Cover Sheet

A Comprehensive Assessment of the FireCCILT11 Global Burned Area Product

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A Comprehensive Assessment of the FireCCILT11 Global Burned Area Product

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Abstract

The FireCCILT11 global burned area (BA) product, developed under the ESA Climate Change Initiative, spans nearly four decades (1982–2018) and is the longest nearly continuous global fire record currently available. Despite its growing use in high-profile studies, its performance has not been comprehensively evaluated. Moreover, while two earlier studies identified severe instrumental artifacts in the FireCCILT11 dataset, the supporting evidence in those studies was primarily circumstantial. Here, we directly assess FireCCILT11 BA using a suite of national fire history datasets and independently derived satellite-based BA products across eight countries. Our analysis reveals substantial limitations in both the accuracy and consistency of FireCCILT11, particularly before 2001. FireCCILT11 frequently diverges from national records in terms of annual BA totals, exhibits poor spatial agreement at the pixel level, and suffers from high omission and commission errors. A pixelation effect further compromises its spatial resolution and usability. These findings suggest that FireCCILT11 may be unsuitable for long-term fire regime analyses, especially in regions or periods not represented in its training data. We highlight the ongoing need for a robust, AVHRR-based global BA product and propose best practices for the development and evaluation of long-term BA datasets.

1. Introduction

Wildfires, ignited by natural causes such as lightning strikes or human activities like agricultural clearing and accidental ignitions, are a widespread phenomenon across diverse ecosystems globally. These fires play a dual role, acting as both ecological regulators in fire-adapted landscapes and destructive forces in human-altered environments. In ecosystems ranging from boreal forests to tropical savannas, wildfires have historically shaped vegetation structure, nutrient cycling, and species composition (Bowman et al. 2009; Moritz et al. 2014). Depending on the ecosystem and the proximity to human populations, they can impose a wide array of ecological, societal, and climatic impacts. For example, in circumpolar boreal forest, the largest terrestrial biome on Earth, wildfires play a pivotal role shaping these forests vegetation compositions, successional trajectories, and carbon storage (Bond-Lamberty et al. 2007; Walker et al. 2019; Whitman et al. 2018). Societally, wildfires are the main driver of decreasing air quality in the northwestern US, which carries major health implications (McClure and Jaffe 2018; O'Dell et al. 2021). Climatically, boreal forest fires release vast stores of carbon, amplifying atmospheric CO_2 concentrations and reducing albedo through soot deposition on ice sheets (Randerson et al. 2006; Zheng et al. 2023). Additionally, megafires like Australia's 2019–2020 Black Summer fires emitted ~715 million tonnes of CO_2, equivalent to nearly half the country's annual fossil fuel emissions (van der Velde et al. 2021).

Coping with wildfires in a changing climate requires a good understanding of their impacts, whether beneficial or undesirable, which in turn generally requires knowing the extent, or burned area (BA), of the fires. It is for this reason that wildfires' burned area have been mapped by various forest and fire management agencies around the world using various methods. Among those methods, satellite remote sensing plays a pivotal role in mapping and analyzing BA, offering a unique capacity to monitor wildfires systematically across expansive, remote, and often inaccessible regions. By detecting spectral changes in vegetation and surface reflectance, satellites provide essential data on fire extent, severity, and ecological consequences.

There have been a myriad of satellite-based BA products developed at the global scale, with most relying on coarse-resolution imaging sensors. Among these, the MODIS-based BA products have been foundational for the scientific community. The now-defunct MCD45A1 product was one of the first MODIS BA products that detected the approximate date of burning at 500-m resolution by locating rapid changes in daily surface reflectance time series data, though it was notably affected by cloud and aerosol contamination (Roy et al. 2002). The MCD64A1, which has become the standard MODIS BA product since Collection 6, employs a hybrid algorithm that applies dynamic thresholds to composite imagery generated from a burn-sensitive vegetation index derived from MODIS short-wave infrared channels 5 and 7, coupled with 1-km MODIS active fire observations (Giglio et al. 2018). This approach enables significantly better detection of small burns, reduced temporal uncertainty, and a substantial reduction in unclassified areas compared to MCD45A1. Meanwhile, the European Space Agency's Climate Change Initiative (ESA CCI) developed an array of global BA products, including FireCCI41 and FireCCI50. FireCCI41, developed using the MEdium Resolution Imaging Spectrometer (MERIS) data, provided global BA estimates at 300 m resolution for 2005-2011 but faced limitations in spatial granularity and temporal coverage (Chuvieco et al. 2018; Chuvieco et al. 2016). Its successor, FireCCI50, marked a significant advancement as the first MODIS-based global BA product at 250 m resolution, utilizing MODIS MOD09GQ daily surface reflectance data in red and near-infrared bands (Chuvieco et al. 2018). The product was subsequently refined and released as FireCCI51 several years later (Lizundia-Loiola et al. 2020). More recently, progress has been made on the development of MCD64A1-compatible BA product for the Visible Infrared Imaging Radiometer Suite (VIIRS) (Giglio et al. in review).

In addition to coarse-resolution BA products, higher spatial resolution BA products have been developed using Landsat data. Based on the algorithm prototyped in Hawbaker et al. (2017), Hawbaker et al. (2020) developed a 30-m BA product for the conterminous US based on Landsat imagery, which was subsequently integrated into the Landsat Level-3 data suite. Meanwhile, Sentinel-2, with its shorter revisit cycle (5 days) and higher spatial resolution, has also shown promising performance in BA mapping (Bastarrika et al. 2024; Gaveau et al. 2021).

Despite the abundance of remotely sensed BA products, there is a notable scarcity of long-term BA products spanning over three decades, which is the minimum temporal span for robust climate-related trend analysis recommended by the World Meteorological Organization (World Meteorological Organization 2017). This limitation exists because such lengthy time series must rely on data acquired by the Advanced Very High Resolution Radiometer (AVHRR) sensors, which present significant data quality challenges. Against this backdrop, the FireCCILT11 product (Otón et al. 2021b) stands out as the only BA product currently available with such temporal extent. Produced from AVHRR data, FireCCILT11 provides global BA mapping for the period 1982–2018 (excluding 1994). While FireCCILT11 has received increasing attention from the scientific community, as exhibited by its use as a primary data source in a lineup of high-profile publications (e.g., Descals et al. (2022), Cardil et al. (2023), Lin et al. (2024)), limited assessments were carried out on FireCCILT11 in the original product publications (Otón et al. 2021a; Otón et al. 2021b). In addition, various problems with the FireCCILT11 product, including prominent spatial and temporal artifacts in BA linked to the orbital drift of the AVHRR-carrying National Oceanic and Atmospheric Administration (NOAA) satellites, were subsequently demonstrated (Giglio and Roy 2022, 2023, 2024; Giglio et al. 2022) but these have yet to be assessed in a systematic and comprehensive fashion. We believe addressing this knowledge gap is crucial for the global fire science community, particularly for researchers looking to appropriately utilize FireCCILT11 in long-term fire regime studies.

2. Datasets

The FireCCILT11 product is a global BA dataset developed under the European Space Agency's Climate Change Initiative, utilizing the AVHRR Land Long Term Data Record (LTDR) at a spatial resolution of 0.05°. The core algorithm employs multiple random forest classifiers trained using reference data from the 250-m MODIS FireCCI51 BA product spanning 2001–2018. These classifiers process spectral indices derived from monthly AVHRR composites to identify BAs. A key innovation in FireCCILT11 is its correction mechanism for satellite orbit drift, particularly critical for pre-2000 data (1982–2000). Outputs are provided at both the native 0.05° pixel resolution and an aggregated 0.25° grid, with the latter generated by summing BA values from the high-resolution data. This methodology ultimately provides monthly global BA maps for 1982–2018, excluding 1994 (Otón et al. 2021b).

In this study, we evaluated the performance of the FireCCILT11 product using six datasets categorized into two groups: 1) national fire history data, and 2) remotely sensed BA products. The national fire history data consist of datasets sourced from the US, Canada, Australia, and Europe, representing a comprehensive compilation of meticulously maintained long-term fire history records available to date. Together, these datasets provide an encompassing portrayal of fire histories within their respective coverage areas. The remotely sensed data comprise two global BA products, namely FireCCI51 (Chuvieco et al., 2018) and MCD64A1 (Giglio et al., 2018). Both products are derived from MODIS imagery and enjoy wide popularity among the global fire science community (Bastos et al. 2020; Boer et al. 2020; Gatti et al. 2021; Harris et al. 2021; Pinto et al. 2020). Further details regarding these six datasets are provided in Table 1.

Table 1. A list of the datasets that are used in this assessment. Citations: NBAC BA (Hall et al. 2020); NIFC BA (National Interagency Fire Center 2024); EFFIS BA (San-Miguel-Ayanz et al. 2012); AIFH BA (Canadell et al. 2021); FireCCI51 (Chuvieco et al. 2018); and MCD64A1 (Giglio et al. 2018). The datasets that are in **bold** indicate those that provide spatially explicit BA maps.

Dataset Name	Category	Spatial Resolution	Spatial Coverage	Temporal Coverage
National Burned Area Composite (NBAC)	**National Fire History**	**Vector-based**	**Canada**	**1986-2022**
National Interagency Fire Center (NIFC) Fire Perimeters	**National Fire History**	**Vector-based**	**US**	**1986-2021**
European Forest Fire Information System (EFFIS)	National Fire History	BA summary at Nomenclature of Territorial Units for Statistics level 3 (NUTS3)	Portugal, Italy, France, Spain, and Greece	1983-2022
Australia Interagency Fire History Data (AIFH)	National Fire History	BA summary at state and territory level	Australia	1988-2019
FireCCI51	**Remotely Sensed Burned Area**	**250 m**	**Global**	**2001-2020**
MCD64A1	**Remotely Sensed Burned Area**	**500 m**	**Global**	**2001-2023**

3. Methodology

3.1. Assessment in terms of annual total BA

For the eight countries where reference BA statistics or maps were available (US, Canada, Australia, Italy, France, Greece, Spain, and Portugal), we computed annual total BA for FireCCILT11 and the other remotely sensed datasets. To minimize errors from projection or resampling, these calculations adhered to the native resolution of each dataset: 250 m for FireCCI51 and 500 m for MCD64A1. For the NBAC and NIFC datasets, which provide vector-formatted fire perimeter polygons, BA statistics were derived at 30-m resolution to match the spatial detail of

Landsat imagery. This resolution aligns with the foundational data used to delineate many fire perimeters in these products (Hall et al., 2020).

The interannual variation of BA as mapped by FireCCILT11 was compared with that of the reference datasets. For every year when both FireCCILT11 and national fire history data were available, a consistency index (CI) was calculated as

$$CI_{i,j} = |BA_{i,j} - R_{i,j}| / R_{i,j} * 100\%,$$

where $BA_{i,j}$ and $R_{i,j}$ represent the annual total BA of country *i* in year *j* according to FireCCILT11 and the national fire history dataset, respectively. In addition to comparing with the national fire history datasets, the FireCCILT11 annual total BA was also compared to the FireCCI51 product in each country in each year. The goal of this comparison was to assess the consistency of FireCCILT11 in relation to FireCCI51, which provided the training data during the production of FireCCILT11 (Otón et al. 2021b).

3.2. Per-pixel-based assessment of FireCCILT11

Compared to assessments based on annual total burned area (BA), per-pixel evaluations provide critical insights into the spatial distribution of mapped burned pixels. This approach is essential for assessing BA product performance, as it reveals how accurately a product represents regional fire regimes across space and time. Among the national fire history datasets analyzed, the NIFC (National Interagency Fire Center) and NBAC (National Burned Area Composite) datasets are spatially explicit and notable for their long-term records. The NBAC dataset, recognized as Canada's most consistent and accurate wildfire polygon database (Gincheva et al. 2024), integrates 30-m Landsat imagery and agency-collected data with spatial resolutions finer than 30 m since 1986, with regular updates to ensure reliability. Both NIFC and NBAC were developed at resolutions much finer than FireCCILT11 (0.05°) and are entirely independent of the dataset, making them suitable references for per-pixel comparisons. We acknowledge that fire perimeters in NIFC and

NBAC may include unburned islands, potentially leading to overestimations of BA within mapped fire scars. Consequently, these datasets were treated as reasonable approximations of "ground truth" rather than absolute references. This inherent uncertainty was explicitly accounted for in our analytical framework to ensure robust conclusions.

A robust assessment of multiple datasets requires a uniform coordinate system and spatial resolution. As the target FireCCILT11 dataset uses a geographic coordinate system (latitude/longitude) at 0.05° resolution, all spatially explicit BA datasets—NBAC, NIFC, FireCCI51, and MCD64A1—were gridded to this system. Binary BA classifications from these datasets were converted to gridded BA (km²) at 0.05° resolution by counting original BA pixels within each 0.05° cell. For per-pixel assessments, gridded national fire history datasets (NBAC for Canada and NIFC for the US) were superimposed annually onto FireCCILT11. The same procedure was applied to FireCCI51 and MCD64A1 to enable performance comparisons with FireCCILT11 using the national datasets as benchmarks. For each dataset pair (e.g., FireCCILT11 vs. NBAC), the Pearson correlation coefficient (*R*) was calculated as:

$$R = \frac{\sum[(\mathrm{BA}_j - \overline{\mathrm{BA}}) \times (\mathrm{Ref}_j - \overline{\mathrm{Ref}})]}{\sqrt{\sum(\mathrm{BA}_j - \overline{\mathrm{BA}})^2 \times \sum(\mathrm{Ref}_j - \overline{\mathrm{Ref}})^2}}$$

where BA_j and Ref_j represent annual BA in year *j* from the target dataset and gridded national fire history data, respectively. To avoid overestimating performance, unburned pixels (where both datasets reported zero BA) were excluded from calculations. Only pixel pairs with at least one non-zero BA value were included in the analysis. While spatially explicit fire history data for Australia and the five EFFIS countries (Italy, France, Greece, Spain, Portugal) are not publicly available, *R* values between FireCCILT11 and FireCCI51 were also computed to assess their consistency outside North America.

In addition to evaluating the Pearson correlation, a confusion matrix-based accuracy assessment was conducted to further evaluate FireCCILT11's performance. For this analysis, NBAC and NIFC were treated as references. Both datasets were converted to binary burned/unburned classifications, where a 0.05° grid cell was classified as "burned" if it contained non-zero BA values and "unburned" otherwise. FireCCILT11 was similarly converted to a binary format.

Following the methodological framework of Olofsson et al. (2014), we generated 1,000 stratified random samples per year for Canada (NBAC) and the United States (NIFC) across the study period (1986–2018, excluding 1994). The sampling strategy allocated 750 points to unburned areas and 250 points to burned areas annually, ensuring proportional representation of fire events. These points were used to extract binary classifications (burned/unburned) from FireCCILT11 maps for the corresponding years. Results were compiled into annual confusion matrices, from which three key accuracy metrics were derived: commission error (burned and unburned pixels incorrectly classified), omission error (burned and unburned pixels missed), and overall accuracy (the proportion of correctly classified pixels, both burned and unburned).

4. Results

4.1. Results of the assessment based on annual total BA

In this study, the FireCCILT11 product was subjected to a series of analyses whose goals were to assess the performance of FireCCILT11 BA from multiple perspectives. When compared with national fire history datasets, including NBAC, NIFC, EFFIS, and AIFH, FireCCILT11 showed generally low consistencies. In our CI-based comparison, we adopted a threshold of 50% (i.e., annual total BA must be at least 50% higher or at least 50% lower than that mapped by the national fire history datasets to be considered as inconsistent), which we believed was quite liberal. Despite this generous criterion, annual BA as mapped by FireCCILT11 was inconsistent with national fire histories in most years between 1986 and 2018 in seven of the eight countries that we assessed: US (Figure 1a), Australia (Figure 1c), Portugal (Figure 2a), Italy (Figure 2b), France (Figure 2c), Spain (Figure 2d), and Greece (Figure 2e). The only exception was Canada, where good interannual consistency between FireCCILT11 and NBAC was found (Figure 1b). In addition to the national fire history datasets, we specifically included FireCCI51 as a reference dataset against which FireCCILT11 was assessed. Considering that FireCCILT11 was trained based on FireCCI51, high consistency between the two datasets was expected in all countries. However, to our surprise, this was not the case, as in four countries (i.e., Portugal, France, Spain, and Greece), FireCCILT11's BA was inconsistent with that of FireCCI51 in most years between 1986 and 2018 (Figure 2).

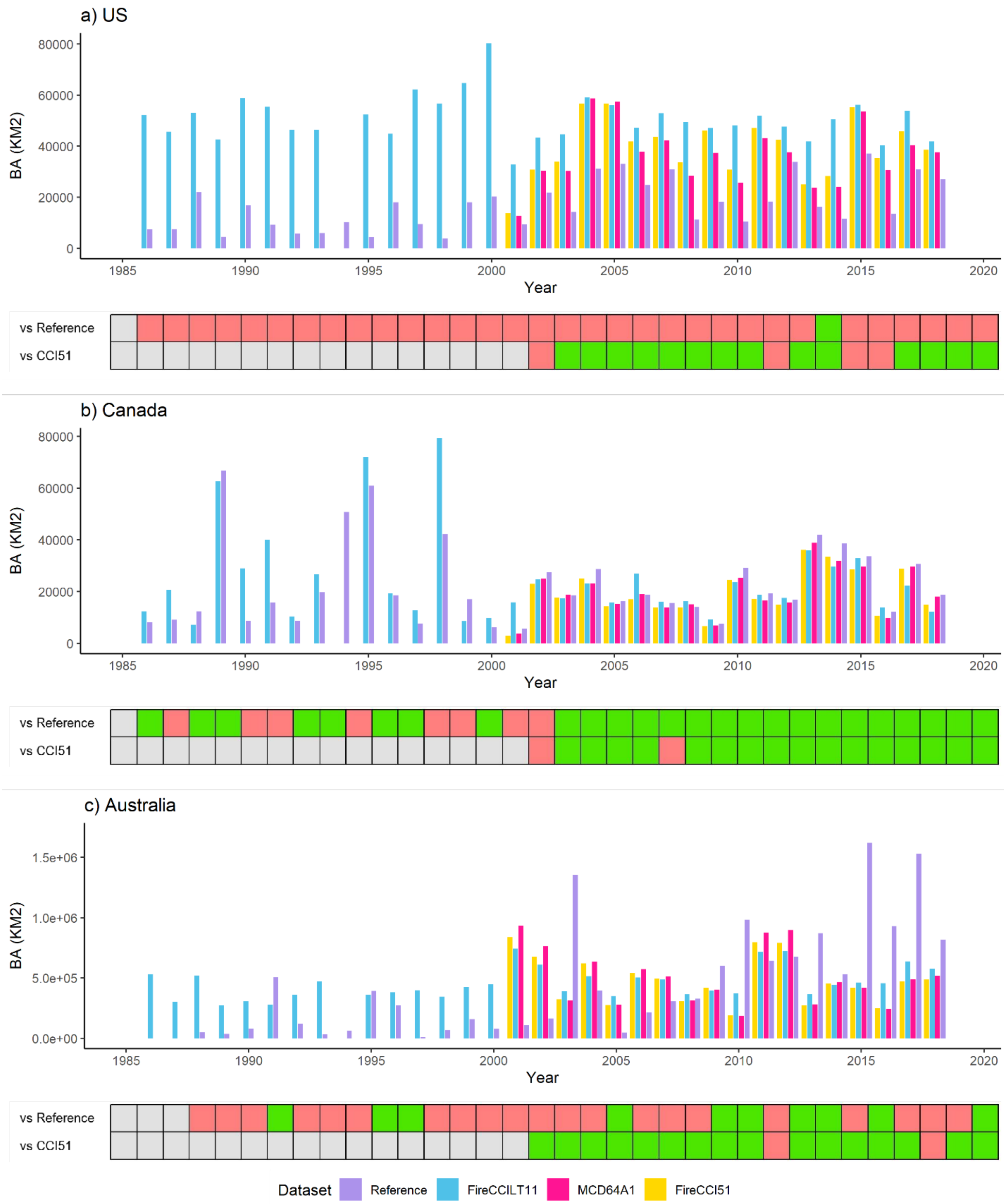

Figure 1. Comparisons of the consistencies of FireCCILT11 against reference datasets and FireCCI51 in terms of annual total BA. The reference datasets in the Panels a-c are NIFC BA, NBAC BA, and AIFH BA, respectively. The color bars below the bar graphs show the levels of

consistency between FireCCILT11 and the reference dataset (top row) and FireCCI51 BA (bottom row), with red, green, and gray indicating larger than 50%, within 50%, and Not Available, respectively.

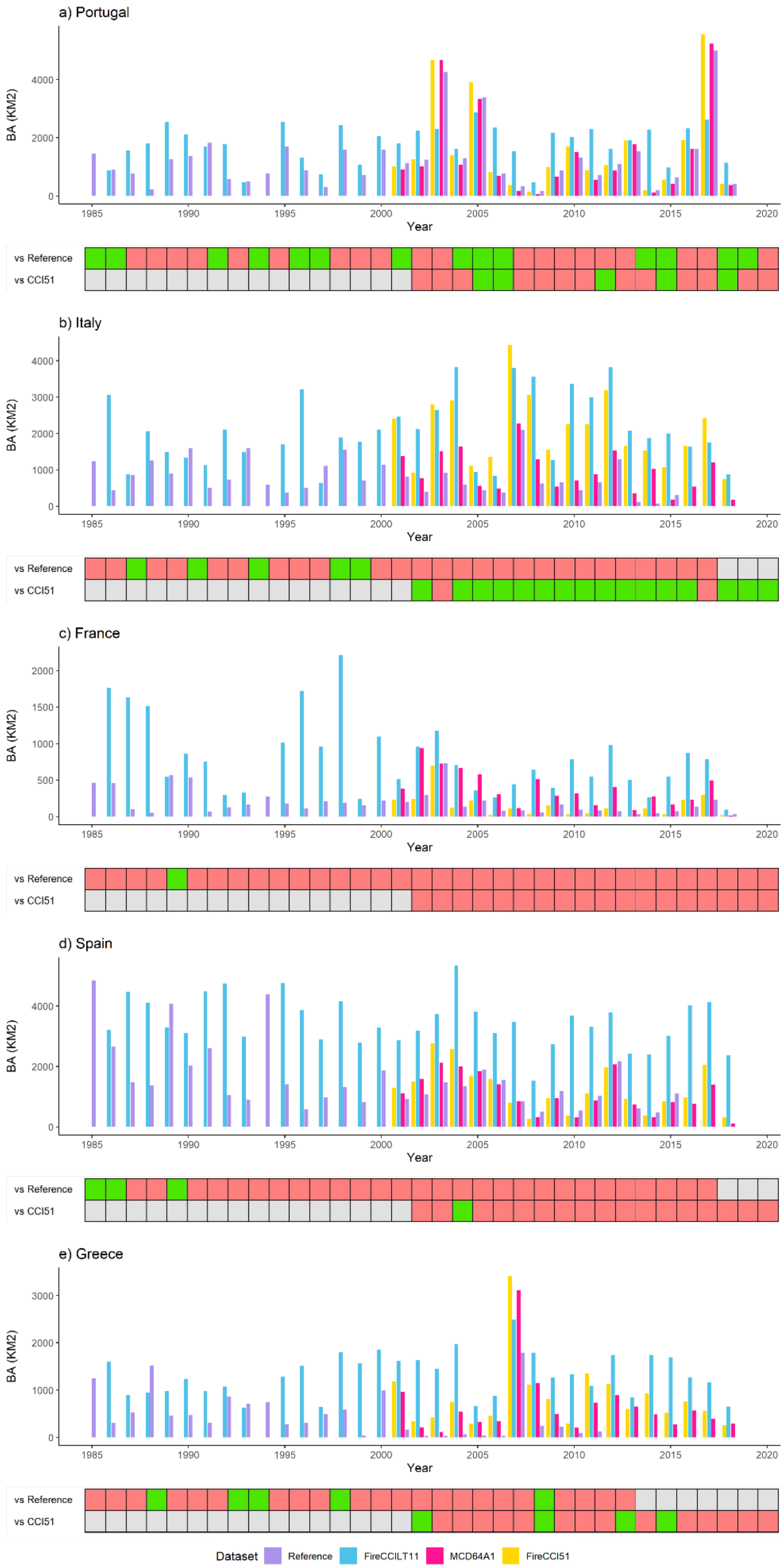
a) Portugal
b) Italy
c) France
d) Spain
e) Greece
BA (KM2)
Year
vs Reference
vs CCI51
Dataset
Reference
FireCCILT11
MCD64A1
FireCCI51

Figure 2. Comparisons of the consistencies of FireCCILT11 against reference datasets (EFFIS BA) and FireCCI51 in terms of annual total BA in each of the five countries covered by EFFIS. The color bars below the bar graphs show the levels of consistency between FireCCILT11 and the reference dataset (top row) and FireCCI51 BA (bottom row), with red, green, and gray indicating larger than 50%, within 50%, and Not Available, respectively.

4.2. Results of the per-pixel-based assessments

Both of our per-pixel-based assessments of FireCCILT11 BA against the US and Canadian national fire history datasets suggest low FireCCILT11 performance, particularly during the pre-2001 era. In the US, the correlation between BA values as mapped by FireCCILT11 and NIFC never exceeded 20% during 1986-2001 (Figure 3a). While the FireCCILT11-NIFC correlation improved since 2002, it fluctuated around a mean value of 30%, with the maximum value below 50% (i.e., 43% in 2004). In Canada, the pre-2001 correlation between FireCCILT11 and NBAC was also strikingly low (Figure 3b). Improvements were also recorded during the post-2001 era, however, the average correlation between the two products over the 17-year period was still below 50% (i.e., 47%). Additionally, The correlation values between FireCCILT11 and NBAC before 2001 were noticeably dominated by negative values (Figure 3b), indicating conflicting trends of BA representation between FireCCILT11 and NBAC. In comparison, both FireCCI51 and MCD64A1 BA products performed much more consistently in both the US and Canada with the corresponding reference datasets.

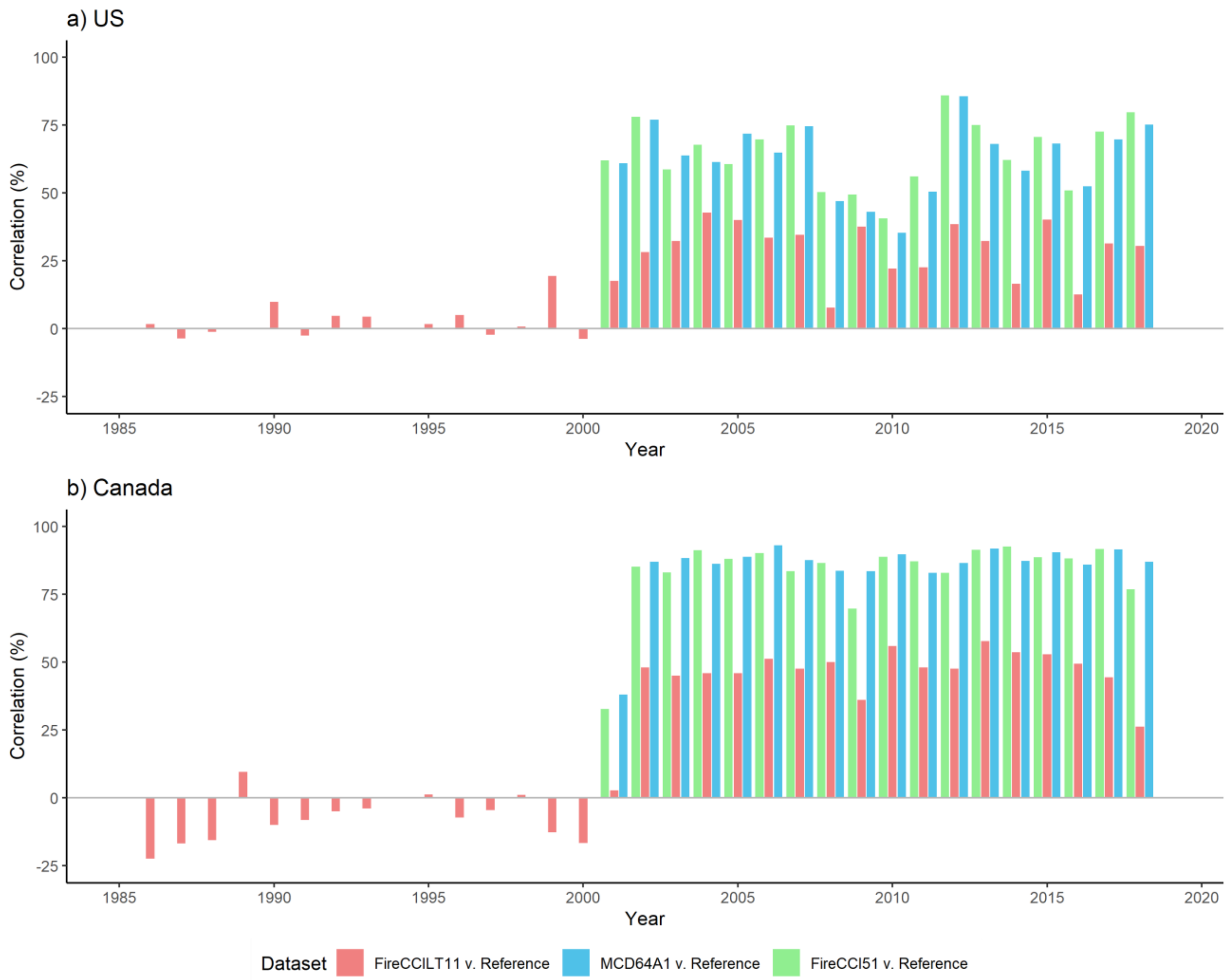

Figure 3. Interannual variation of the Pearson correlation coefficients (*R*) as calculated between the following dataset pairs on a per-pixel basis: red: FireCCILT11 v. Reference, blue: MCD64A1 v. Reference, green: FireCCI51 v. Reference. The reference datasets in Panels a and b are NIFC BA and NBAC BA, respectively.

In the five EFFIS countries as well as Australia where spatially explicit national fire history data are not openly available, our pixel-based correlation analysis cannot be used to infer the accuracy of FireCCILT11 BA. However, by correlating FireCCILT11 and MCD64A1 with FireCCI51 respectively, we can reveal the consistency of FireCCILT11 in relation to the two existing MODIS-based BA products. Our results showed that FireCCILT11/FireCCI51 BA consistency was routinely lower than MCD64A1/FireCCI51 consistency during 2001-2018 in both EFFIS countries and Australia (Figure 10).

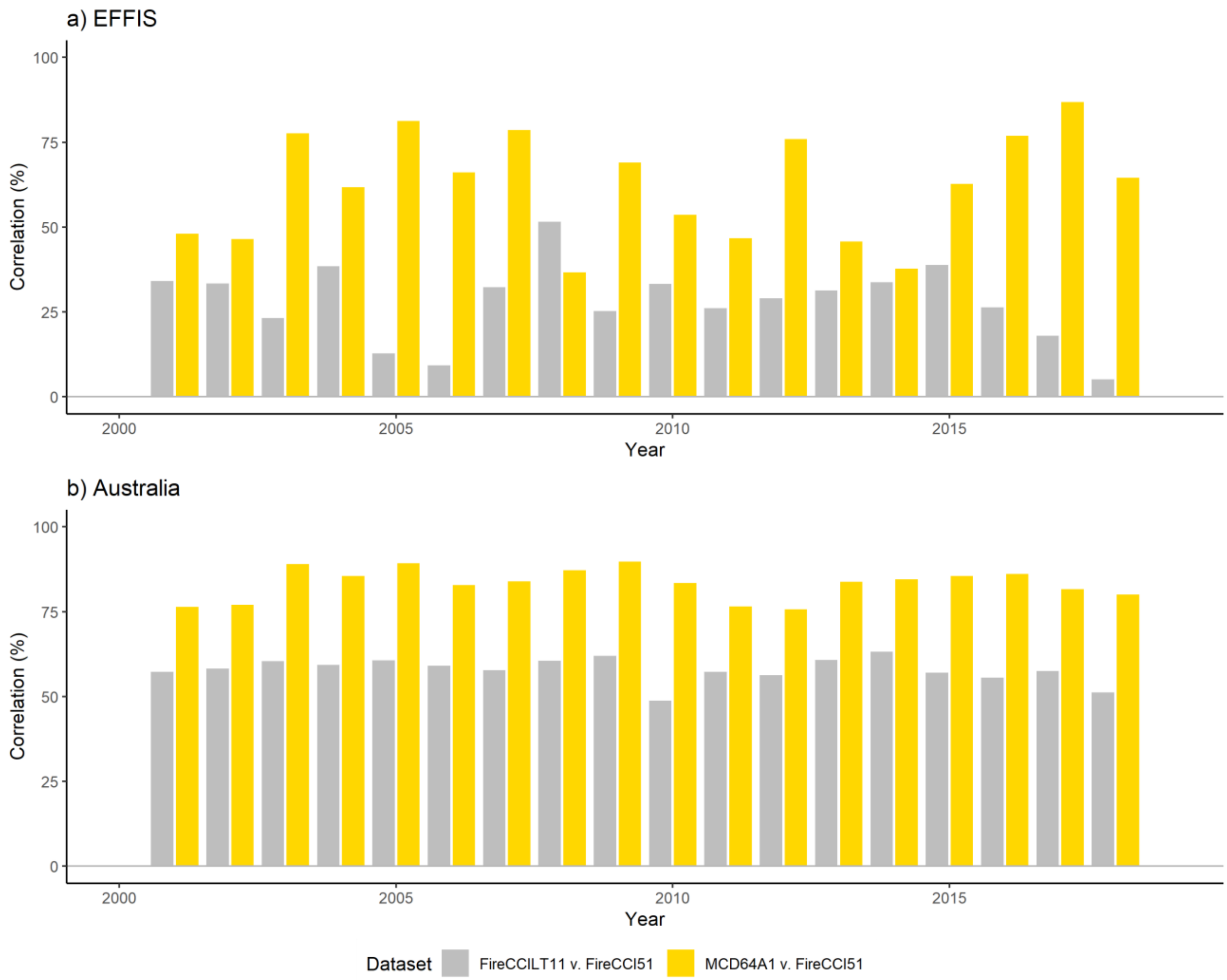

Figure 4. Interannual variation of the Pearson correlation coefficients (*R*) as calculated between the following dataset pairs on a per-pixel basis: gray: FireCCILT11 v. FireCCI51, yellow: MCD64A1 v. FireCCI51.

Our confusion matrix-based analysis provided additional insights into the performance of FireCCILT11. In Canada, FireCCILT11 (in its binary form) showed exceptionally high omission error (i.e., 79.5%) for the burned class during 1986-2000 (Table 2). This metric dropped to 50.4% during 2001-2018, but was still considerable. In terms of the commission error for the burned class, FireCCILT11 mistakenly classified 18% of unburned pixels as burned during 1986-2000. Between 2001 and 2018, however, FireCCILT11's commission error for the burned class dropped substantially to 1.5%. In comparing FireCCILT11's performance against FireCCI51 and MCD64A1 for the common period of 2001-2018, both FireCCI51 and MCD64A1 outperformed FireCCILT11 in every metric, particularly with respect to the omission error for the burned class (Table 2). In the US, the confusion matrices revealed a similar pattern. FireCCILT11 had the highest values of omission error and commission error among the three products during 2001-2018. During 1986-2000, FireCCILT11 not only showed high omission error for the burned class (i.e., 70.7%), but also high commission error (i.e., 48.7%).

Table 2. Confusion matrices for FireCCILT11, FireCCI51, and MCD64A1 based on NBAC for Canada.

			Reference (NBAC)			
FireCCILT11 1986-2000			Burned	Unburned	Total	Commission Error
	Classified	Burned	717	157	874	18.0%
		Unburned	2,783	10,343	13,126	21.2%
		Total	3,500	10,500	14,000	
		Omission Error	79.5%	1.5%		79.0%
FireCCILT11 2001-2018			Reference (NBAC)			
			Burned	Unburned	Total	Commission Error
	Classified	Burned	2,232	35	2,267	1.5%
		Unburned	2,268	13,465	15,733	14.4%
		Total	4,500	13,500	18,000	
		Omission Error	50.4%	0.3%		87.2%
FireCCI51 2001-2018			Reference (NBAC)			
			Burned	Unburned	Total	Commission Error
	Classified	Burned	3,129	24	3,153	0.8%
		Unburned	1,371	13,476	14,847	9.2%
		Total	4,500	13,500	18,000	
		Omission Error	30.5%	0.2%		92.3%
MCD64A1 2001-2018			Reference (NBAC)			
			Burned	Unburned	Total	Commission Error

	Classified	Burned	2,896	32	2,928	1.1%
		Unburned	1,604	13,468	15,072	10.6%
		Total	4,500	13,500	18,000	
		Omission Error	35.6%	0.2%		90.9%

Table 3. Confusion matrices for FireCCILT11, FireCCI51, and MCD64A1 based on NIFC for the US.

			Reference (NIFC)			
			Burned	Unburned	Total	Commission Error
FireCCILT11 1986-2000	Classified	Burned	1,026	974	2,000	48.7%
		Unburned	2,474	9,526	12,000	20.6%
		Total	3,500	10,500	14,000	
		Omission Error	70.7%	9.3%		75.4%
			Reference (NIFC)			
			Burned	Unburned	Total	Commission Error
FireCCILT11 2001-2018	Classified	Burned	2,305	847	3,152	26.9%
		Unburned	2,195	12,653	14,848	14.8%
		Total	4,500	13,500	18,000	
		Omission Error	48.8%	6.3%		83.1%
			Reference (NIFC)			
			Burned	Unburned	Total	Commission Error
FireCCI51 2001-2018	Classified	Burned	2,676	237	2,913	8.1%
		Unburned	1,824	13,263	15,087	12.1%
		Total	4,500	13,500	18,000	
		Omission Error	40.5%	1.8%		88.6%
			Reference (NIFC)			
			Burned	Unburned	Total	Commission Error
MCD64A1 2001-2018	Classified	Burned	2,396	265	2,661	10.0%
		Unburned	2,104	13,235	15,339	13.7%
		Total	4,500	13,500	18,000	
		Omission Error	46.8%	2.0%		86.8%

5. Discussion

5.1. FireCCILT11 performance

In this study, we systematically assessed the performance of FireCCILT11 against the best available reference datasets as well as alternative BA products that overlap temporally with the

FireCCILT11 data record. The results reveal FireCCILT11's generally low performance which is reflected in two aspects: accuracy and consistency. First, FireCCILT11 does not provide an accurate representation of the interannual BA dynamics in many parts of the world. Our analysis of yearly total BA revealed large discrepancies between FireCCILT11and the national fire history datasets between 1985 and 2018 in the US (Figure 1a), Australia (Figure 1c), Portugal (Figure 2a), Italy (Figure 2b), France (Figure 2c), Spain (Figure 2d), and Greece (Figure 2e). Admittedly, the BAs in the latter 5 EFFIS countries are relatively small, which means it may be somewhat easy for a BA product to show large discrepancies with the official BA statistics in these countries. However, the large differences between FireCCILT11 and the official BA statistics in the US and Australia are particularly alarming considering the prevalence of fires in both countries. In the US, in 32 of the 33 years that we examined, yearly total BA as mapped by FireCCILT11 differs more than 50% from what the NIFC dataset recorded (Figure 1a). In Australia, 21 out of 31 years showed larger-than-50% discrepancies between FireCCILT11 and AIFH, which is still not trivial (Figure 1c).

In addition to the yearly total BA, the spatial distribution of burned pixels as reflected by FireCCILT11 is sometimes severely flawed. In the US and Canada, where high-quality spatially explicit national fire history datasets are available, FireCCILT11 showed extremely low per-pixel correlations with the reference fire history datasets before 2001 (Figure 3). The strikingly low spatial correlation during this period offers additional insight into FireCCILT11's performance in Canada since our yearly-total BA analysis revealed that FireCCILT11 performed well temporally in Canada (Figure 1b). This discrepancy means that while FireCCILT11 can provide a generally good representation of the overall interannual dynamics of BA for Canada, it is unable to do so for a spatially explicit representation of burned pixels. Our confusion matrix-based assessment lends further evidence of FireCCILT11's poor performance in this regard. Specifically, FireCCILT11 shows exceptionally high omission errors for the burned pixels, particularly during the pre-2001 era

(Tables 2 and 3), which suggests that FireCCILT11 is very likely to miss BAs when a pixel was actually burned according to the national fire history datasets. In the US, FireCCILT11 also shows high commission errors for the burned class, suggesting that it also tends to overestimate BAs at unburned pixels. These pieces of evidence, taken together, indicate that FireCCILT11 is unable to represent BA reliably in the US and Canada. This claim is corroborated by visual examination of the yearly BA maps. As shown in Figures 5 and 6, which depict 1989 and 2011, respectively, the spatial distribution of the BAs as mapped by FireCCILT11 is strikingly different visually from those mapped by NIFC and NBAC. While we do not have spatially explicit official fire history datasets that allows for such visual comparisons in EFFIS countries and Australia, the large contrasts between FireCCILT11 and other two existing BA product (i.e., FireCCI51 and MCD64A1) indicate that FireCCILT11 may suffer from the same issues in these countries (Figures 7 and 8).

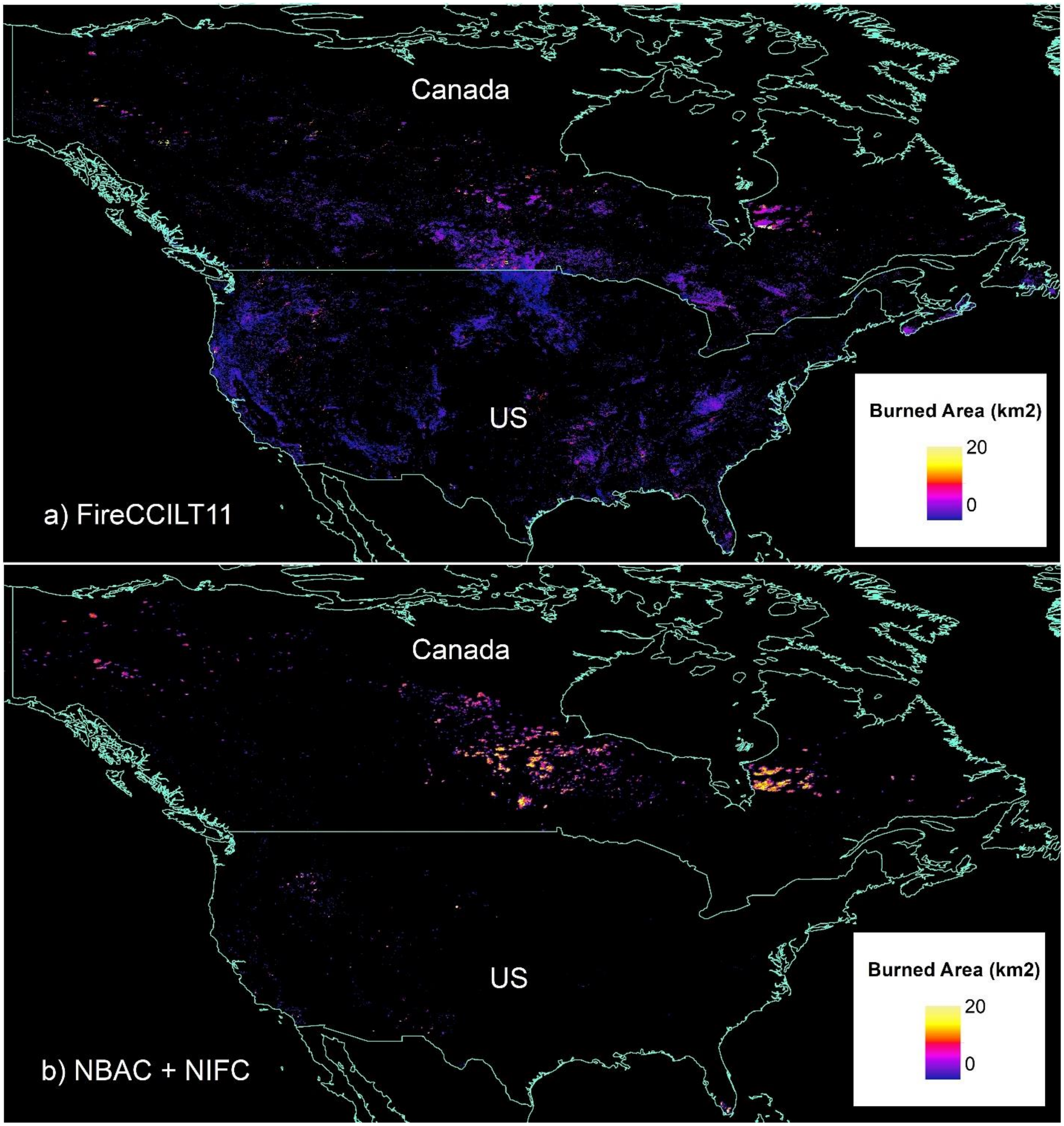

Figure 5. Comparisons of BA in 1989 as mapped by a) FireCCILT11 and b) reference datasets (NBAC in Canada and NIFC in the conterminous US). Both NBAC and NIFC BA were projected and resampled to 0.05° to be consistent with FireCCILT11.

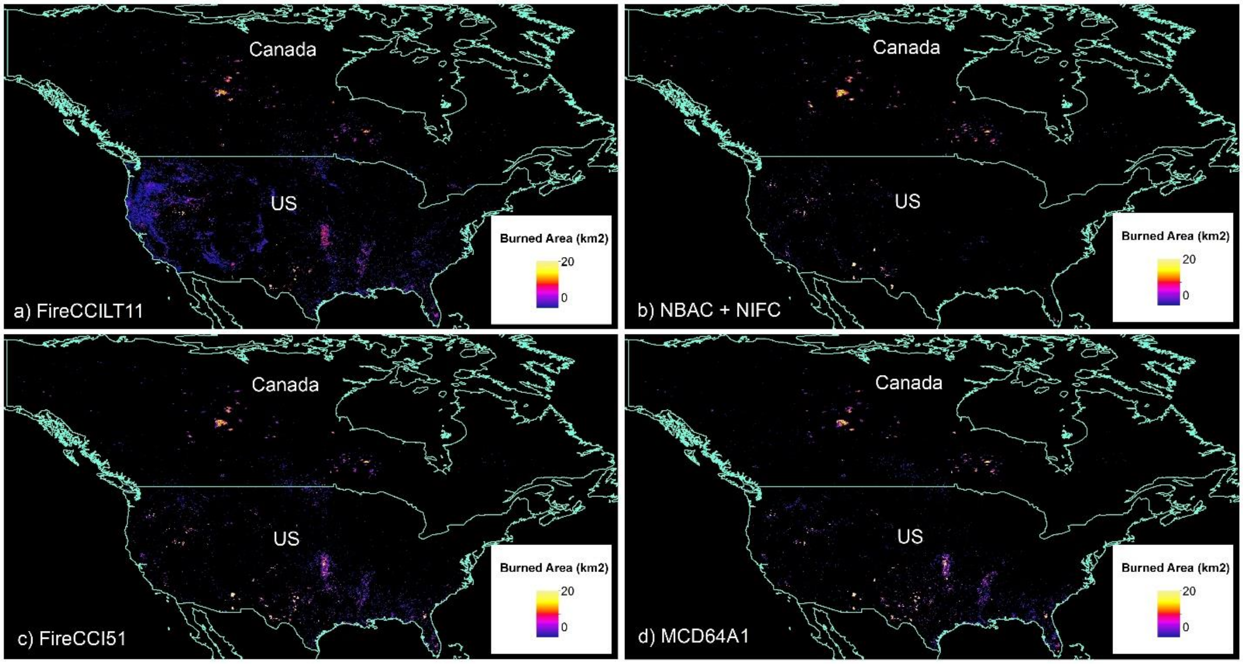

Figure 6. Comparisons of BA in 2011 as mapped by a) FireCCILT11, b) reference datasets (NBAC in Canada and NIFC in the conterminous US), c) FireCCI51, and d) MCD64A1. All datasets were projected and resampled to 0.05° to be consistent with FireCCILT11.

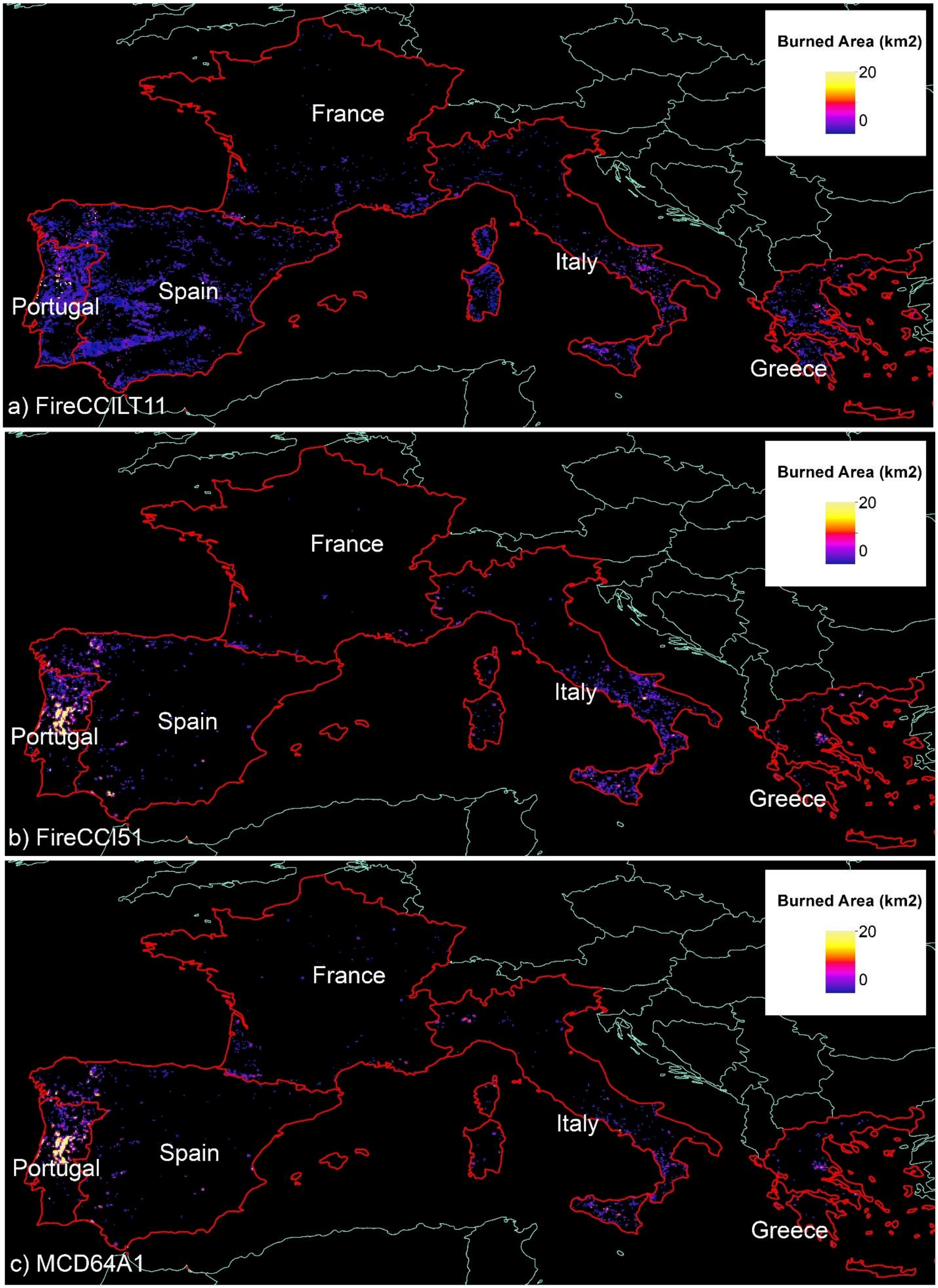
Burned Area (km2)
20
0
France
Italy
Spain
Portugal
Greece
a) FireCCILT11
Burned Area (km2)
20
0
France
Italy
Spain
Portugal
Greece
b) FireCCI51
Burned Area (km2)
20
0
France
Italy
Spain
Portugal
Greece
c) MCD64A1

Figure 7. Comparisons of BA in 2017 in the five European countries as mapped by a) FireCCILT11, b) FireCCI51, and c) MCD64A1. Both FireCCI51 and MCD64A1 BA were projected and resampled to 0.05º to be consistent with FireCCILT11.

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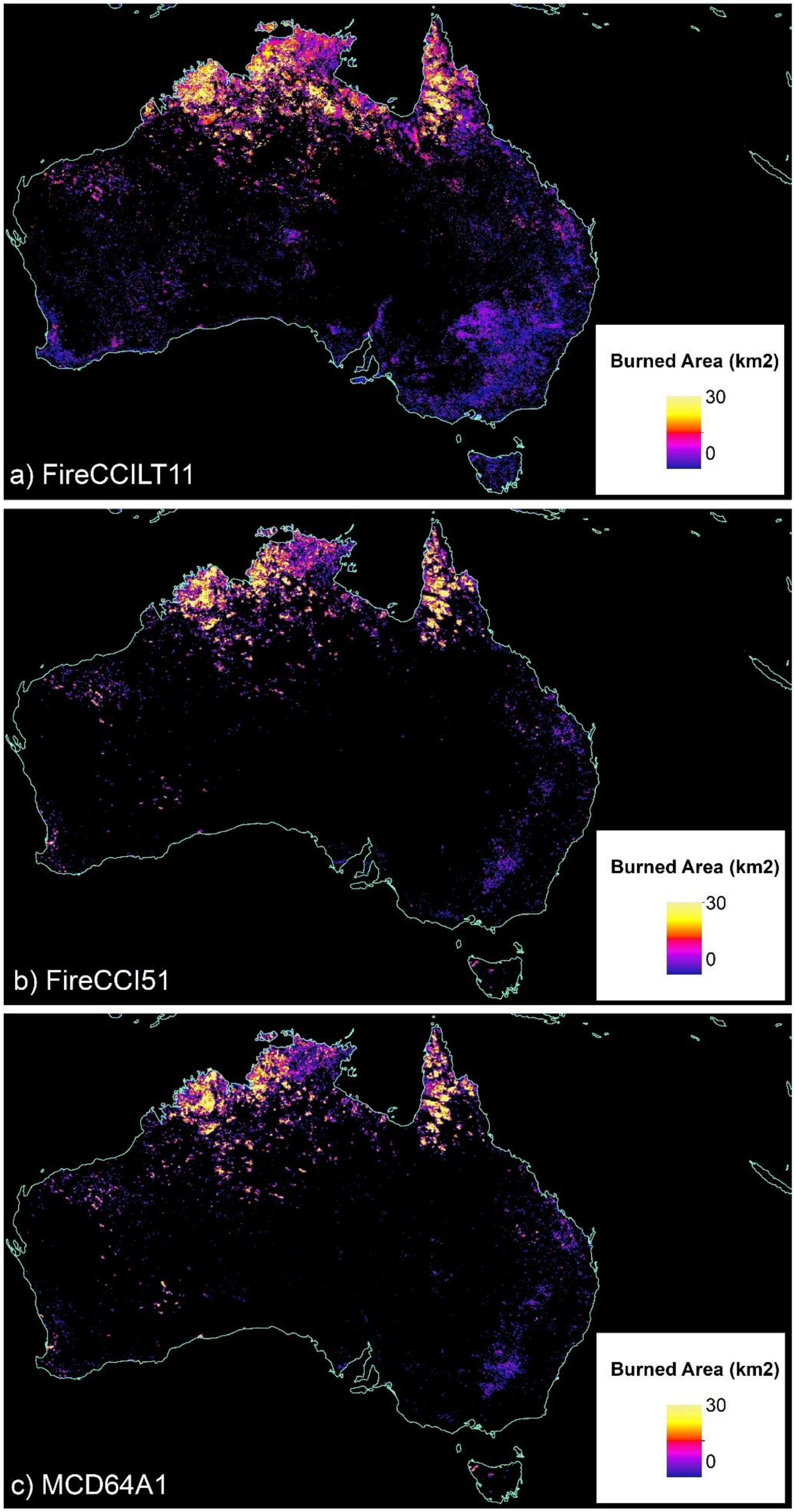

Burned Area (km2)
30
0
a) FireCCILT11
Burned Area (km2)
30
0
b) FireCCI51
Burned Area (km2)
30
0
c) MCD64A1

Figure 8. Comparisons of BA in 2016 in Australia as mapped by a) FireCCILT11, b) FireCCI51, and c) MCD64A1. Both FireCCI51 and MCD64A1 BA were projected and resampled to 0.05º to be consistent with FireCCILT11.

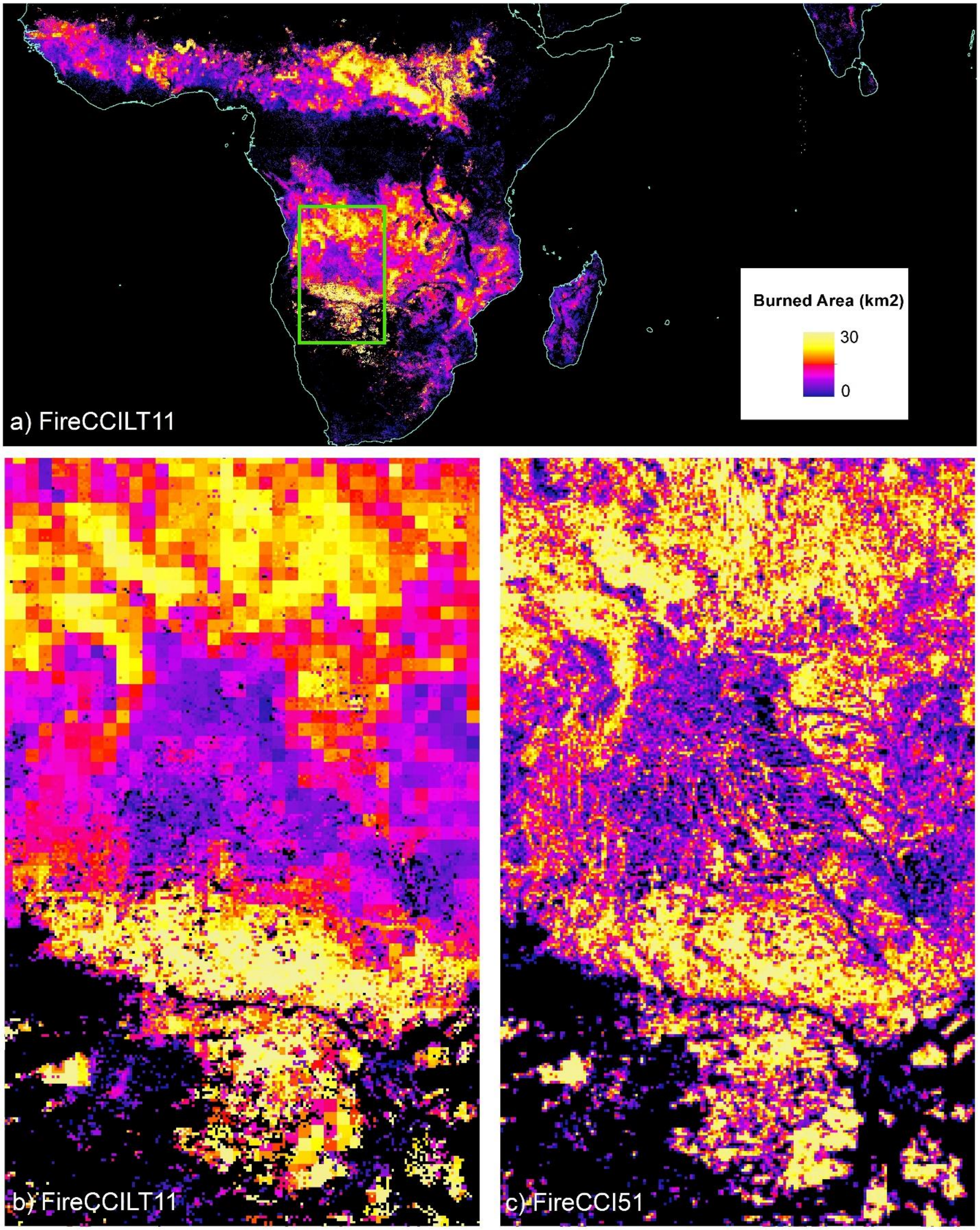
Second, FireCCILT11 has low consistency in mapping BAs. The ability to map BAs consistently is a prerequisite of a reliable BA product, particulary one that is used for long-term trend analyses. However, FireCCILT11 lacks in this regard. Numerous pieces of evidence presented by our study suggest a strong dichotomy in FireCCILT11's performance between the pre-2001 (i.e., 1986-2000) and post-2001 (i.e., 2001-2018) eras, whether based on yearly total BAs (Figures 1 and 2) or per-pixel comparisons (Figure 3, Tables 2 and 3). In general, the accuracy of FireCCILT11 during the pre-2001 era is much lower than that of the post-2001 era. Such low accuracies are not only reflected in the inconstancies in BA values with the reference fire history datasets, but also in the drastically different spatial representation of the overall fire regimes (Figures 5-8). While this phenomenon itself is not surprising considering FireCCILT11 was trained based on data from the post-2001 era, the strong deterioration in performance of FireCCILT11 going back in time to the pre-2001 era indicates that FireCCILT11 is not generally suitable for robust long-term trend analyses. Another indicator of FireCCILT11's lack of consistency involves the overall poor correlation of FireCCILT11 BA with FireCCI51 BA, which was the training input used to produce FireCCILT11. As revealed in our analyses based on yearly total BAs (Figure 2), FireCCILT11's yearly BAs deviate from those of the FireCCI51 product substantially in all five EFFIS countries except for Italy (Figure 2). This pattern is corroborated by our per-pixel analyses, which show that FireCCILT11 always has lower correlations relative to FireCCI51 when compared against a common BA product (Figures 3 and 4, Tables 2 and 3).

5.2. Limitations of the FireCCILT11 design and original accuracy assessment

The lack of accuracy and consistency in the performance of FireCCILT11 deviates from the goal set by its producers of delivering a reliable long-term global BA product. These issues were likely not clearly identified in the original accuracy assessment as a result of two key features of the Otón et al. (2021b) FireCCILT11 product and assessment methodologies acting in combination: the heavy and exclusive reliance on interannual total BA as the basis for the assessment, and the involvement of the FireCCI51 product in FireCCILT11 training, calibration, and assessment. In the first case, per-region total annual BA as mapped by the various BA products was the sole metric (Otón et al. (2021b). This included both visual comparison of interannual distribution of the regional BA values, and correlation coefficients. Such a design is not sufficient to fully examine the spatial distribution of burned pixels within a particular region in a given year, which is required for a reliable BA product. In the second case, FireCCI51 was used not only as the training data for the initial FireCCILT11 binary burned/unburned mapping algorithm, but also as a crucial input guiding the final allocation of actual burned area to burned pixels within larger ~25-km patches. While the use of FireCCI51 for training and calibration was a reasonable practice by itself, it substantially weakens the reference power of FireCCI51 in accuracy assessments, particularly those involving only total BA. This dual use suggests that the level of involvement of FireCCI51 in developing the FireCCILT11 mapping algorithm was perhaps too heavy, which explains the great deterioration of mapping accuracies in the pre-2001 era compared with the MODIS era when FireCCI51 was available. And FireCCI51 should have been excluded in the accuracy assessment, as suggested by Humber et al. (2018). We note that Otón et al. (2021a) later conducted an independent accuracy assessment of FireCCILT11 using Landsat data. However, that assessment was limited to a single Landsat path/row in southern Africa, which limits its validity for evaluating a global BA product.

5.3. FireCCILT11 pixelation effect

A notable feature of FireCCILT11 BA, which was reported by Giglio and Roy (2023) but has not been discussed extensively, is that at its native resolution of 0.05º, the product appears to be highly pixelated. Specifically, in many parts of the BA maps, the BA values of the 25 spatially adjacent 0.05º grid cells (that form a 0.25º grid cell) are highly similar (Figure 9). Because of this pixelation effect, FireCCILT11 is unable to resolve the spatial details of fire distribution at 0.05º, which the 0.05º version of the FireCCI51 product is able to (as exemplified by the comparison between Panels b) and c) in Figure 9). This means that the effective spatial resolution of FireCCILT11 should be considered as 0.25º instead of 0.05º. This may be one of the reasons why the per-pixel accuracies of FireCCILT11 at the 0.05º resolution was low (Tables 2 and 3).



Burned Area (km2)
30
0
a) FireCCILT11
b) FireCCILT11
c) FireCCI51

Figure 9. a) BA in Sub-Saharan Africa in 2011 as mapped by FireCCILT11. b) A zoomed-in view of an area in a). c) The same area as in b) but as mapped by FireCCI51 from the same year. Both FireCCILT11 and FireCCI51 datasets visualized in these graphs have the same resolution of 0.05º.

Another noticeable feature associated with the pixelation effect is that the pixelation is not spatially consistent. As shown in Figure 9b, which is a zoomed-in view of FireCCILT11 for Sub-Saharan Africa in 2011, the pixelation effect is present in northern areas, whereas in the south its presence is much less prevalent. This inconsistency in spatial distribution is yet another factor that weakens the spatial coherence of FireCCILT11 as the users will essentially be dealing with two effective spatial resolutions (i.e., 0.05º and 0.25º) in any given image.

5.4. The need for a consistent, long-term AVHRRBA product

While a laudable step toward a long-term BA record, the FireCCILT11 product was released with only a high-level, regional accuracy assessment conducted on an annual basis, and extremely limited validation (Otón et al. (2021a). In hindsight, it is clear that those assessments were not sufficiently comprehensive for a global BA product whose temporal coverage spans nearly four decades. While Giglio and Roy (2022) and Giglio et al. (2022) have since documented pervasive orbit-drift artifacts in the FireCCILT11 product, the evidence in those studies was primarily circumstantial and similarly conducted at large spatial scales. Here, through a series of pixel-level accuracy assessments utilizing remotely sensed global burned area data and independent regional burned area data, we showed that the FireCCILT11 product suffers from significant quality issues at much finer spatial scales and in additional locations, particularly in areas outside Canada during the pre-2001 era, which weaken its usability as a reliable global BA product. While the performance of FireCCILT11 is substantially better in Canada and the US during the post-2001 era, its performance does not overshadow that of FireCCI51 or MCD64A1, two global BA products that have been extensively assessed in the literature and proven to be high quality (Boschetti et al. 2019; Franquesa et al. 2022; Huang et al. 2023; Katagis and Gitas 2022). This diminishes the need to use FireCCILT11 if the study period is within the post-2001 era, due to the presence of better quality alternatives. Consequently, it seems fair to say that the long-recognized need for a reliable, multi-decadal global BA product necessarily derived from AVHRR data (Giglio and Roy 2020) remains unsatisfied. Continued effort is required to address the many challenges of using data from this sensor.

5.5. Best practice for assessing long-term BA product

Due to the limited operational lifespan of satellite-based remote sensing sensors and the continual advancement of imaging technologies (e.g., MODIS being superseded by VIIRS, Landsat TM by ETM+, and subsequently by OLI), generating and validating long-term BA products requires integrating data from multiple sensor generations, usually involving space-for-time interpolation. This introduces additional complexity beyond standard validation challenges for single-sensor products. While substantial research exists on accuracy assessment methods for short-term BA products (<20 years) through validation protocols, reference databases, and comparative analyses against ground data, there remains a critical gap in established methodologies for evaluating long-term, multi-sensor BA datasets. Current validation frameworks primarily address temporal consistency within individual sensor records rather than cross-mission harmonization, leaving unresolved questions about error propagation and spectral compatibility across sensor lineages.

Here we argue that the evaluation of long-term BA products must adhere to several fundamental protocols to ensure robust and meaningful accuracy assessments. First, the training data used in algorithm development should ideally encompass the entire spatial and temporal range of the BA product. This broad coverage helps capture the full variability of fire regimes, including differences in fire size, intensity, and vegetation types. In cases where complete spatial coverage is unattainable, it is essential that training data are sampled from all major ecosystems with distinct fire characteristics, thereby reducing potential biases arising from underrepresented regions or fire types. Additionally, the temporal distribution of training data must account for the interannual variability of wildfire activity. Specifically, training datasets should include samples from years with both low and high fire activity, as data from only small fire years may not adequately represent the conditions present in large fire years, and vice versa.

Second, testing data-used for independent validation-must be both spatially and temporally consistent throughout the product's spatio-temporal domain. This consistency is best achieved by leveraging long-term, standardized datasets such as Landsat Analysis Ready Data (Dwyer et al. 2018), which provide harmonized surface reflectance records across decades. When such datasets are unavailable, especially for older sensors like the AVHRR, explicit calibration and harmonization methods (e.g., approaches developed by Berner et al. (2023) in conducting cross-sensor calibration harmonalizing Landsat 5, 7, and 8 data) must be implemented to minimize inter-sensor discrepancies. This requirement is particularly challenging for AVHRR-based BA products, where sensor degradation and lack of standardization can introduce significant uncertainties.

Finally, reference data used for accuracy assessment must be strictly independent of the data production process to avoid circular validation. These reference datasets should ideally be available for all unique spatiotemporal domains, including periods of sensor transition and across ecosystems with different fire regimes, ensuring comprehensive coverage and representativeness. Furthermore, performance assessment should not rely solely on aggregate BA statistics; it must also include per-pixel accuracy metrics, such as omission and commission errors, calculated over the entire spatial and temporal extent of the BA product. This dual approach enables a more robust and nuanced understanding of product performance, particularly in heterogeneous landscapes.

6. Conclusion

This study conducted a comprehensive assessment of the FireCCILT11 global BA product, revealing significant limitations in its accuracy and consistency. The evaluation, based on national fire history data and comparisons with other remotely sensed BA products like FireCCI51 and MCD64A1, highlighted several critical issues with FireCCILT11. Key findings indicate that FireCCILT11 generally exhibits low consistency with national fire records in terms of annual total BA across most of the eight countries assessed, with Canada being the exception. Even when compared to FireCCI51, which served as its training data, FireCCILT11 showed inconsistencies in annual BA in several European countries. Per-pixel assessments in the U.S. and Canada revealed particularly low performance for FireCCILT11, especially during the pre-2001 period, with low correlations and high omission errors. In the U.S., FireCCILT11 also demonstrated high commission errors. The product's performance was markedly different and generally worse in the pre-2001 era compared to the post-2001 era, undermining its suitability for robust long-term trend analyses. Furthermore, a "pixelation effect" was observed, suggesting that the effective spatial resolution of FireCCILT11 is closer to 0.25° rather than its native 0.05°, and this effect was not spatially consistent.

These findings demonstrate that the spatial distribution of burned areas in FireCCILT11 can in some instances diverge spectacularly from higher-quality independent reference data, particularly before 2001, and the product is therefore unable to reliably represent BA in many regions. The original FireCCILT11 accuracy assessment at the time the product was released likely did not identify these issues due to its heavy reliance on interannual total BA and the triple-use of the "parent" FireCCI51 BA product for FireCCILT11 training, calibration, and assessment. While FireCCILT11's performance improved in the post-2001 era in North America, it did not surpass existing products like FireCCI51 and MCD64A1, diminishing the necessity for its use during this period.

In conclusion, this assessment underscores significant quality issues with the FireCCILT11 product, which weaken its utility as a reliable long-term global BA dataset. There remains a pressing need for the development of a robust and consistent long-term global BA product, likely based on AVHRR data, but this will require extensive work to address the inherent challenges of those data. To ensure the reliability of future long-term BA products, adherence to stringent assessment protocols is advisable. These ideally include training data that span the product's full spatiotemporal range, employing temporally consistent testing data independent of the production process, and conducting per-pixel accuracy assessments alongside aggregate statistics. Such rigorous evaluation is crucial for providing the scientific community with dependable data for understanding long-term fire regime dynamics and their impacts.

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