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Development and mapping of fuel characteristics and associated fire potentials for South America

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Abstract. The characteristics and spatial distribution of fuels are critical for assessing fire hazard, fuel consumption, greenhouse gas emissions and other fire effects. However, fuel maps are difficult to generate and update, because many regions of the world lack fuel descriptions or adequate mapped vegetation attributes to assign these fuelbeds spatially across the landscape. This paper presents a process to generate fuel maps for large areas using remotely sensed information and ancillary fuel characteristic data. The Fuel Characteristic Classification System was used to build fuelbeds for South America and predict potential fire hazard using a set of default environmental variables. A land-cover map was combined with a biome map to define 98 fuelbeds, and their parameters were assigned based on information from global datasets and existing Fuel Characteristic Classification System fuelbeds or photo series. The indices of potential surface fire behaviour ranged from 1.32 to 9, whereas indices of potential crown fire and available fuel for combustion had low to medium values (0–6). This paper presents a geospatial fuels map for South America. This map could be used to assess fire hazard, predict fire behaviour under defined environmental conditions or calculate fuel consumption and greenhouse gas emissions. It could also be easily updated as new remotely sensed information on vegetation becomes available.

Additional keywords: FCCS, fuel map, fuelbeds.

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Introduction

Wildfires play an important role in land-cover change and production of greenhouse gas emissions. The spatial distribution, structure and moisture status of existing fuels are key variables in wildland fire behaviour and effects. Fuel maps provide critical information for fire planning and assigning resources for fire prevention and suppression (Burgan *et al.* 1998; Dymond *et al.* 2004; Lasaponara and Lanorte 2007). Furthermore, regional and global fuel maps are used for carbon-cycle dynamic simulations (Kasischke and Hoy 2012), greenhouse gas calculations and estimations of fire risk (Sebastián-Lopez *et al.* 2001; Chuvieco *et al.* 2010).

Fuel maps must describe all the structural characteristics of the vegetative biomass that influence fire behaviour and emissions (Xiao-Rui *et al.* 2005; Chuvieco *et al.* 2009). Often, fuel types used for fuel maps include only those fuel components required by the specific fire models they support (Keane *et al.* 2001). Approaches to fuel mapping that rely on field surveys may provide detailed information on fuel characteristics but have a limited spatial coverage and are costly to implement. Alternatively, remote-sensing (aerial photo interpretation or satellite imagery) methods have been used (Oswald *et al.* 1999; Riaño *et al.* 2002; Van Wagtendonk and Root 2003), which broaden the spatial coverage and are frequently updated but have limited capabilities in describing surface fuels where canopies are dense owing to obstruction problems. Keane *et al.* (2001) and Arroyo *et al.* (2008) provide a detailed description of fuel-mapping techniques and their advantages and disadvantages. At continental or global scales, land-cover maps are used as proxies for fuel maps. General parameters are derived for each land-cover unit by considering ancillary data from other sources (vegetation cover, potential vegetation, etc.) owing to the difficulty in describing the vegetation's structural characteristics at large scales (Nadeau *et al.* 2005; Wiedinmyer *et al.* 2006).

An example of a broad-scale fuel map is the European fuel map used by the European Forest Fire Information System (EFFIS) (San Miguel-Ayanz *et al.* 2012, http://forest.jrc.ec.europa.eu/effis/, accessed May 2013). This fuel map is based on the Corine Land Cover 2000 map (Bossard *et al.* 2000) and a natural vegetation map of Europe. It follows the fuel classification scheme of the National Fire Danger Rating System (NFDRS) (Cohen and Deeming 1985). Another example is the

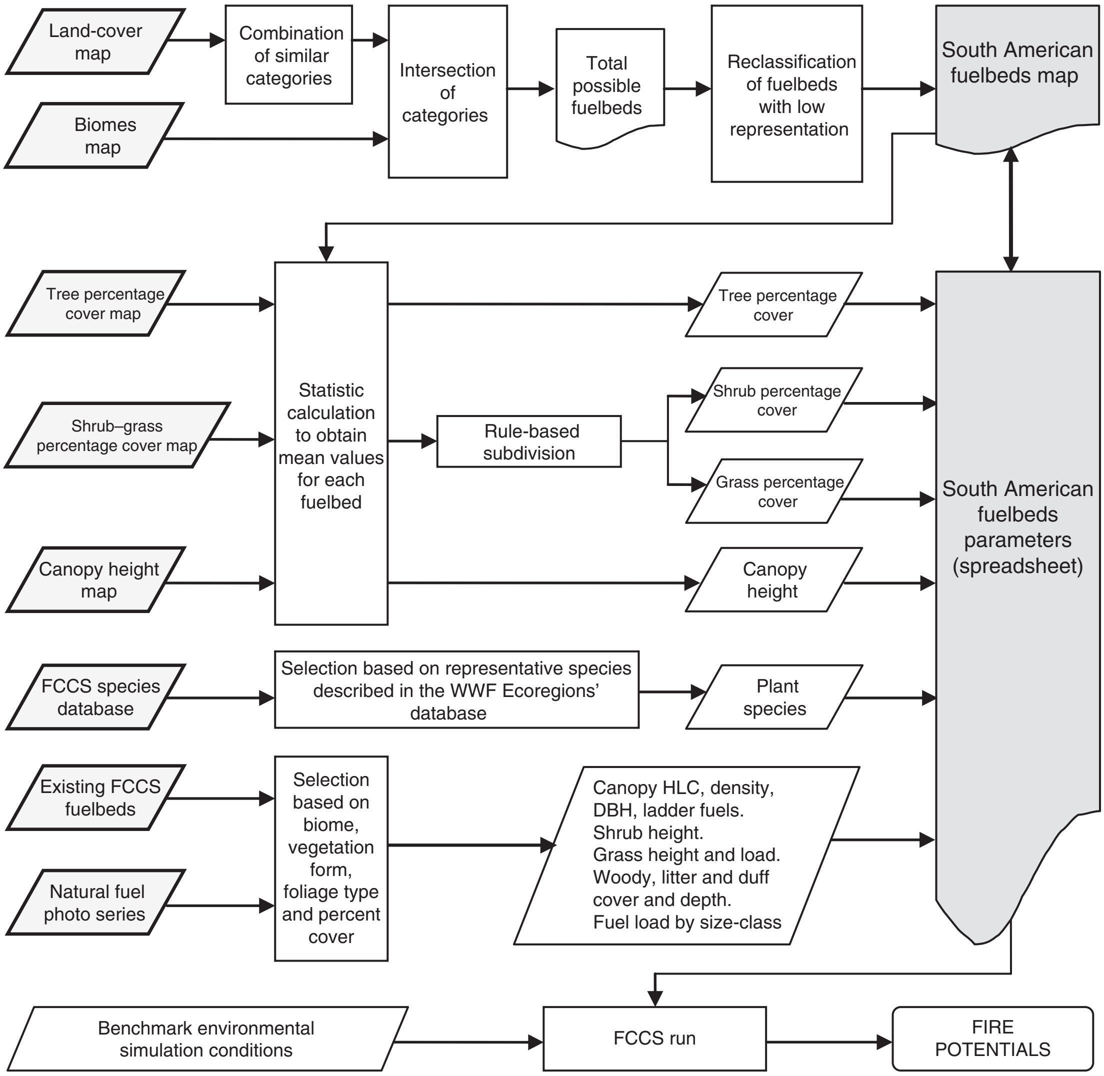


Fig. 1. Flowchart of steps performed to develop the fuelbeds for South America (FCCS, Fuel Characteristic Classification System; HLC, height to live crown; DBH, diameter at breast height).

LANDFIRE fuel maps for the United States (Rollins 2009) (available at http://www.landfire.gov/fuel.php, accessed July 2012). These maps were developed using fuel model classifications including the Behave fuel types (Anderson 1982), Scott and Burgan (2005) fuel types, NFDRS (Deeming *et al.* 1972), Canadian Forest Fire Danger Rating System (Stocks *et al.* 1989) and Fuel Characteristic Classification System (FCCS) (Ottmar *et al.* 2007).

The South American continent includes some of the most intensively burned areas in the world, particularly those associated with the agricultural frontier in the Amazon basin (Brazil, Paraguay, Bolivia), the temperate forests of Argentina and Chile, and the herbaceous areas of Colombia and Venezuela (Los Llanos). In spite of this, there is no fuel map of the continent that can be used to assess fire hazard, fire effects and greenhouse gas emissions within most countries of South America at the continental scale.

This study presents a process to derive a fuel map for national to global scales. The South American continent is used as a case study, but the approach can be used at a global scale. To develop an approach that could map fuels across the globe, we required a standard classification system that would be adaptable to a wide range of fuel conditions. We selected the Fuel Characteristic Classification System (Ottmar *et al.* 2007).

The FCCS was designed to represent the structural and geographic diversity in wildland fuels and organises fuel characteristics into six strata including trees, shrubs, grasses, woody surface fuels, litter and soil organic matter (duff) (Ottmar *et al.* 2007). The different fuel properties are combined into 'fuelbeds', which include the physical and chemical variables used to model fire behaviour, model fuel consumption and predict emissions (Riccardi *et al.* 2007*a*).

FCCS uses fuel characteristics (e.g. percentage cover, loading, depth) to calculate and report nine fire potentials, organised into three categories: surface fire behaviour potential, crown fire potential and available fuel potential (Sandberg *et al.* 2007*a*).

Based on input environmental variables such as midflame windspeed, slope gradient and fuel moisture scenario, the FCCS

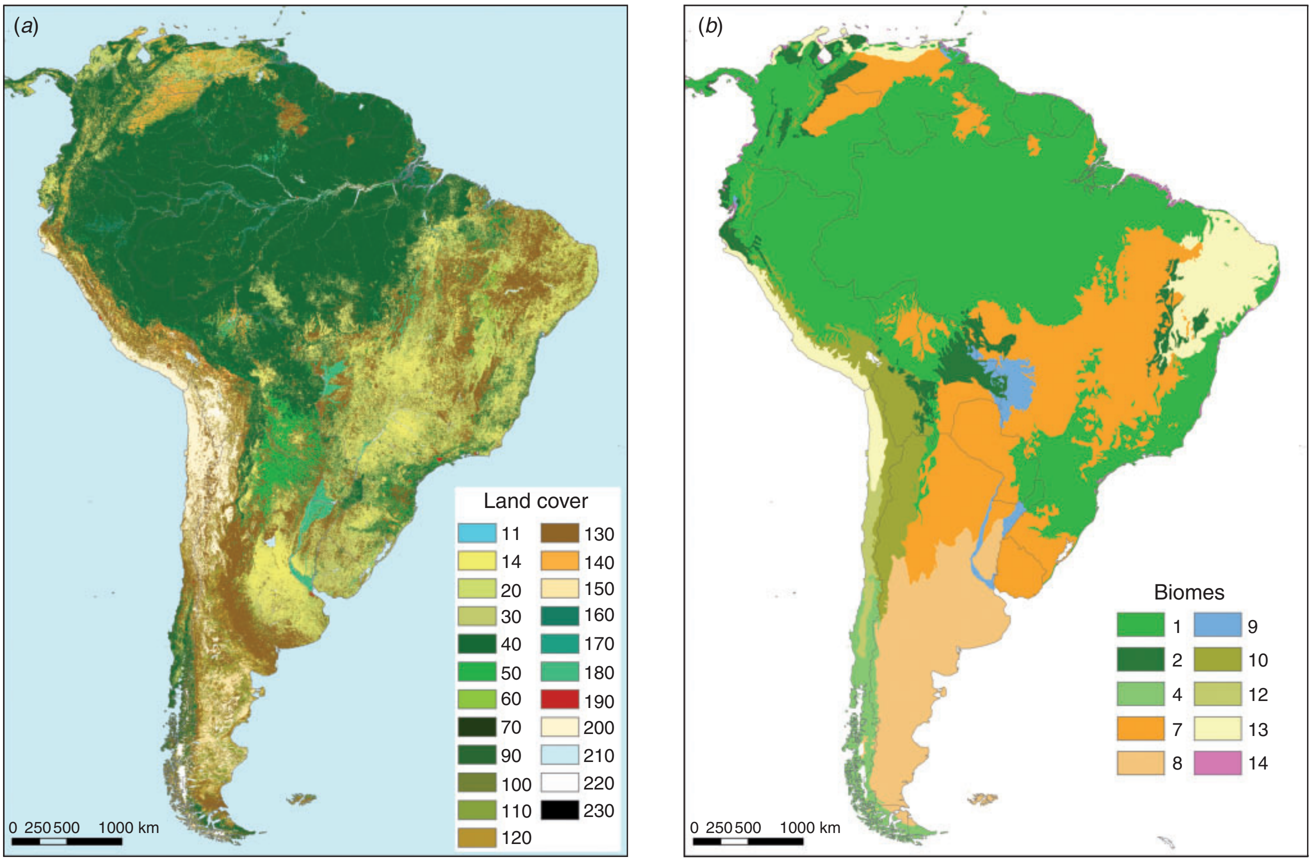


Fig. 2. Land cover (*a*) and South American biomes (*b*) used to delineate fuelbeds. Definitions of legend codes are presented in Tables 1 and 2.

also predicts surface fire behaviour including rate of spread (m min^{-1}), flame length (m) and reaction intensity (kW m^{-2}). Surface fire behaviour calculations are based on a reformulation of the Rothermel (1972) fire behaviour model (Sandberg *et al.* 2007*b*). Crown fire potentials provide an indexed value of potential crown fire behaviour (Schaaf *et al.* 2007).

To generate global-scale fuel maps, data should be taken from existing global databases that provide relevant information on fuel characteristics. Different products derived from earth observation satellites have been used and extensively combined with existing field information.

Methodology

Process to develop the South American fuelbeds

For this study, we used FCCS v2.2 (available at http://www.fs.fed.us/pnw/fera/fccs/downloads.shtml, accessed July 2012). It includes a library of more than 300 fuelbeds developed for the United States, which describe a wide variety of vegetation associations from Alaska's tundra to Florida's subtropical forests. This version also includes a database of ~2000 plant species (trees, shrubs, grasses, forbs, etc.) that characterise each fuelbed.

The classification of fuelbeds was based on vegetation data provided by a land-cover map that was then adjusted by using a biomes map to account for differences in vegetation characteristics due to the influence of climate. Once the fuelbeds were defined, parameters required to characterise each fuelbed were estimated from global geographic products and existing databases (Fig. 1).

Land-cover information was extracted from the GlobCover V2.2 product (Bicheron *et al.* 2008), developed from a temporal series of MERIS (Medium-Resolution Imaging Spectrometer) images acquired between December 2004 and June 2006. This product has a spatial resolution of 10 arc seconds (~300 m at the Equator) and its legend was defined using the Land-cover Classification System of the United Nations' Food and Agricultural Organization (Di Gregorio 2005). Although there is a new 2009 GlobCovermap (Bontemps *et al.* 2010), we used the 2004–06 version because the data of this map are closer in time to the data from the other global products used to characterise the fuels.

The categories of the land-cover map are shown in Fig. 2*a* and detailed in Table 1. Similar land-cover categories in terms of fuel properties were combined. Rain-fed (category 14) and Irrigated croplands (category 11) were merged into Croplands (with the new category numbered as 15), and the categories that differed only in their vegetation density (close or open) were merged (categories 50 and 60 merged into 61, as well as 70 and 90 into 91).

The biomes description was based on the Map of Terrestrial Ecoregions (Olson *et al.* 2001), because it is widely used by different international organisations, including the World

Table 1. List of land-cover categories

Land-cover categories	Description
11	Irrigated croplands
14	Rain-fed croplands
20	Mosaic croplands (50–70%), vegetation (20–50%)
30	Mosaic vegetation (50–70%), croplands (20–50%)
40	Closed to open broadleaved evergreen or semi-deciduous forest
50	Closed broadleaved deciduous forest
60	Open broadleaved deciduous forest
70	Closed needleleaved evergreen forest
90	Open needleleaved deciduous or evergreen forest
100	Closed to open mixed broadleaved and needleleaved forest
110	Mosaic forest–shrubland (50–70%), grassland (20–50%)
120	Mosaic grassland (50–70%), forest–shrubland (20–50%)
130	Closed to open shrubland
140	Closed to open grassland
150	Sparse vegetation
160	Closed to open broadleaved forest regularly flooded (fresh or brackish water)
170	Closed broadleaved forest or shrubland permanently flooded (saline or brackish water)
180	Closed to open grassland or woody vegetation regularly flooded (fresh, brackish or saline water)
190	Artificial areas
200	Bare areas
210	Water bodies
220	Permanent snow and ice
230	No data

Table 2. List of South American biomes

Biome number	Description
1	Tropical and subtropical moist broadleaf forests
2	Tropical and subtropical dry broadleaf forests
4	Temperate broadleaf and mixed forests
7	Tropical and subtropical grasslands, savannas and shrublands
8	Temperate grasslands, savannas and shrublands
9	Flooded grasslands and savannas
10	Montane grasslands and shrublands
12	Mediterranean forests, woodlands and scrub
13	Deserts and xeric shrublands
14	Mangroves

Wildlife Fund (WWF). The description includes 14 global vegetated biomes, and more than 800 ecoregions. Some of these biomes are not found in South America (Tropical and Subtropical coniferous forests (biome 3), Temperate coniferous forests (biome 5), Boreal Forest/Taiga (biome 6) and Tundra (biome 11)) and therefore were not analysed (Fig. 2*b*, Table 2).

The intersection of the land-cover and biomes maps was performed at the spatial resolution of the land-cover map to retain as much detail as possible in the first characterisation of fuels. Categories with a very low frequency (smaller than 0.01% of the study area: 1700 km^2) were reclassified into other similar categories. Once the basic fuelbeds were classified, it was necessary to populate each of them with several key parameters to estimate fire risk (Riccardi *et al.* 2007*b*). Global products based on remote sensing were used when it was possible, to guarantee information that was spatially consistent.

Percentage cover of trees, shrub and grass was extracted from the MODIS Vegetation Continuous Field, Collection 3 (Hansen *et al.* 2003). This product has a spatial resolution of 500 m and includes layers with tree cover (>5 m high) (Fig. 3*a*) and shrub and grass cover (<5 m) (Fig. 3*b*). For the shrub and grass-cover layer, it was necessary to subdivide the assignment of percentage cover between shrub and grass using rules based in the land-cover type (see Supplementary material, see http://www.publish.csiro.au/?act=view_file&file_id=WF12137_AC.zip). Although there are more recent versions of the MODIS Vegetation Continuous Field product, we selected this version because it is the only one that includes non-forest vegetation. Both Collection 4 (http://glcf.umiacs.umd.edu/data/vcf/, accessed July 2012), and Collection 5 (https://lpdaac.usgs.gov/products/modis_products_table/mod44b, accessed July 2012), currently only offer information on tree cover.

To estimate canopy height, we used the global canopy height map developed by Simard *et al.* (2011), with a resolution of 1 km (Fig. 4). This map was developed using lidar data for the year 2005 from the Geoscience Laser Altimeter System (GLAS) aboard the ICESat satellite and ancillary data corresponding to slope, climate and vegetation characteristics.

Proportion of tree cover, shrub and grass cover, and canopy height were rescaled to the fuelbed map spatial resolution, and for each fuelbed the mean value was obtained to represent the percentage cover and canopy height of that fuel category.

To assign the main species of trees, shrub and grass to each fuelbed, the representative plant species for each biome were evaluated from the description of the ecoregions of the WWF Ecoregions database (http://www.worldwildlife.org/science/wildfinder, accessed July 2012). A representative species of each type of vegetation in each biome was assigned to each individual fuelbed if that species was included in the FCCS database. Otherwise, a similar species (based on vegetation form and foliage type) was selected from the list available in the database.

Remaining variables for each fuelbed (canopy height to live crown (HLC), tree density, diameter at breast height (DBH), the presence or absence of ladder fuels, shrub height, grass height and load, dead woody fuels cover and depth, fuel loads by size class of dead woody fuels, and litter and duff cover and depth) were assigned based on information from existing fuelbeds in the FCCS database or from the Natural Fuels Photo Series from Mexico (Morfín-Ríos *et al.* 2008) and Brazil (Ottmar *et al.* 2001). Natural Fuels Photo Series were used for the tropical fuelbeds because they most accurately represent vegetation found in those biomes. Some variables were populated based on expert opinion when there was no information available.

We used existing FCCS fuelbeds when possible, because they already have all the necessary parameters required to calculate the fire potentials. Fuelbeds were selected based on the biome in which they appear and their vegetation form, foliage type, plant species and percentage cover of each

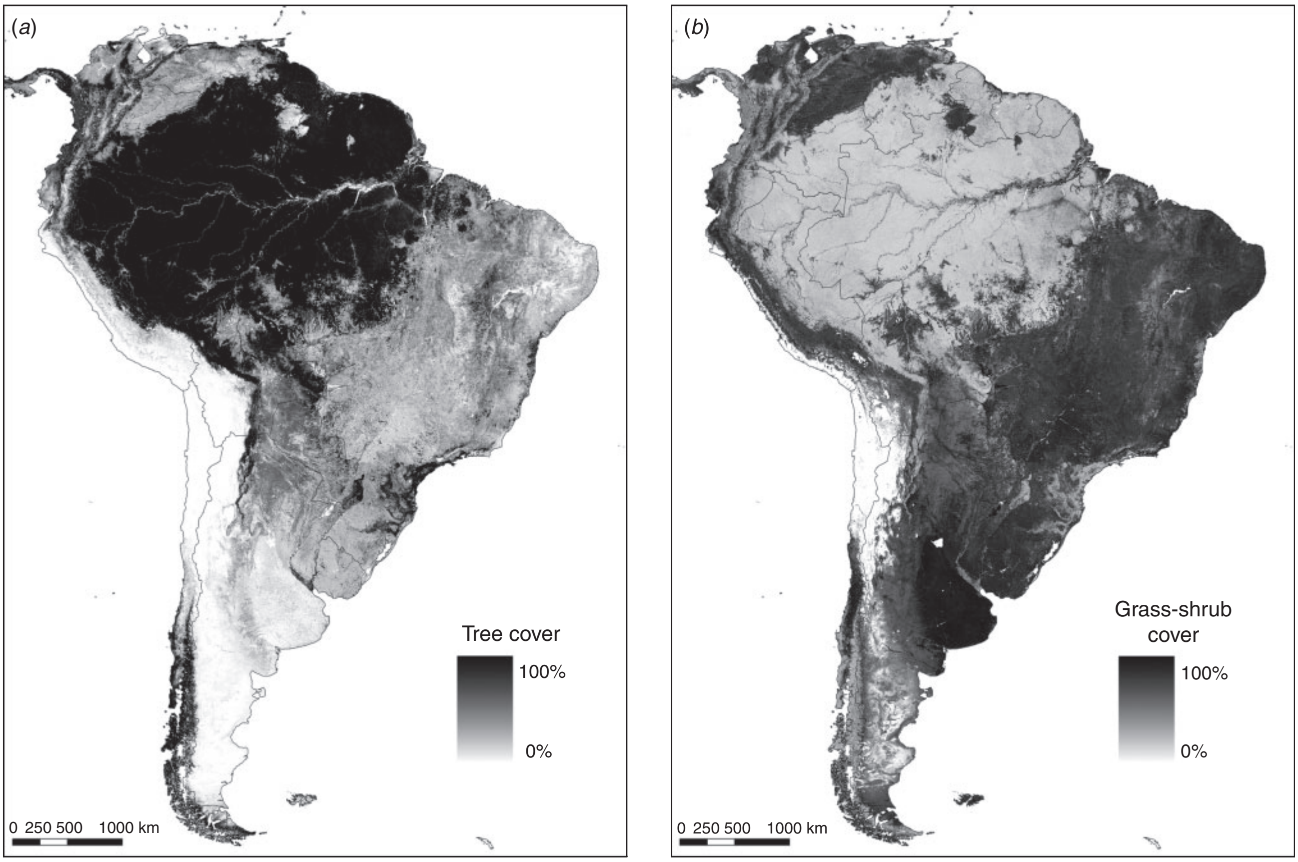


Fig. 3. Percentage cover of vegetation strata obtained from the MODIS Vegetation Continuous Field Collection 3 for: (*a*) tree percentage cover; (*b*) shrub and grass percentage cover.

vegetation type. This allowed us to best characterise the vegetation conditions found in South America. Although the FCCS fuelbeds generally were created from large datasets and represent broad fuelbed types, the assignment of parameters required a simplification and generalisation of the vegetation for the South American ecosystems.

Fire potential simulation conditions

To demonstrate some possible applications of the fuelbed map, we computed and mapped the fire potentials of each fuelbed.

The FCCS fire potentials rate the intrinsic physical capacity of a fuelbed to release energy and spread, and to crown, consume and smoulder under benchmark weather and topographic conditions (Sandberg *et al.* 2007*a*). As indexed values, they provide an objective means of comparing fuelbeds that have different physical characteristics. The Surface Fire Behaviour Potential (FBP) is calculated based on the three components: reaction potential (RP, which represents the reaction intensity under dry fuel conditions), spread potential (SP, proportional to the rate of spread) and flame length potential (FP, proportional to fireline intensity).

Crown Fire Potential (CFP) is a ranking based on whether or not the energy supplied by a surface fuelbed layer is sufficient to ignite and sustain fire spread in the canopy. It is composed of the following components: crown fire initiation (IC, represents the likelihood that a surface fire will propagate into a crown fire), crown-to-crown transmissivity (TC, potential for fire to be carried through a forest canopy) and crown fire rate of spread (RC, relative index of crown fire spreading potential).

Available Fuel Potential (AFP) represents the mass of fuel present in the outer layers of each fuel stratum that is potentially combustible under extremely dry conditions. It is composed of three components: flame-available fuel (FA), which is the mass within 1.27 cm (0.5″) of the surface of the fuel element; smouldering available fuel (SA), which accounts for the mass between 1.27 (0.5″) and 5.08 cm (2″) of a fuel surface; and residual available fuel (RA), which is the mass between 5.08 (2″) and 10.16 cm (4″) of a fuel surface. For further details on how the potentials are calculated, refer to Sandberg *et al.* (2007*a*) and the FCCS V2.2 User's Guide (http://www.fs.fed.us/pnw/fera/fccs/pubs.shtml, accessed July 2012).

To calculate fire potentials, FCCS uses a benchmark fuel moisture scenario from Scott and Burgan (2005), which has the following benchmark values: 1-h, 6% fuel moisture content (FMC); 10-h, 7% FMC; 100-h, 8% FMC; live herbaceous, 60% FMC; and live woody, 90% FMC. Benchmark midflame wind speed is 1.8 m s^{-1} and slope gradient is 0%. Because the benchmark moisture scenario represents dry conditions with two-thirds-cured grasses, the 'non-woody percentage live' (grass) variable in all the fuelbeds developed for South America

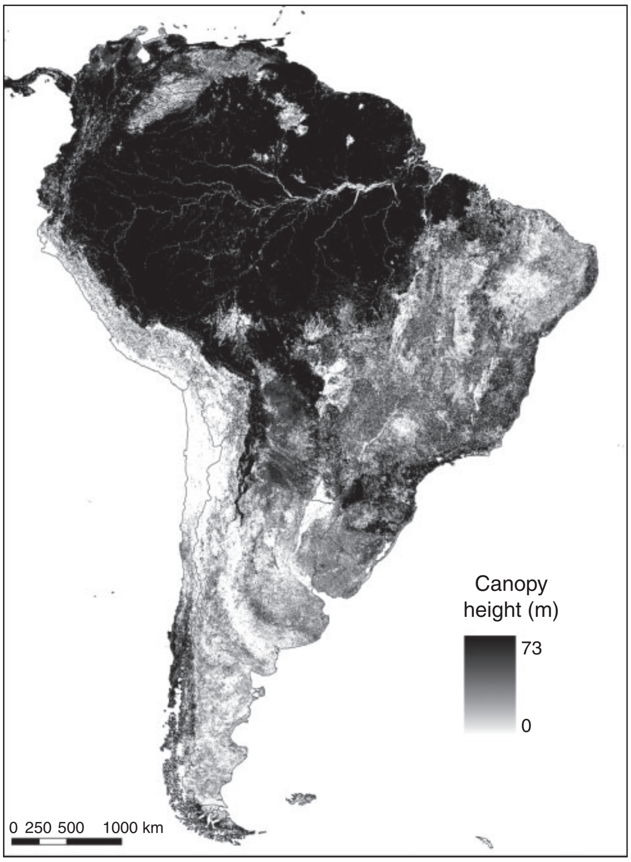


Fig. 4. Canopy height obtained from the canopy height map of Simard *et al.* (2011).

was assumed to be 33%. The 'shrubs percentage live' variable was assumed to be 50%. The only exception to this rule was croplands, where the 'non-woody percentage live' was assigned according to the moment in which the crops usually burn with respect to crop development: 100% for sugarcane (burned before harvest) and 0% for the rest of the crops (burned after harvest). Other environmental variables that affect the calculations in FCCS were left as the default settings, which are the benchmark conditions to calculate the fire potentials.

Results

Fuel map for South America

The intersection of vegetated land-cover categories and the biomes generated 150 combinations. According to the minimum area rule, 52 of these combinations had an area smaller than the threshold and were reclassified into other categories. As a result, a total of 98 fuelbeds were developed.

The resulting fuel map is shown in Fig. 5, and the list of the developed fuelbeds appears in the table that is the legend of that figure. Each fuelbed is identified by a number where the thousands value corresponds to the biome, and the following three values identify the land-cover type associated with a pixel. For example, fuelbed 12 130 is in the Mediterranean forests, woodland and scrub biome (12) and associated with shrub vegetation (130). The mean area of the fuelbeds is 173 013 km^2. The fuelbed with the largest area is 1040 – Broadleaved evergreen or semi-deciduous forest vegetation in a Tropical and Subtropical moist broadleaf forest biome, with $6.17 \times 10^6\ km^2$, mostly located in the Amazonian forest.

The biome with the fewest fuelbeds was the Mangroves because this vegetation unit is limited on the continent. For this reason, it was necessary to reclassify several of its land-cover categories to comply with the minimum area requisite, and only six Mangroves fuelbeds were retained for the final map.

The only fuelbed that included needle-leaved vegetation was 4100 (Mixed broadleaf and needleleaf vegetation in a Temperate Broadleaf and Mixed Forest).

A spreadsheet with the fuelbeds, assigned parameters and the sources of those parameters is provided as Supplementary material.

Fire potentials

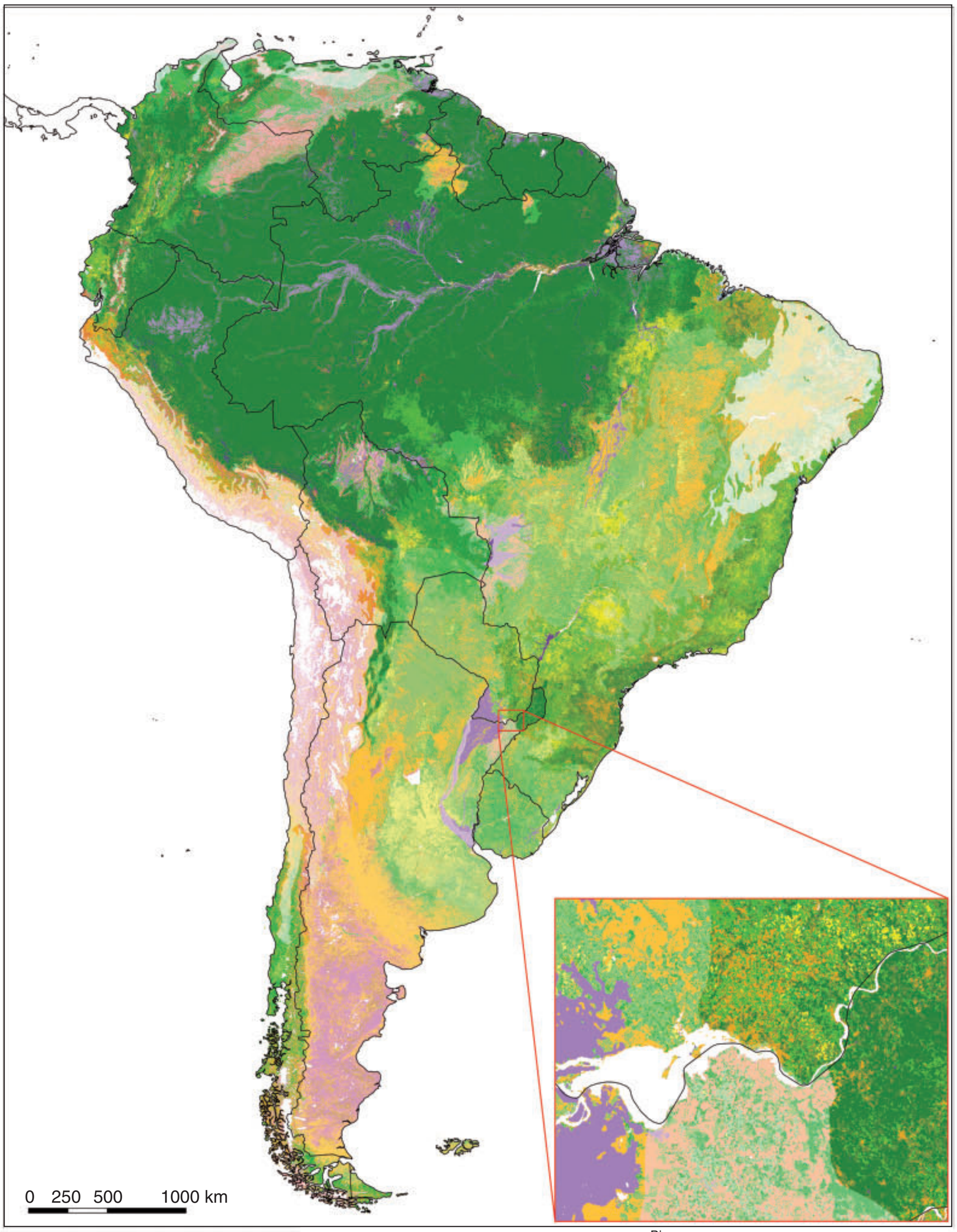
A summary of the fire potentials for each fuelbed is listed in Table 3. The FBPs have index values that range from 1.3 to 9 (see Fig. 6*a*). The highest FBP is generally associated with grassland and cropland fuelbeds (land-cover classes 15 and 140) owing to the abundance of grasses that contribute significantly to fire spread. The minimum FBP is associated with shrubs in temperate grasslands (fuelbed 8130), followed by the sparse vegetation in temperate grasslands (fuelbeds 13 150).

Crown Fire Potential ranged from 0 to 6.199 (Fig. 6*b*), with the highest value associated with fuelbed 4040 (Broadleaf evergreen vegetation in a Temperate forest biome). Over 73% of the fuelbeds (72) had a CFP of 0, which included 37 fuelbeds with no tree cover and 22 fuelbeds with sparse tree cover.

The AFP ranged between 0.015 and 4.924 (see Fig. 6*c*), with the highest value associated with fuelbed 4040 and the lowest associated with crop fuelbeds. FCCS calculates the AFP as the amount of fuel that could be consumed during the different phases of combustion (flaming, smouldering and residual smouldering). The calculation considers the contribution of dead fuels (snags, sound and rotten woody fuels, litter, etc.), live fuels of the shrubs and grasses, and only trees categorised as 'flammable' according to the plant list classification in the FCCS. Because tropical tree species are not classified as 'flammable', they are not included in the available fuel potentials. For this reason, values of AFP for the Broadleaved evergreen forests in Tropical biomes (fuelbeds 1040 and 2040) were significantly lower than the ones obtained for the Broadleaved evergreen forests in Temperate and Mediterranean biomes (fuelbeds 4040 and 12 040). The values of all the fire potentials and their components for each fuelbed appear in the Supplementary material spreadsheet.

Discussion

The fuel map we present is the first map at this scale for South America. The methodology presented in this paper used standard land-cover categories, which allows map improvement to be easily completed as new information becomes available. Also, because all the fuelbed variables are included in a spreadsheet, the values can be easily updated and the results shown on a map bringing together the fuelbed information and results based on their fuelbed number.



Land cover \ Biome	Tropical/Subt. moist broadleaf forest	Tropical/Subt. dry broadleaf forest	Temperate broadleaf and mixed forest	Tropical/Subt. grasslands, savannas and shrublands	Temperate grasslands, savannas and shrublands	Flooded grasslands and savannas	Montane grasslands and shrublands	Mediterranean forests, woodlands and scrub	Desert and xeric shrublands	Mangroves
Crops	1015	2015	4015	7015	8015	9015	10 015	12 015	13 015	
Mosaic crops (50–70%)/Vegetation (20–50%)	1020	2020	4020	7020	8020	9020	10 020	12 020	13 020	14 020
Mosaic vegetation (50–70%)/Crops (20–50%)	1030	2030	4030	7030	8030	9030	10 030	12 030	13 030	14 030
Broadleaved evergreen or semi-deciduous forest	1040	2040	4040	7040	8040	9040	10 040	12 040	13 040	14 040
Broadleaved deciduous forest	1061	2061	4061	7061	8061	9061		12 061	13 061	
Mixed broadleaved and needleleaved forest			4100							
Mosaic forest-shrub (50–70%)/Herb (20–50%)	1110	2110	4110	7110	8110	9110	10 110	12 110	13 110	14 110
Mosaic herb (50–70%)/Forest-shrub (20–50%)	1120	2120	4120	7120	8120		10 120	12 120	13 120	
Shrub	1130	2130	4130	7130	8130	9130	10 130	12 130	13 130	
Herb	1140	2140	4140	7140			10 140		13 140	14 140
Sparse vegetation			4150	7150	8150		10 150	12 150	13 150	
Broadleaved forest regularly flooded (fresh/brackish water)	1160			7160						
Broadleaved forest or shrubs permanently flooded (saline/brackish water)	1170									14 170
Herb/Shrub regularly flooded	1180	2180	4180	7180	8180	9180				

Fig. 5. Fuelbed map of South America. The table legend of the map lists the 98 fuelbeds developed for the continent.

Table 3. Fire potentials obtained for each fuelbed (dimensionless)
FBP, surface fire behaviour potential; CFP, crown fire potential; AFP, available fuel potential

Fuelbed	FBP	CFP	AFP	Fuelbed	FBP	CFP	AFP	Fuelbed	FBP	CFP	AFP	Fuelbed	FBP	CFP	AFP
1015	9	0	0.05	4030	3.77	3.05	1.87	8030	2.77	0	0.24	12 015	6.16	0	0.60
1020	7.22	0	0.65	4040	4.55	6.20	4.92	8040	4.79	4.69	2.97	12 020	2.80	2.61	1.12
1030	5.22	0	1.22	4061	3.81	0	1.21	8061	7.29	0	0.55	12 030	3.68	2.86	0.95
1040	4.97	0	1.52	4100	3.87	5.48	4.47	8110	1.51	0	0.15	12 040	3.22	2.44	3.16
1061	6.10	0	1.64	4110	3.93	3.31	0.76	8120	1.20	0	0.18	12 061	2.27	0	0.57
1110	6.09	0	1.19	4120	5.88	4.22	0.92	8130	1.323	0	0.19	12 110	3.15	1.80	0.28
1120	9	0	1.01	4130	3.16	0	0.29	8150	1.36	0	0.15	12 120	4.31	2.07	0.27
1130	3.70	0	0.43	4140	6.38	0	0.36	8180	7.49	0	0.54	12 130	5.36	0	0.65
1140	9	0	0.21	4150	3.19	0	0.20	9015	9	0	0.05	12 150	4.50	0	0.15
1160	1.85	0	2.24	4180	3.24	0	0.22	9020	5.00	0	0.60	13 015	9	0	0.08
1170	7.93	0.87	1.28	7015	9	0	0.05	9030	4.44	0	0.79	13 020	5.84	1.76	0.91
1180	5.45	0	0.37	7020	4.64	0	0.32	9040	5.73	5.28	2.97	13 030	3.92	1.16	0.77
2015	9	0	0.05	7030	3.23	0	0.34	9061	6.45	0	0.92	13 040	3.98	5.77	3.49
2020	4.61	0	0.31	7040	5.82	0	1.49	9110	5.69	0	1.30	13 061	3.70	0	0.75
2030	3.18	0	0.34	7061	5.97	0	0.43	9130	4.45	0	0.80	13 110	4.02	0.83	0.38
2040	5.51	0	1.44	7110	4.17	0	0.44	9180	7.40	0	0.51	13 120	9	0.87	0.17
2061	5.65	0	0.40	7120	5.65	0	0.41	10 015	9	0	0.08	13 130	5.72	0	0.68
2110	4.09	0	0.44	7130	3.77	0	0.44	10 020	6.04	2.40	0.56	13 140	9	0	0.01
2120	6.39	0	0.40	7140	9	0	0.39	10 030	5.58	2.73	0.82	13 150	1.47	0	0.15
2130	3.71	0	0.44	7150	4.03	0	0.44	10 040	4.74	3.10	2.53	14 020	9	0	1.05
2140	9	0	0.39	7160	6.51	2.70	1.61	10 110	2.43	1.45	0.27	14 030	9	0	1.61
2180	7.28	0	0.48	7180	5.36	0	0.71	10 120	7.01	2.48	0.18	14 040	5.72	0	1.48
4015	9	0	0.05	8015	9	0	0.05	10 130	3.01	0	0.27	14 110	9	0	1.49
4020	3.44	3.33	1.63	8020	2.86	0	0.12	10 140	6.98	0	0.16	14 140	9	0	0.33
								10 150	3.71	0	0.04	14 170	7.19	1.67	1.31

Assumptions and limitations

It is important to note that at this scale, it is impossible to account for the complexity of the South American ecosystems by developing individual fuelbeds. Some ecosystems are more homogeneous and dominated by a small number of species, as is the case with the Patagonian Steppe (Golluscio and Sala 1993) or the Argentinean Pajonal (Vignolio *et al.* 2003). The Amazonian forest, however, possesses one of the highest levels of biodiversity in the world (ter Steege *et al.* 2006). Despite this, all fuelbeds were assigned one plant species per vegetation form that would best describe the fuel characteristics of that type of vegetation. The FCCS species database is regularly updated and as more South American species appear in the database, the fuelbeds will become more representative of the particular conditions of the continent.

The South American fuel map indicates that the biomes are in some cases too general and do not address the changes in land cover. For example, as can be seen in the magnified area of Fig. 5, sometimes the land covers on both sides of the limits between biomes are similar, generating fuelbed limits that appear to be arbitrary. This could be because the biomes and ecoregions map were developed based on boundaries that approximate the original extent of natural communities before major land-use change caused by human activities and other land-cover change factors (Verburg *et al.* 2009). But in reality, the limits between the different biomes are not often clearly delineated from one another, because they are composed of mosaics and ecotones that define a gradual transition between the different vegetation covers (Walker *et al.* 2003).

Our application of the mean value of vegetation cover and canopy height resulted in a generalised representation of each fuelbed. At this stage of the work, this simplification was assumed in order to obtain a first version of the fuel map that would be useful to estimate the fire potentials. We plan to create additional fuelbeds based on ranges of canopy and shrub–grass cover from the MODIS Vegetation Continuous Field product (Hansen *et al.* 2003), which will also affect the canopy height assignment. This will allow more realistic results for vegetation covers to be obtained with different densities within each current fuelbed.

Defining the fuelbeds based on land-cover categories assumes the inherent possible errors caused by inaccuracies in the land-cover categories of the original map that are due to the data and methodology used for their development. Some of these issues have already been addressed in the GlobCover validation report (Bicheron *et al.* 2008), including the underestimation of land covers with small spatial extent and the problems with mountain shadows in rugged terrain that affect the land-cover assignments in mountainous regions. Comparison of different land-cover products has shown a reasonable agreement at a global level in terms of total area and general spatial pattern (Herold *et al.* 2008; Kaptué Tchuenté *et al.* 2011), but further validation is needed to identify the most consistent approach. We selected the GlobCover map for this research because it is based on the Land Cover Classification System (LCCS, Di Gregorio 2005), which has become a standard in land-cover classification. It also provided a consistent legend that will simplify the updating of the fuelbed map as newer and improved land-cover products are developed. Other

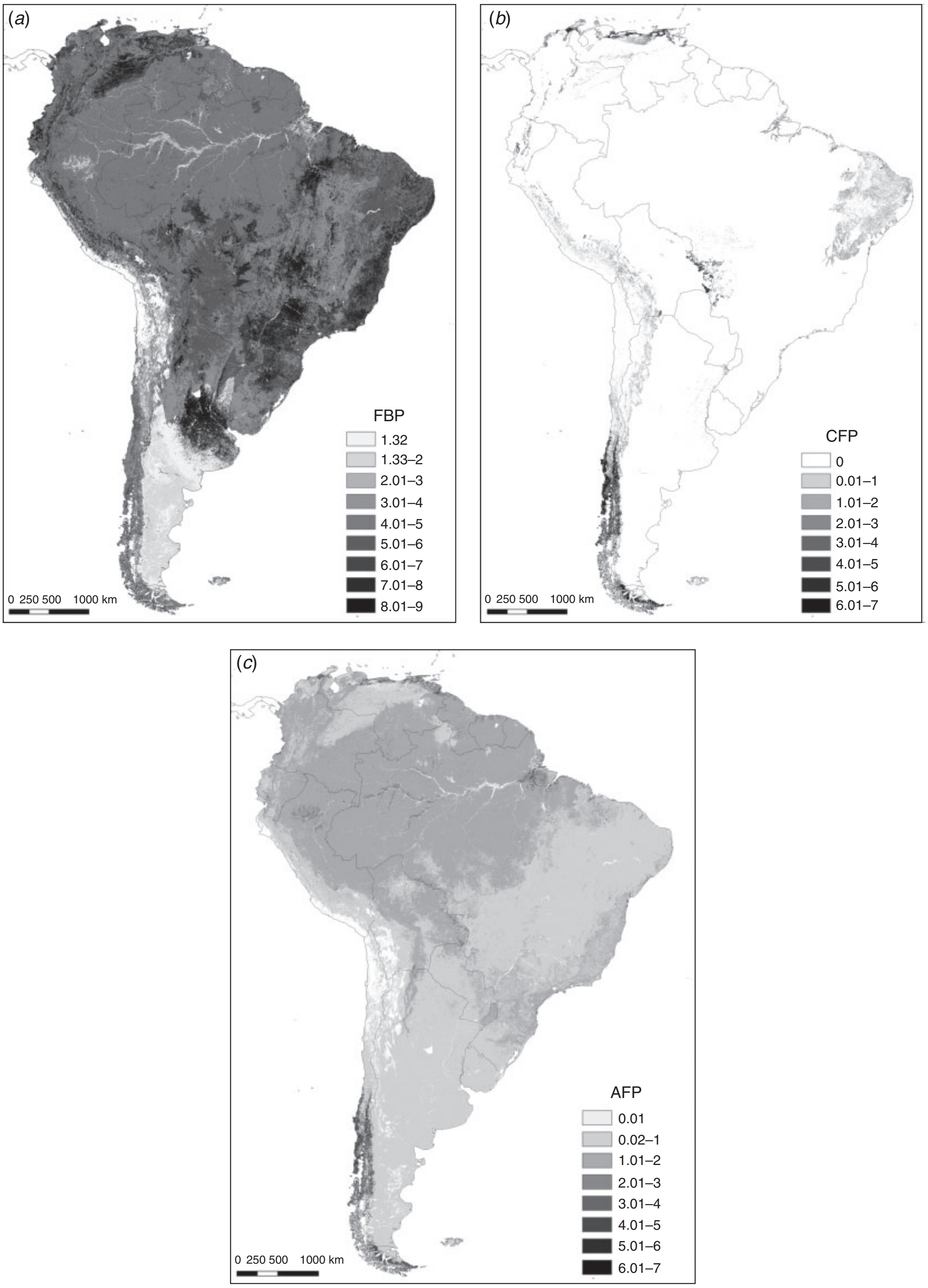


Fig. 6. Surface fire behaviour potential (FBP) (*a*); crown fire potential (CFP) (*b*); and available fuel potential (AFP) (*c*) mapped for the South American fuelbeds assuming benchmark environmental conditions. All the potentials are dimensionless.

land-cover products of a similar spatial resolution (e.g. MODIS Land Cover Type Product Collection 5) do not comply with the LCCS legend requirements. Efforts are being made to improve land-cover maps, both through new versions of the existing land-cover products and through the use of crowdsourcing to validate existing products (Fritz *et al.* 2009). The developers of the MODIS Land Cover product, for example, plan to migrate the classification to the LCCS in the next Collection (Friedl *et al.*

2010), which will provide an additional source of land-cover information to improve the assignment of the fuelbeds to the territory.

Environmental variables and fire potentials

The FCCS fire potentials are designed to compare fuel characteristics and fire potentials under the same benchmark environmental variables (Sandberg *et al.* 2007*a*). In the case of South America, and because it covers a wide range of latitudes and climates, this implies an assignment of moisture conditions that are not expected to occur in real life in some regions. For example, the dry fuel moisture scenario may be unrealistically dry for some tropical moist forests. Future work will need to consider expected mean climate values in the different biomes. This will allow fire potentials to be more realistically compared.

Similarly, validating the results using data from actual fire occurrence is not possible because the environmental conditions used for the calculations are not the same as the ones that would be found in actual fires. Once climate values are incorporated into the model, it will be feasible to compare the results of some of the fire potentials with existing products describing actual fire behaviour. For example, predicted surface fire reaction intensity could be compared with the Fire Radiative Energy obtained from products such as the MODIS MYD14 of Thermal Anomalies (https://lpdaac.usgs.gov/products/modis_products_table/myd14, accessed July 2012; Wooster *et al.* 2005) to analyse the variations in energy release within the different fuelbeds.

Applications

The FCCS has the advantage that it includes a wide set of physical characteristics of the fuels, and not only the ones required by a particular fuel model. For this reason, it can be useful for different applications. In this article, we have focussed on fire potentials, but other results can also be obtained from FCCS, such as total fuel loadings per stratum or carbon stores. For example, the available fuel and carbon results obtained for each fuelbed could be used to calculate fuel consumption and pollutant emissions from wildland fires at a country or continental scale, using tools such as Consume (Hollis *et al.* 2010).

Furthermore, specific weather scenarios and environmental variables could be assigned to calculate expected fire risk and fire behaviour, which could be useful for the countries that do not have a fuel map or a developed fire danger system.

Conclusions

This work presents a new methodology to generate a fuel map for South America by using the FCCS. A fuel classification was generated based on land cover and biomes (organised into 98 fuelbeds) and a fuel map was generated with the spatial distribution of the different fuels. The fuel characteristics of vegetation that influence fire occurrence and behaviour were extracted from global maps (using mean values for each fuelbed) and from existing databases from the United States, Mexico and Brazil.

The surface fire behaviour, crown fire and available fuel potentials were calculated for each fuelbed and mapped using benchmark environmental conditions. In order to obtain estimated fire behaviour parameters for a particular fire scenario, specific weather conditions and topography will have to be set before the FCCS calculations.

The fuelbeds associated with this map could also be used to assess fire hazard, predict fire behaviour under defined environmental conditions or calculate fuel consumption and greenhouse gas emissions. A GeoTIFF version of the fuel map, as well as a spreadsheet including all the fuelbed variables, can be obtained in the Supplementary material (see http://www.publish.csiro.au/?act=view_file&file_id=WF12137_AC.zip).

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