the grasses fuelbeds is similar to the one obtained from the Orchidee
12 | biomass map, but the correlation is poor ($\rho_s = 0.20$). The box plot in Fig. 7(f) shows a
13 | significant number of outlier values that could explain this low coefficient. In the case of the
14 | savanna+shrub areas, on the other hand, the mean biomass values are much lower for the
15 | fuelbeds than for the Orchidee estimations (52%). The box plot for this land cover (Fig. 7(e))
16 | show that the median values are similar for both products (7.04 for this study and 6.23 for the
17 | Orchidee map), but the mean value is different due to the much higher positive skew of the
18 | Orchidee biomass data. Still, the value obtained for the Spearman's correlation is moderate
19 | ($\rho_s=0.66$), showing a reasonable association between the values of the two products.
20 | Regarding the crops biomass (Fig. 7(c)), the differences in the skewness and the median
21 | values (3.76 vs. 8.56) between the two distributions are more appreciable. This results in the
22 | mean biomass of the Orchidee product being 2.3 times higher than the value obtained for this
23 | study.

24 | **4 Discussion**

25 | The fuelbed map developed in this study is the first global product that describes the
26 | characteristics of the vegetation related to fire behavior and effects, and should be useful for
27 | studies modeling fire impacts on the climate system as well as fire risk and fire management
28 | analysis. While different global land cover maps are available (e.g. Loveland et al., 2000;
29 | Bartholomé and Belward, 2005; Bicheron et al., 2008), none of these products can be directly
30 | used to determine fire behavior, because they lack the required parameters to run fire behavior
31 | models. The fuelbeds, on the other hand, include the necessary information on fuel

1 characteristics to be input in FCCS, and can provide estimations of fuel potentials, biomass,
2 and surface fire behavior.

3 To generate a global fuel dataset product several generalizations and assumptions had to be
4 made, which prevent the comparison of our product with regional more-detailed products. In
5 addition, the uncertainty of each input variable to generate the final database should also be
6 taken into account if using our product for regional-scale studies. A few thoughts on our
7 product limitations and strengths follows.

8 **4.1 Fuelbed Map**

9 The development of the global fuelbed map includes several improvements compared to the
10 previous product elaborated using this methodology, corresponding to the fuel map of South
11 America (Pettinari et al., 2014). Supplementary information was added to the canopy stratum,
12 which now includes a secondary layer of trees, and also duff information was incorporated,
13 which is particularly relevant in the temperate and boreal biomes of the Northern Hemisphere.
14 This information adds to the total fuel and biomass information, and affects both the behavior
15 outputs and total available carbon biomass. The canopy cover data was also improved. On the
16 one hand, a more recent version of the MODIS VCF was used (collection 5 vs. collection 3),
17 which has a higher accuracy compared to previous versions (Townshend et al., 2011). And on
18 the other hand, the subdivision of the canopy cover into 3 groups, as well as the creation of
19 sub-fuelbeds according to percentage of canopy cover, allowed obtaining more realistic
20 results than before, because it allowed keeping a higher variability of canopy structure than in
21 the case of using one mean value for the whole fuelbed.

22 Another improvement for this global map was the use of mean values from several existing
23 fuelbeds or Photo Series, instead of using only one existing value as representative of each of
24 the global fuelbeds. The use of different existing data of the same land cover and biome
25 combination, but from separate locations, provided a better characterization of the diverse
26 ecosystems, generalized by the use of the mean values. With this approach, each global
27 fuelbed represents the mean conditions that could be found in different ecosystems of the
28 same land cover – biome combination.

29 The disaggregation of the cropland land cover, addressed as the selection of crop species with
30 highest cultivated area per administrative division, also improved the characterization of the
31 crops' fuelbeds compared to the previous product. While the viability of different crops is

1 dependent on biophysical parameters (Sacks et al., 2010), it is also affected by socio-
2 economic factors (Rasul and Thapa, 2003; Olesen et al., 2011). Distinct crops have different
3 biomass, react differently to fire, and also the period and conditions in which crops are
4 usually burned are not the same. For example, most of the crops are burned after harvest, to
5 eliminate crop residue and for pest and weed control (Jenkins et al., 1992; McCarty et al.,
6 2009). Sugar cane, on the other hand, is usually burned previous to harvesting, to remove
7 trash, kill pests and facilitate the harvesting process (Cannavam Rípoli et al., 2000), and for
8 this reason the biomass is live, and its amount is high compared to other crops. The inclusion
9 of different crop fuelbeds in different geographic regions of the same land cover-biome
10 combination tackles these issues, and will be able to provide more realistic results when fire
11 behavior or effects are calculated from the fuelbed map.

12 The FCCS fuelbed database and the Photo Series from which the global fuelbeds were
13 created, while including data from the different existing biomes, reflect the conditions of
14 American ecosystems, and do not have information from other continents. Many studies have
15 shown continental differences within biogeographical regions, including species richness
16 (Barthlott et al., 2007; Kreft and Jetz, 2007), total biomass (Saatchi et al., 2011; Baccini et al.,
17 2012; Banin et al., 2014; Thurner et al., 2014), and fire behavior (Lehmann et al., 2014;
18 Rogers et al., 2015). Some of the most evident differences regarding vegetation behavior to
19 fire were addressed with the inclusion of the regional GlobCover map to account for
20 needleleaved deciduous trees (*Larix*) in Asia (fuelbeds with land covers 92, 102, 112 and
21 122), and with the creation of specific fuelbeds for Australia with *Eucalyptus* vegetation (land
22 covers 43, 113, 123 and 133). The disaggregation of the crops also tackled this issue. Still,
23 variation of vegetation structure and characteristics within different continents has not been
24 directly addressed, and mean values from global canopy cover and height were used for each
25 fuelbed.

26 At this point, only the existing FCCS fuelbeds and the Photo Series were used to populate the
27 global fuelbed parameters, because they include all (in the case of the FCCS fuelbeds) or most
28 (in the case of the Photo Series) of the required variables. Many other vegetation databases
29 exist, but they only have information for some of the parameters required. For instance, there
30 are few field databases that include information on dead woody fuels, such as some in the
31 Brazilian Amazon (Cochrane et al., 1999) or in South African and Zambian savannas (Shea et
32 al., 1996). This fuel stratum is critical in determining surface fire behavior, and as such should

1 be included in the information used for the creation of the fuelbeds. But many databases,
2 while having detailed information on tree characteristics, do not specify the dead woody fuels
3 or other surface fuels such as shrubs or grasses (Prasad et al., 2001; Muche et al., 2012). Also,
4 information on litter, lichen, moss and duff loadings (which affect the total combustible
5 biomass and the fire emissions) is usually published without including detailed data on the
6 rest of the fuels present in the site (Harden et al., 2006). Future improvements of the fuelbed
7 map will involve the inclusion of fuel data from other continents, developing methods to
8 homogenize the information from different sources into fuelbed variables.

9 The global fuelbed map maintains some of the same limitations as the South American map.
10 Modeling terrestrial ecosystems at a global scale implies the use of a generalized
11 representation of their characteristics (Running and Hunt, 1993). This necessary
12 generalization of the fuelbeds loses much of the complexity of the ecosystems, as mean
13 values of the fuel parameters are assigned globally. Also, only one representative species (or
14 two in the case of mixed forests) were assigned for each vegetation stratum. For this reason,
15 while it is appropriate for global or continental applications, it should be used carefully when
16 working at ~~country~~ or more ~~local~~ detailed scales. Adjustments to the fuelbed parameters
17 should be applied to approximate them to particular regions if possible.

18 The map also carries the uncertainties and limitations of the original products from which it is
19 based. The GlobCover product, as any other land cover map, includes some misclassification
20 of pixels in certain regions, which has been addressed in their validation report (Bicheron et
21 al., 2008). Also, the Olson biomes' map has ~~sharp~~ abrupt boundaries between biomes, while ~~in~~
22 ~~reality there is a~~ gradual transition of environmental variables and vegetation cover between
23 adjacent biomes are more realistic (Walker et al., 2003).

24 **4.2 Carbon Biomass**

25 Even though the objective of our study was not estimating carbon biomass, we considered
26 ~~comparing this variable-output of FCCS with other products as a suitable indicator to provide~~
27 ~~a first assessment of our results, as this variable has been estimated by different~~
28 ~~methodologies. In this regard, we can consider~~ the comparison can be considered quite
29 successful, as the main spatial trends and actual values of our product agree quite acceptably
30 with existing ones, particularly when considering the differences in methods and scopes
31 between ~~the compared~~ products that were compared.

1 Terrestrial biomass is an essential indicator for the monitoring of Earth's ecosystems and
2 climate and for studying biogeochemical cycles, and has promoted the development of many
3 biomass maps in the past few years. We selected diverse products for the comparison of the
4 fuelbeds' biomass, which were generated employing different methods. As a global biomass
5 product, we used the map obtained by the Orchidee DGVM (Yue et al., 2015), because the
6 biomass is calculated separately for different fuel strata, and we were able to select the layers
7 that corresponded to the fuel strata from the fuelbeds, hence obtaining comparable results.
8 Although there is a global biomass product currently available (Ruesch and Gibbs, 2008), it
9 includes data of both living above and below (root) ground biomass. Since the fuelbeds do not
10 include root biomass information, while they do include information on dead ground fuels,
11 the two products were not analogous. We also compared the biomass from the most important
12 forested regions of the world (tropical forests, and northern hemisphere temperate and boreal
13 forests) with products developed using remote sensing technology: Envisat ASAR in the case
14 of the BiomasarH product (Santoro et al., 2011), and GLAS in the tropical forest maps
15 (Saatchi et al., 2011; Baccini et al., 2012).

16 The carbon biomass values for the boreal forests obtained in this study (considering only the
17 tree stratum) were very similar to those obtained for the BiomasarH map, with only a 5%
18 difference in their mean (30.9 vs 32.4 MgC ha⁻¹). Also, both these products and the Orchidee
19 estimations had a similar distribution of the values (see Fig. 37(b)). On the other hand, when
20 the biomass obtained for all the strata of the fuelbeds was considered, the resulting biomass
21 was much higher. This reflects the significant contribution of the ground fuels to the total
22 carbon pool, as shown in other studies (Yu et al., 2010).

23 In the case of the temperate forests, our estimations differed from the BiomasarH's in about
24 30%. This divergence can be explained by different reasons. First, it should be noted that both
25 products are based on different land cover maps: while the fuelbeds are based on the
26 GlobCover 2005, the land cover map used to determine the forest pixels in BiomasarH was
27 the GLC2000 (Bartholomé and Belward, 2005), with a different spatial resolution (1 km
28 versus ~~10 arc-seconds~~ ~ 300 m in our case). Different land cover products generally agree in
29 land cover classification in relatively homogeneous areas, whereas in heterogeneous
30 landscapes or transition zones the disagreement between diverse products can be high (Song
31 et al., 2014). The temperate biome includes some of the widest cropland areas, in many cases
32 intermixed with forest regions or other natural vegetation (García-Feced et al., 2015). These

1 heterogeneous landscapes can be easily classified as forest, mosaic forest with crops or other
2 vegetation, or even other classes, depending on the satellite sensor systems, the classification
3 algorithms, or the diverse legends of the different land cover products. This could cause
4 discrepancies between the two products that are being compared. Simultaneously, as the
5 objective of the biomass assessment was to compare homogeneous land cover areas, only the
6 0.5° pixels which had at least 80% of forest fuelbeds (or mosaics with predominant forest
7 fuelbeds) were included in the analysis, and many European forested areas were excluded.
8 These forests have the highest carbon biomass value in the BiomasarH map (Thurner et al.,
9 2014), and their exclusion explains why the values in Table 2 were lower than the ones
10 obtained for this study (49.5 vs 70.6 MgC ha⁻¹). But if the total BiomasarH forest pixels in
11 the temperate biome are analyzed (see Thurner et al. (2014), Table 3), the results show values
12 between 58 and 62 MgC ha⁻¹, ~~which are much more similar to our estimations~~
13 ~~obtained in this study.~~

14 For the tropical forests, the value obtained as the mean biomass from all the pixels with
15 homogeneous forest cover was within the values found for the other three maps, and closest to
16 the Baccini map (110.0 MgC ha⁻¹ ~~in the case of the fuelbeds~~ ~~for our estimations versus~~ ~~and~~
17 109.1 MgC ha⁻¹ ~~in for~~ the Baccini ~~map~~ ~~product~~). The two tropical biomass maps show
18 differences in local biomass values, which have been explored and described by Mitchard et
19 al. (2013; 2014). The results from our analysis showed biomass values for the Baccini higher
20 than for the Saatchi one, which is in line with the results obtained by Mitchard et al. (2013).
21 Even a combined product has been proposed to reduce the discrepancies (Langner et al.,
22 2014). For the purpose of our analysis, we considered the separate products to be both
23 adequate as comparison data. As in the case of the boreal and temperate forests, the biomass
24 from the fuelbeds' map represent a global mean, and do not take into consideration the
25 continental variations. The values of carbon biomass for tropical forests obtained for the
26 Orchidee map were around 30% higher than the fuelbed map; that could be explained in part
27 because the Orchidee model does not include forest degradation (C. Yue, personal
28 communication). Another important note should be made regarding the methodology used to
29 obtain the carbon biomass values. Orchidee, as many other DGVMs, rely on the use of plant
30 functional types (PFT) to parameterize vegetation properties (Poulter et al., 2011). PFTs
31 aggregate multiple species traits according to physiognomy, phenology, photosynthetic
32 pathway and climate, resulting in a group of small functional classes (Bonan and Levis,
33 2002). In the case of the Orchidee map, the PFTs were created assigning vegetation

1 proportions from the IGBP DISCover map (Loveland et al., 2000), and the resulting PFTs
2 include classes of woody vegetation (tropical, temperate or boreal; broadleaved or
3 needleleaved; summergreen, raingreen or evergreen) and grasses and crops (both C3 and C4).
4 This means that the vegetation characteristics are generalized to a much greater extent than in
5 our fuelbed classification.

6 The differences between the savanna+shrub biomass results between the Orchidee and the
7 fuelbed maps (15.5 vs 8.1 MgC ha⁻¹) could be explained both due to the discrepancies
8 between the undelaying land cover products, and because the biomass assigned for the woody
9 vegetation in Orchidee does not account for the lower biomass of the shrublands compared to
10 forested areas. These discrepancies are likely aggravated in the case of the croplands.
11 Cultivated areas are one of the most difficult categories to classify in land cover maps, since
12 they can be confused with natural grasslands, and can also be characterized as different kinds
13 of mosaics, depending on the sensor, criteria, threshold, etc., used for the land cover map
14 development (You et al., 2008; Fritz et al., 2015). Discrepancies in cropland classification
15 will produce significant variation in biomass results, especially when comparing crops after
16 harvest with very low biomass (as are most of the fuelbed crop categories) versus other land
17 cover categories such as shrubland or forests.

18 In all, the carbon biomass obtained for the fuelbeds show acceptable results compared to the
19 other products analyzed. The results also show consistency between the diverse approaches
20 used to develop the different maps. Future work could include further information to the
21 assessment of the biomass results, such as an estimation of soil carbon biomass using data
22 extracted from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC,
23 2012), as was done by Carvalhais et al. (2014).

24 Future work will also analyze the continental differences in biomass from other products, in
25 order to improve the spatial distribution of biomass worldwide. This is related to the
26 incorporation of fuel data from different continents, as stated in the previous Section.

27 **4.3 Possible applications of the fuel dataset**

28 The global fuelbed dataset developed in this study can be used for different applications, as
29 the FCCS includes a wide set of characteristics of the fuels, and not only the ones required for
30 a particular fuel model. For example, FCCS calculates three fuel potentials (surface fire
31 behavior potential, crown fire potential and available fuel potential) using benchmark

1 environmental variables, which can be used to evaluate fire danger based solely on fuel
2 characteristics (Sandberg et al., 2007; Prichard et al., 2013). Also, specific environmental
3 variables (fuel moisture, slope and wind speed) can be assigned to calculate expected surface
4 fire behavior for different weather conditions, as it provides results on rate of spread, flame
5 length and reaction intensity. Furthermore, the available fuel and carbon results obtained for
6 each fuelbed can be used to calculate fuel consumption and pollutant emissions using tools
7 such as Consume (Prichard et al., 2005).

8 All these results provide information for different applications. The fuelbed map could be
9 used for global or continental fire danger assessment, using the values of fire potentials or fire
10 behavior to complement existing early warning systems, such as EFFIS,
11 (<http://forest.jrc.ec.europa.eu/effis/>) (San Miguel-Ayanz et al., 2012) or the Global Wildland
12 Fire Early Warning System (GWFEWS, <http://www.fire.uni-freiburg.de/gwfews/>) (de Groot
13 et al., 2006). For those countries lacking information on fuel types, it may enhance current
14 fire danger systems that are based solely on weather information.

15 Finally, our product could also be used to calculate emissions from wildland fires at country
16 or continental scale from Consume or other fire emission models, complementing information
17 supplied by other products as the Global Fire Emissions Database (GFED,
18 <http://www.globalfiredata.org/>, accessed September 2015).

19 Due to the resolution of the map and the global characteristics of the fuelbeds, all of these
20 applications are intended for regional to global studies and are not intended for the local scale.
21 For example, this map is not intended to predict “real-world” fire behavior at a local scale,
22 which would need a much finer spatial resolution of the fuelbeds and equally detailed weather
23 information. For this purpose, other systems such as FlamMap (Finney, 2006) or FARSITE
24 (Finney, 2004) would be a more appropriate option.

25 To obtain a more detailed fuelbed map for a local region (such as a country or province) we
26 would suggest to use the methodology described in this article to create a custom fuelbed
27 map, using local vegetation information if possible. If no local information is available, it
28 would be possible to create a dataset with the same data sources used in this article, but
29 assigning mean information on canopy cover, height, and fuelbed parameters related only to
30 the study area, thus describing better the local conditions.

1 Future research will focus on the application of this fuelbed dataset to different fire
2 management issues, particularly obtaining fire behavior and potentials values for fire danger
3 estimation.

4 **5 Conclusions**

5 This study developed the first global fuel dataset for modeling wildland fire danger and fire
6 effects. The dataset is based on the Fuel Characteristic Classification System (FCCS), and
7 includes parameters that may be used to obtain quantitative estimations of fire behavior
8 variables. The geographical distribution of the fuelbeds was created by combining the
9 GlobCover 2005 V2.2 land cover map and the Olson biomes' map, with the aid of some
10 ancillary information for particular land cover types or regions. A total of 274 fuelbeds were
11 created (359 if the sub-fuelbeds are considered). Each fuelbed was assigned a set of
12 parameters related to fire behavior, extracted from global or regional databases. With these
13 parameters, FCCS can be run to obtain fire potentials, surface fire behavior and carbon
14 biomass for each fuelbed.

15 A comparison between the carbon biomass obtained for our fuelbeds and four other regional
16 or global biomass products showed reasonable agreement both in terms of geographical
17 distribution and biomass load. The highest Spearman's rho coefficients were found for
18 Tropical and Boreal forests ($\rho_s = 0.79$ and 0.77 , respectively), with moderate results for the
19 remaining land covers analyzed (coefficients between 0.20 and 0.66).

20 This fuel map could be used for a varied range of applications, including fire danger
21 assessment, fuel consumption calculations or emissions inventory. The resulting global
22 fuelbed map in GeoTIFF format, as well as a spreadsheet containing all the variables assigned
23 to each fuelbed and the sources of the information used for their creation, is available from
24 Pettinari (2015).

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1 Table 1: Parameters assigned to each fuelbed

Stratum (and categories)	Parameter
Canopy (primary and secondary layers)	Percent cover ^a , height ^a , height to live crown (HLC), tree density, diameter at base height (DBH), existence of ladder fuels, tree species and relative cover ^b
Shrub (primary layer)	Percent cover, height, percent live, shrub species and relative cover ^b
Herb (primary layer)	Percent cover, height, percent live, load, herb species and relative cover ^b
Woody fuels (sound woody)	Percent cover, depth, fuel load by size class (1-hr, 10-hr, 100-hr, 1000-hr)
Litter, lichen and moss	Percent cover, depth, litter arrangement and percent relative cover by type, moss type
Ground Fuels (upper and lower duff)	Percent cover, depth, type

2 ^a These data were extracted from global products developed from remote sensing. ^b Plant
 3 species were assigned based on vegetation form and foliage type. The rest of the variables
 4 were extracted from existing databases.

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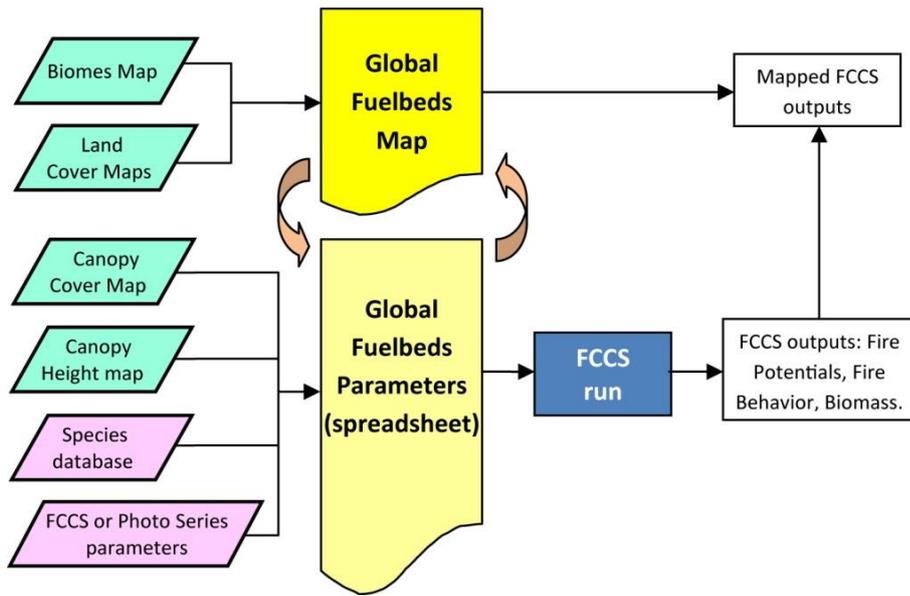
1 Table 2: Carbon Biomass obtained as mean values of the 0.5 degree pixels with at least 80%
 2 of the land cover analyzed, in units of MgC ha⁻¹. Standard deviation values are shown in
 3 parenthesis. The values of the Spearman's rho coefficient compared to the results from this
 4 study are shown in brackets*.

Land Cover	This study, total biomass	Orchidee ^a	Baccini ^b	Saatchi ^c	Biomasar-H, AGB ^d	This study, tree biomass only
Tropical Forest	110.0 (50.3)	146.6 (64.1) [0.67]	109.1 (46.3) [0.79]	99.4 (42.4) [0.59]		
Boreal Forest	107.3 (36.6)	28.8 (17.7) [0.27]*			30.9 (13.6) [0.77]*	32.4 (19.6)
Temperate Forest	91.8 (25.0)	63.2 (39.1) [0.39]*			49.5 (20.4) [0.42]*	70.6 (21.3)
Savanna + Shrub	8.1 (5.2)	15.5 (18.1) [0.66]				
Grasses	3.3 (5.3)	4.2 (7.0) [0.20]				
Crops	5.2 (4.4)	12.3 (14.7) [0.40]				

5 References to the data: a. Yue et al. (2015); b. Baccini et al. (2012); c. Saatchi et al. (2011); d.
 6 Thurner et al. (2014).

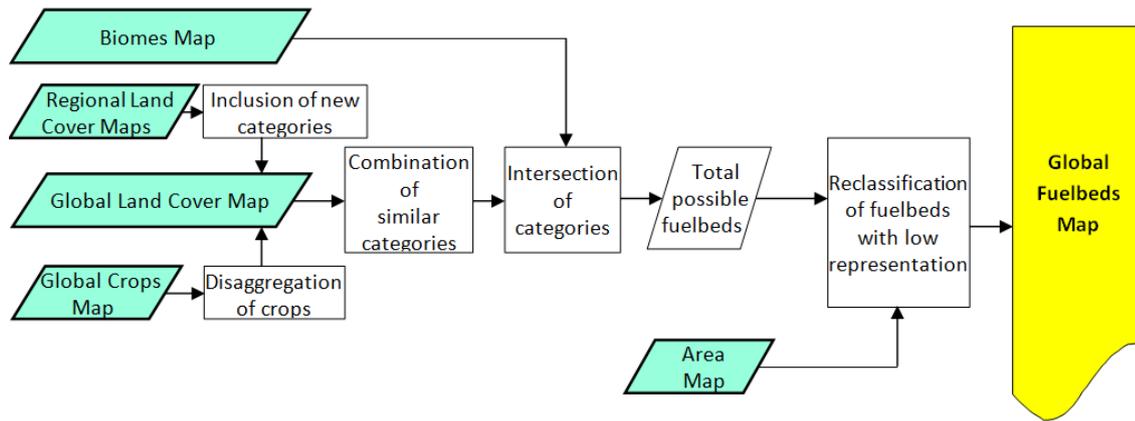
7 * The coefficients marked with the asterisk are compared to the results from this study,
 8 considering tree biomass only. The rest of the values compare the different products with the
 9 results of this study considering the total biomass.

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Figure 1. General flowchart of the methodology used for the generation of the global fuel dataset. More detailed steps are shown in Figs. 2 and 3.

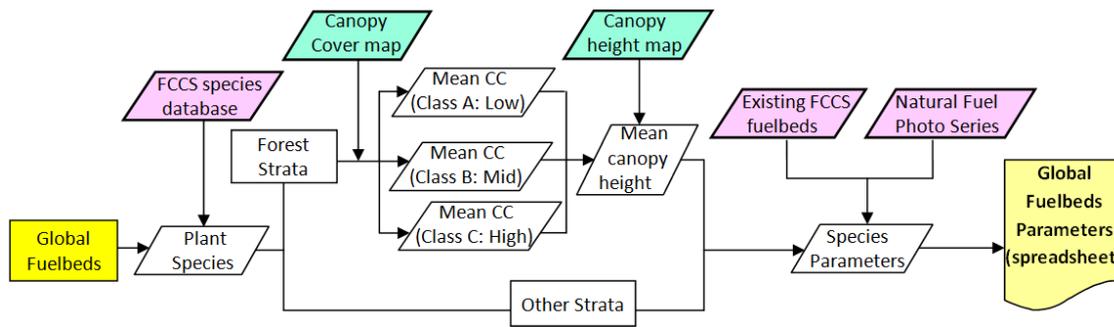


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2 Figure 2. Flow chart of the steps performed for the generation of the fuelbeds.

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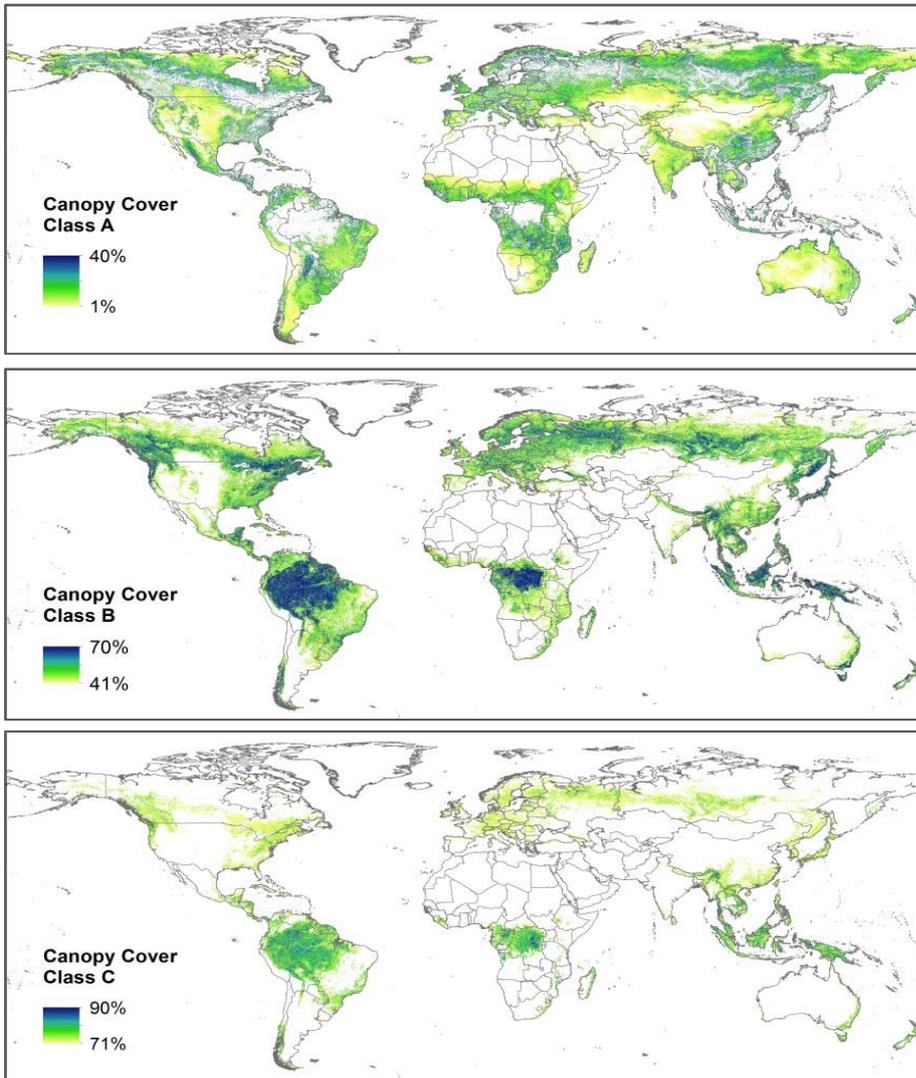


1

2 Figure 3. Flow chart of the steps performed for the parameterization of the fuelbeds. CC:

3 Canopy Cover.

4

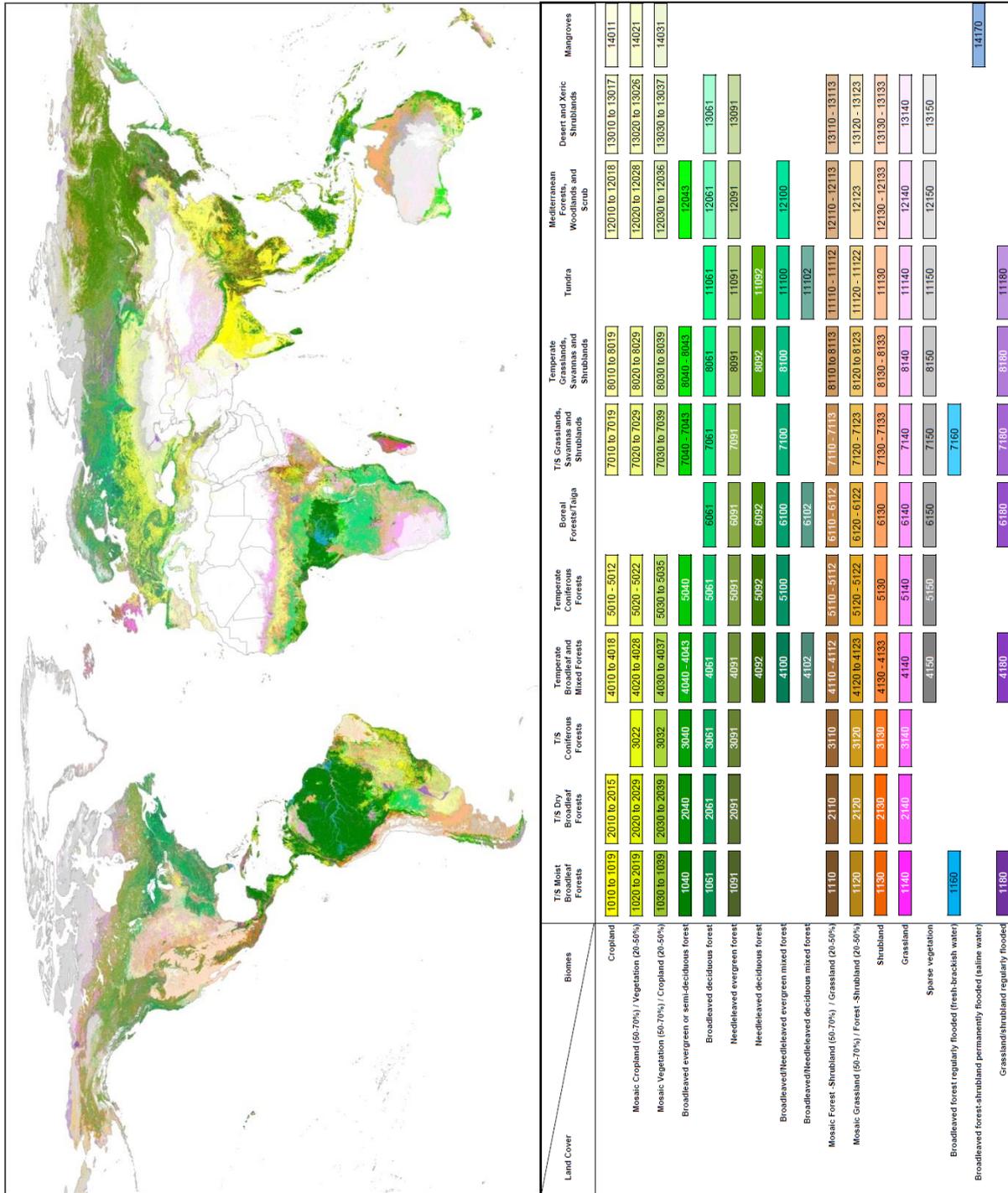


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2 Figure 4. Percentage canopy cover, derived from the MODIS VCF Collection 5 product. The
 3 maps show the subdivision of the CC into the three classes considered for classification.

4

5

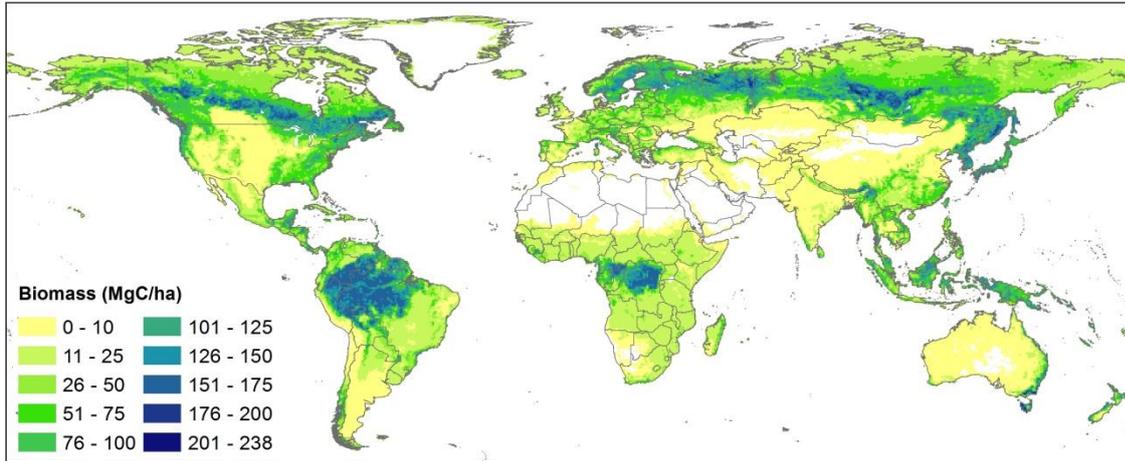


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2 Figure 5. Global fuelbed map. The color legend details the number of the fuelbeds, and the
 3 land cover and biome that they represent.

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2 Figure 6. Estimated global carbon biomass obtained from the global fuelbed dataset.

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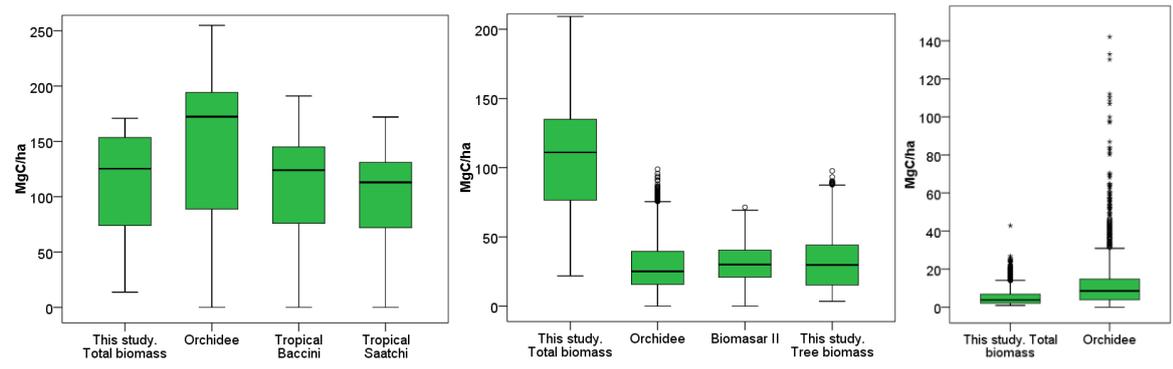
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(a)

(b)

(c)



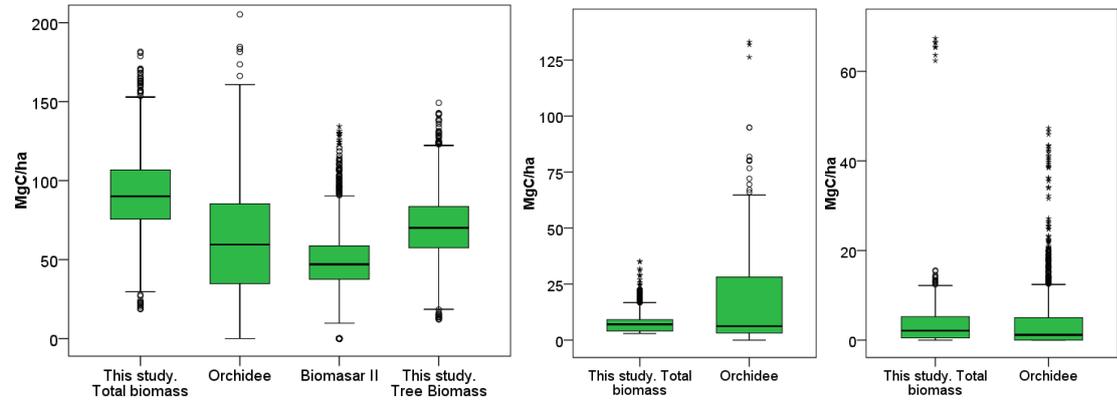
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(d)

(e)

(f)



4

5 Figure 7. Box plots of the carbon biomass obtained for each product for the different land
 6 covers: (a) Tropical Forest, (b) Boreal Forest, (c) Crops, (d) Temperate Forest, (e) Savanna +
 7 Shrub, (f) Grasses.

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