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Assessment of the effectiveness of coarse resolution fire products in monitoring long-term changes in fire regime within protected areas in South Africa

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ABSTRACT

Although high-resolution satellite and in situ airborne observations are becoming a common data source for fire monitoring, reconstruction of the historical fire record is based on less suitable data. In many regions, managers and policy-makers rely solely on coarse resolution global fire datasets. This study assessed the suitability of readily available products to accurately depict several fire metrics by comparing them to the manually derived fire scars within three natural reserves in South Africa (2003–2020). Contrary to previous findings, we showed that MCD64A1 and FireCCI51 products detected the majority of the burned area (70–97 %) within protected areas and showed high temporal consistency. Additionally, active and burned area products accurately detected the length and the peak of the fire season. Nonetheless, we found neither medium nor coarse resolution data suitable for evaluating long-term changes in fire size distribution. Coarse resolution burned area products demonstrated a very limited capacity to detect fires smaller than 100 ha, while a lack of sufficient non-cloudy Landsat images led to substantial gaps in fire reconstruction, bringing an unknown level of uncertainties in fire metrics estimates. Similarly, the only available medium-resolution burned area product (GABAM) was unsuitable for fire monitoring since unmapped areas were classified as unburned, making no distinction between regions with an absence of data and an absence of fires. Meanwhile, the performance of FireCCILT11 was ranked the lowest among all the available fire products. Given the lack of resources in many protected areas in South Africa and the pressing need to evaluate current and historical fire management practices and policies, we conclude that, in the absence of a more accurate higher-resolution alternative, MCD64A1 was the most suitable product for capturing year-to-year fluctuations in fire activity and a combination of MODIS and VIIRS active fire products for monitoring changes in fire seasonality.

1. Introduction

Fire is an important ecological process in maintaining the structure of tropical savannas since it creates a spatio-temporal mosaic of patches at different successional stages and, therefore, directly impacts the habitats of many species (Parr and Brockett 1999; van Wilgen 2009). The vegetation structure and composition of savannas are regulated by the availability of resources (e.g., water); woody species require a certain amount of annual precipitation, after which a disturbance regime (e.g., fire) regulates the competition of grasses and woody plants (Staver et al. 2011). Frequent fires commonly observed in tropical savannas due to strong rainfall seasonality limit woody encroachment and promote a continuous grass layer that rapidly regrows and becomes flammable, favoring the savannas' grass component (Staver et al. 2011). Consequently, fire has been recognized as an integral part of natural savanna systems and used to achieve a range of management goals such as suppression of bush encroachment and the spread of alien invasive species, promotion of vegetation diversity, and improvement of habitat for game and game-viewing (Hudak and Brockett 2004; van Wilgen 2009). The essential significance of fire application for biodiversity management is also widely acknowledged (Miller et al., 2019; Topp et al., 2022).

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Due to fire's intrinsic role in shaping plant communities, managers of protected areas are often concerned about the potential negative consequences of burning for managing protected areas (Eckhardt et al., 2000; van Wilgen et al., 2003). This concern led to the introduction of a number of fire-management policies over the last several decades, from complete fire exclusion, prescribed rotational burning, suppression of only anthropogenic fires, and burning management blocks to a patch-mosaic burning system to simulate a variable fire regime on the landscape based on the premise that it is more natural and will promote heterogeneity and the conservation of biodiversity (van Wilgen 2009). Despite the long fire history in African savannas, fire management in protected areas remains a controversial issue, with no consensus regarding the most appropriate burning system (Parr and Brockett 1999). The reason behind those considerable debates, in part, is the absence of comprehensive fire records in Africa in general and within protected areas in particular since detailed information on fire regimes has been documented for only a few African national parks (Nieman et al. 2021; van Wilgen et al. 2004). The lack of adequate and accurate data on the regional occurrence, size distributions, or trends in fire activity leaves managers little choice other than to base the need to intervene on general principles without necessarily understanding the nature of the current and past fire regimes and the effectiveness of different interventions within a specific region (Forsyth and van Wilgen 2008).

Remote sensing is often the only source of objective and spatially explicit information in data-sparse environments like African savannas (Archibald and Hempson 2016; Goodwin and Collett 2014), which can fill important knowledge gaps such as understanding the role of fire as a natural process, and its relationship with climate and vegetation, and to develop informed and feasible fire-management policies and procedures (van Wilgen 2009). Specifically, more than two decades of freely available data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board NASA's Terra (launched 1999) and Aqua (launched 2002) polar-orbiting satellites that has specific features for fire monitoring (Justice et al. 2002) made it possible to analyze recent trends and fire activity pattern from local to global scale (Giglio et al. 2013). A number of global MODIS-derived products from NASA and ESA provide information about the spatial extent of fire, approximate day of burning, and thermal signature of fire with high temporal (1 day) and coarse spatial resolution (e.g., MCD64A1 [500 m], MCD14ML [1 km], FireCCI51 [250 m]). Although those fire products provide free, ready-to-use, objective fire statistics at regular temporal intervals across very large areas, there is an open debate on whether the observation record available to-date is sufficiently long to conduct meaningful analyses of fire regimes (Bowman et al. 2020). Additionally, the above-mentioned coarse resolution fire products are unsuitable for detecting small fires, resulting in significant underestimates of burned area and emissions from fires in Africa (Ramo et al. 2021). Importantly, those undetected fires usually occur early in the season; therefore, coarse resolution products might be ineffective in monitoring shifts in fire activity resulting from a change in fire management (Laris 2021).

As an alternative source for fire scar mapping, Landsat imagery at 30 m spatial resolution has been available for over 40 years and, therefore, can be used to reconstruct long-term fire history with more detail (Hudak and Brockett 2004; Russell-Smith et al. 1997). However, unlike the MODIS sensor, Landsat imagery has a lower temporal resolution (16 days versus daily cycle of MODIS), and prior to Landsat 8, not every scene was acquired globally due to mission resource constraints. The former limitation was largely overcome by combining Landsat 8 data with Sentinel-2, allowing Roy et al. (2019) to successfully map burned areas in Southern Africa at medium resolution. Unfortunately, this approach cannot produce a multidecadal-scale fire history essential for resource managers, policy, decision-makers, and scientists.

Current research aims to evaluate the applicability of remotely sensed data to monitor fire activity in protected areas in African savannas in response to some of the issues documented in the literature regarding the suitability of those datasets to map small, fragmented, low-intensity fires. To that end, here we (i) reconstructed nearly two decades of fire regime within three nature reserves in South Africa using all available Landsat and Sentinel-2 imagery; (2) compared currently existing medium and coarse resolution data to determine which can accurately depict spatio-temporal distribution of fire activity; and (3) determined limitations of each ready-available fire products in estimating fire frequency and seasonality in regards to the sizes of contiguously burnt area (fire scar).

2. Materials and methods

2.1. Study area

Fire history reconstruction was conducted in three protected areas located in the northeastern part of South Africa (Fig. 1): Manyeleti Nature Reserve, Blyde River Canyon Nature Reserve, and Songimvelo Nature Reserve (hereafter Manyeleti, Blyde, and Songimvelo, respectively). Manyeleti is a 22,498-ha reserve contiguous with Kruger National Park. The gentle terrain of Manyeleti supports an open savanna dominated by woody species like *Sclerocarya birrea* and *Senegalia nigrescens* (Marshal et al. 2012). While located only 50 km west of Manyeleti, Blyde is located along the Northern Drakensberg escarpment and is characterized by its rugged topography and altitudinal gradient (600 m – 2000 m above sea level), including the third-largest vegetated canyon in the world (Marais et al. 2005). Due to its topographically complex landscape, the 38,706-ha Blyde reserve hosts a variety of habitats, including high-altitude grassland plateaus, wetlands, sponge areas, grassland-dominated slopes gradually changing into savanna, afromontane forests, riparian forests, moist woodlands, dry woodlands, and shrublands. Numerous endemic and species of conservation concern can be found there (Lötter and Beck 2004). Additionally, about 80 % of Blyde is neighbored by commercial forestry, which influences the reserve's management environment, stream flow, and fire regime (Marais et al. 2005). Approximately 90 km south of Blyde, Songimvelo is located on the South African–Eswatini border. This approximately 49,000-ha nature reserve comprises a 31,000-ha game-fenced southern and central section. Like Blyde, Songimvelo's terrain is generally rugged, with elevation ranging from 650 m to over 1895 m above sea level, supporting highly diverse vegetation from grassland to savannah and numerous isolated patches of forest, mostly at higher elevation and along rivers (Stalmans et al. 2001).

Although the three reserves are situated in the summer rainfall area of South Africa, rainfall occurs mainly from November to March, with January-February being the hottest months; temperature and especially rainfall vary widely between and even within the protected areas. Manyeleti experiences the driest and hottest conditions, with a mean annual rainfall of around 588 mm and an average daily temperature of 22.5 °C. Along the more than 50-km long north–south axis of Blyde, climate conditions vary from hotter and drier on the north (564 mm and 17.7–26.1 °C) to cooler and wetter on the south (2217 mm and 10.9–18.6 °C). A strong elevation gradient dictates the climate in Songimvelo, with mean annual rainfall between 874 mm in the lowland areas (southwest) and around 1533 mm in the high-altitude areas (northeast). Similarly, great temperature variations are experienced between the lowlands (7.9 – 34 °C) and highlands (5.4 – 22 °C).

2.2. Data

Datasets used for fire scar mapping included Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 Operational Land Imager (OLI), and Sentinel-2 MultiSpectral Instrument (MSI). All currently available global multi-year burned area (BA) and active fire (AF) products were analyzed in this study. BA products consisted of coarse resolution MODIS MCD64A1 Collection 6 at 500 m (2001–2022, Giglio et al. 2018), ESA's FireCCI51 at 250 m

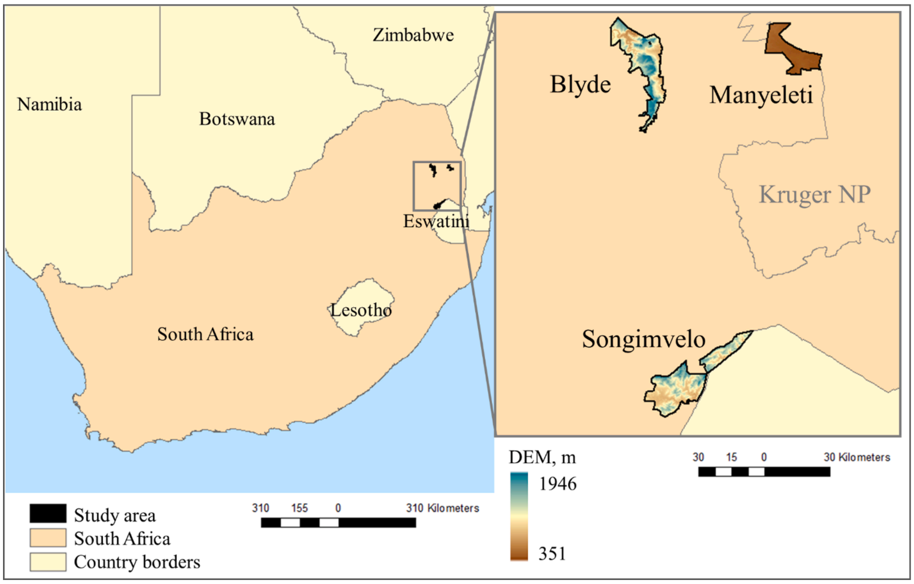

Fig. 1. Study area. DEM – Digital Elevation Model (Verdin 2017).

(2001–2020, Lizundia-Loiola et al. 2020) and FireCCILT11 at 0.05° (1982–2018, Otón et al. 2021), and the only global medium resolution BA dataset GABAM at 30 m (1985–2020, Long et al. 2019). The 0.25°coarse resolution of the latest Global Fire Emissions Database (GFED, Chen et al. 2023) rendered that data set unsuitable for the current study. AF products included Collection 6 MODIS Aqua and Terra at 1 km (MCD14ML) fire location product (Giglio et al. 2016) and VIIRS S-NPP Collection 2 (VNP14IMGML) at 375 m (Schroeder and Giglio 2018).

2.3. Fire scar mapping

The individual fire scars were manually mapped annually from 2003 (the first complete year that data from both the Terra and Aqua MODIS was available) to 2020 (the last year when data from FireCCI51 and GABAM was available) using all images from Landsat 5, 7, 8 and Sentinel-2. Specifically, 300 images were used for reconstructing fire history in Manyeleti, 314 in Blyde, and 319 in Songimvelo. While visual interpretation and manual burn scar digitizing are extremely time-consuming to implement, and many automated techniques have been recently developed to map BA using medium-resolution imagery (e.g., Roteta et al. 2019; Roy et al. 2019; Sismanis et al. 2023), those techniques are either only applicable to map extensive fires in regions with spectral persistence much longer than the 16-day Landsat acquisition period (e.g., forest fires) or require a large amount of data. Therefore, they can only be applied using a combination of Landsat and Sentinel-2 data. Additionally, small, spatially fragmented fires and/or burns with low combustion completeness might be especially hard to map automatically and differentiate from spectrally similar unburned features (Roy et al. 2005a). The interpretation approach was based upon a multitemporal visual comparison of a false-color composite of shortwave infrared, near-infrared, and red bands (Landsat 8: 7–5-4, Landsat 5/7: 7–4-3, Sentinel-2: 12-8A-4) similar to previous studies (Nakalembe et al. 2022; Roy et al. 2005a). Each fire scar was characterized by the size of the area burned and the beginning and end dates (the latest image prior to the detection of the fire and the first image that depicted the entire fire scar). As was expected, the quantity of cloud-free images during the years before Sentinel-2 was a limiting factor for BA mapping. The issue was exacerbated by the failure of the Scan Line Corrector in the ETM+instrument of the Landsat 7 satellite. As a result, there were several years (2009–2012) when the lack of at least one clear Landsat image per month during the fire season potentially biased the fire history reconstruction. Specifically, 2009 was a year when BA could not be mapped since no cloud-free images were available for Manyeleti after May 12th and in Songimvelo between May 12th and November 12th.

2.4. Fire regime metrics

The mean *fire return interval* was defined as the length of time needed to burn an area equal to the area of the study region (Heinselman 1973), and it was calculated as

$FRI = (N \times S) / A$ (I).

where N is the number of years in the study period, A is the total BA, and S is the total area of the study region.

The timing of controlled burns can have important consequences for biodiversity, especially for fire-sensitive species due to seasonally dependent fire intensity. The length of the main *fire season* was estimated as the minimum number of consecutive months required to reach 80 % of the total average annual BA (Abatzoglou et al. 2018). The *peak in fire activity* was defined as the calendar month during which the maximum number of average monthly burnt pixels or AFs were detected (Giglio et al. 2006).

Global annual BA products provide the day of burning of each pixel but not the information at individual fire scar levels despite the importance of fire size for several ecological reasons (Forsyth and van Wilgen 2008). As discussed earlier, several fire-management policies were implemented within protected areas specifically to regulate the size of fire patches. Therefore, to evaluate the effectiveness of those policies, we first need to determine the *size of fire scars* that coarse resolution BA and AF products can detect. Specifically, we performed a simple comparison: if at least 35 % of pixels within the fire scar perimeter were classified as burned by coarse resolution BA products within the same time interval (±5 days), we considered that fire scar being detected by ready-available BA products. The 35 % threshold was selected based on the results of the sensitivity analysis (Appendix Figure A1), which showed that the detection capability of FireCCI51 decreased dramatically once the threshold exceeded 35 %. GABAM and FireCCILT11 were excluded as the former only provides annual BA maps with no burn date beyond the calendar year, and the latter contains data only through 2018. Similarly, if the center of an AF pixel was observed within or sufficiently near the perimeter of a fire scar during the same time interval (±5 days), we concluded that AF product successfully detected the fire scar. The distance threshold representing "sufficiently near" was calculated taking into consideration the pixel growth across the scan (Ichoku and Kaufman 2005) and varied between 500–2286 m for MCD14ML and between 164–397 m for VNP14IMGML.

Since the peak, the length of the fire season, and fire size required precise date of burning information; these metrics were calculated using only the last three years of data (2018–2020) when a combination of Landsat 8 and Sentinel-2A and −2B data provided a sufficiently short revisit time to allow the date of burning to be determined with much smaller uncertainties compared to earlier years. For example, Roy et al. (2019) reported that the temporal bias of the day of burning based on Landsat 8 and Sentinel-2 data was as low as three days. In contrast, our mapping efforts demonstrated that, prior to Landsat 8, the lack of clear images can introduce up to several months of uncertainty regarding the date of fire detection. Additionally, since burned scars were only mapped inside the borders of the three protected areas, the analysis of the fire size was restricted to fires with the entire perimeter located within the borders of the reserves.

2.5. Accuracy estimates

To quantitatively characterize the accuracy of global BA products within the protected area, we utilized the most commonly used for BA validation accuracy metrics, such as per-class BA of omission (Oe) and commission (Ce) errors (Boschetti et al. 2016, Boschetti et al. 2019, Franquesa et al. 2022). Accuracy metrics were calculated only for MCD64A1 and FireCCI51 as those products provide information of the day of burning and the precise location of fire occurrence in contrast to GABAM and FireCCILT11.

3. Results

3.1. Fire reoccurrence

From Fig. 2, it is apparent that fire reoccurrence varies drastically between the three protected areas. The driest reserve, Manyeleti, had the lowest fire activity. The estimated average FRI for the entire reserve was 14.2 years, with almost a quarter of the areas being fire-free, half experiencing fire once, and only less than 1 % affected by fire five or more times over the 17-year study period (2009 was excluded due to lack of data). Although approximately half of Blyde remained untouched by fire, particularly in the east part of the reserve represented by indigenous forests that do not burn, the rest of the area was more susceptible to fire than Manyeleti. Of all the areas affected by fire, 40 % were frequently burnt (five times or more). Over the 18 years, the average FRI was 8.9 years. Songimvelo was the most fire-prone reserve, with an average FRI of 2.2 years; fire was detected at least once in 92 % of the area, and frequently burnt areas comprised 73 %. The unfenced northeast part of the reserve experienced the most frequent fire activity.

Overall, readily available BA products detected a similar spatial distribution of fire scars and fire reoccurrence compared to fire reconstruction maps produced in this study. The spatial pattern observed by FireCCILT11 was not evaluated since the product does not report the

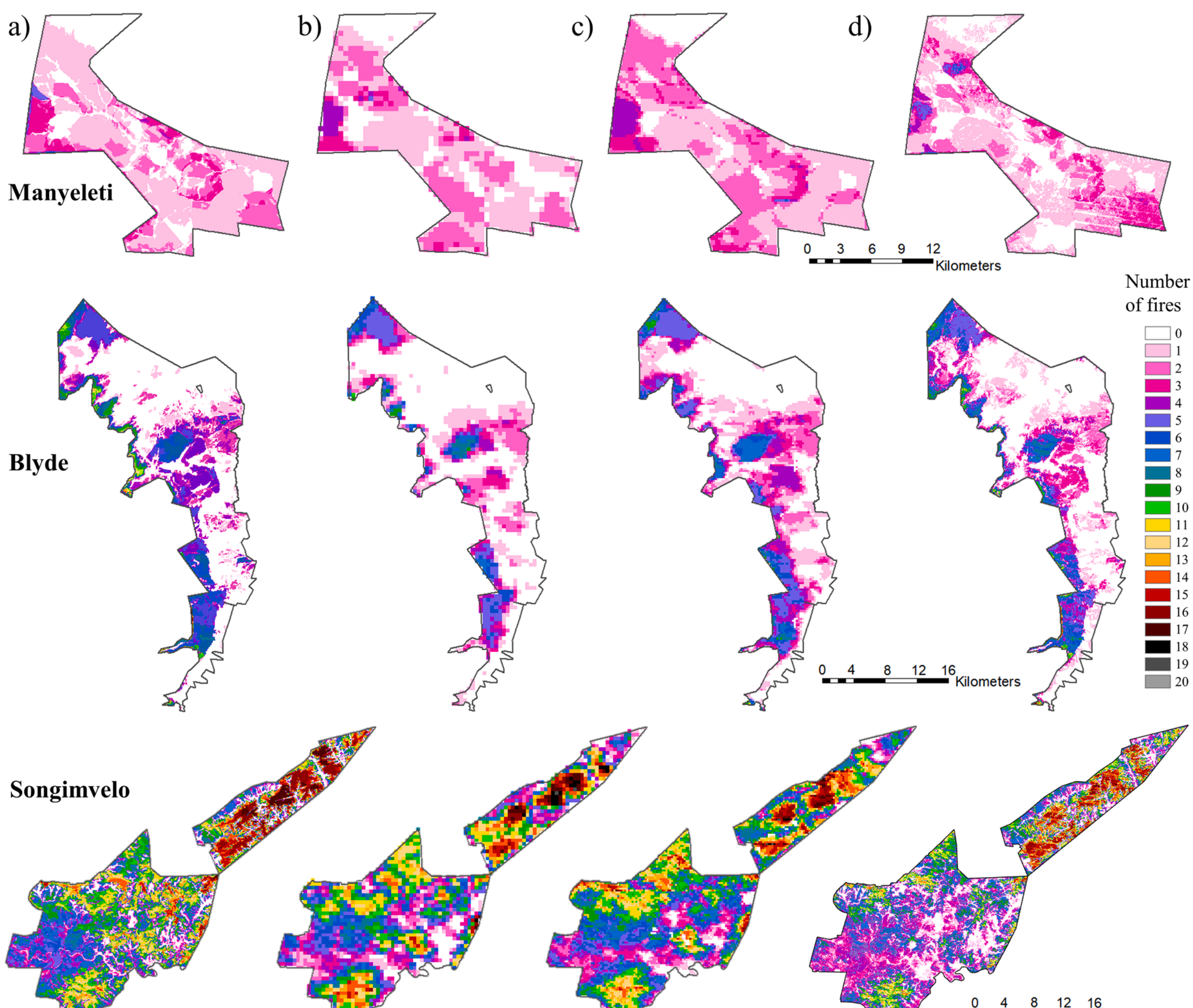

Fig. 2. Maps of 2003–2020 fire occurrences within three protected areas using Landsat 5,7,8 and Sentinel-2 data (**a**), MCD64A1 (**b**), FireCCI51 (**c**), and GABAM (**d**).

precise location of fire occurrence but rather the proportion of the 0.05° pixel burned within a specific month. As expected, coarse resolution products detected, on average, less fire activity. MCD64A1 and FireCCI51 omitted 2–30 % BA depending on the product and the reserve (Table 1). Interestingly, in Manyeleti, the coarse-resolution products detected higher fire frequency in some parts of the reserve compared to the medium-resolution BA maps. This inconsistency can be explained by the omission of extensive fires from medium-resolution imagery that occurred in 2009 and late-season fires in 2010, the extent of which could not be mapped from Landsat imagery. By providing data at the higher spatial resolution, FireCCI51 detected 16 % and 25 % more BA than MCD64A1 in Manyeleti and Blyde, respectively, while in Songimvelo, MCD64A1 was slightly superior. GABAM, being the only product with matching resolution (30 m), showed inconsistent results, reporting 10 % higher average BA in Manyeleti and 10 % lower in Blyde compared to our fire reconstruction maps. Meanwhile, in Songimvelo, GABAM detected the least amount of BA compared to the products mentioned above due to its inability to detect large areas with frequent (burnt five times or more) and very frequent (burnt ten times or more) fire activity. As a result, GABAM detected 30 % less frequently burnt areas in Songimvelo and 570 % less annually burnt areas within the unfenced part of the reserve. FireCCILT11 appeared to be the least suitable dataset in BA detection within protected areas, underestimating average fire activity in Blyde and Songimvelo by 31 % and overestimating in Manyeleti by 46 %.

3.2. Inter-annual variability

The lowest inter-annual variability was observed within Songimvelo, whereas Manyeleti had the strongest year-to-year variability, with 4 out of 17 years being fire-free (Fig. 3). The number of fire-free years was even higher according to the coarse resolution BA products: five for MCD64A1 and seven for FireCCI51. In contrast, FireCCILT11 reported an annual reoccurrence of fire activity. Additionally, MCD64A1 depicted 2009 as the most fire-prone year in Manyeleti, whereas reconstructed fire data and GABAM failed to record any fire activity. Similarly, a year later, FireCCI51 detected almost twice as much BA as maps based on Landsat data. Meanwhile, according to GABAM, 2008 was the second most fire-prone year in Manyeleti, whereas negligible fire activity was detected by all other fire products that year, with the exception of FireCCILT11. A less drastic but similar situation was observed in 2017 and 2018.

Pearson's correlation coefficients from Table 1 indicate an overall agreement between the manually mapped fire scars and available fire products. Despite the low spatial resolution, MCD64A1 was superior in accurately depicting the inter-annual fluctuation of fire activity. On the other hand, FireCCILT11 was the least suitable product to replicate BA variability, with correlation coefficients below 0.4 in Blyde and Songimvelo. Note that correlation analysis within Manyeleti and Songimvelo was performed on data that excluded 2009.

3.3. Fire seasonality

Most of the areas for which fire season was recorded burned from late fall to early spring (May-September, Fig. 4). With respect to each reserve, the main fire season (80 % of mean annual fire activity) occurred within three months in Manyeleti (June-August) and Blyde but was delayed by a month (July-September) and lasted four months in Songimvelo (June-September). Fire activity was more evenly spread through the year in Songimvelo, where around 26 % of BA was detected during the peak of fire season (July); the peak was more pronounced in Blyde (56 % of BA occurring in September), whereas in Manyeleti, August represented almost the entire fire season (77 % of the annual BA). All BA and AF products were able to correctly depict the length and the peak of the fire season with a slight overestimation of BA during the peak of fire season and under detection of fire activity outside of the main fire season. Expectedly, AF products were superior in accurately detecting fires even outside the main fire season, as was apparent in Songimvelo, the only reserve where fire occurred in all months of the year.

It is important to note that fire season was analyzed using only three years of data when images from Landsat 8 and Sentinel-2A and 2B were available. Therefore, it might not accurately represent long-term seasonality within each protected area. It was particularly an issue in Manyeleti, which experienced negligible fire activity in 2018 and 2019. To illustrate this point and evaluate the FireCCILT11 product, which does not offer data during the last two years of the study period, the fire seasonality of a single year, 2018, was analyzed in the Appendix. Although Figure A2 demonstrates a significant shift in the timing of fire activity in Manyeleti, it is important to note that only one small fire (≈50 ha) was observed that year. Early season fire activity was also detected by FireCCILT11; however, the coarse resolution product detected 3.5 times more fire activity in Manyeleti in 2018 with no fire pixels coinciding with the small fire detected by the combination of Landsat 8 and Sentinel-2 data. In Songimvelo, FireCCILT11 showed higher fire activity during pre-fire season months, while in Blyde FireCCILT11 observed the peak of the fire season two months earlier than one was depicted by moderate resolution imagery. We recognize that the coarse resolution product such as FireCCILT11 was designed to study fire at continental to global scales, and as such, some discrepancies at a local scale are expected.

3.4. Fire size

Between 2018 and 2020, 20 fires were recorded in Manyeleti, 98 in Blyde, and 679 in Songimvelo, with the median (max) fire size 15.17 (1201.44) ha, 25.35 (2414.76) ha, and 18.12 (3791.64) ha, respectively. Additionally, 15 % of all the fires in Manyeleti were 100 ha or larger, contributing to 87.9 % of the total BA; those numbers were higher in Blyde (22.7 % and 89.6 %, respectively). In Songimvelo, 17.4 % of fires $\geq$ 100 ha burnt 82.4 % of the total BA. On the other hand, in Manyeleti and Blyde, 60 % and 50 % of all the fires could be characterized by very small size (<25 ha), but those fires accounted for less than 0.03 % of BA, respectively. While in Songimvelo, very small fires represented 56.5 %

Table 1
The mean annual amount of burned area (BA, 2003–2018) and Pearson's correlation coefficients (r) of inter-annual variability between produced fire maps and five ready-available fire products. The years 2019 and 2020 were not included to allow for comparison with FireCCILT11.

	Manyeleti		Blyde		Songimvelo	
	BA (ha)	Pearson's r	BA (ha)	Pearson's r	BA (ha)	Pearson's r
L5,7,8/S2	1512.1		4800.8		20811.5	
MCD64A1	1240.0	0.93	3365.7	0.91	18603.9	0.77
FireCCI51	1477.9	0.91	4483.0	0.92	18062.2	0.74
FireCCILT11	2209.6	0.72	3300.2	0.28	14436.3	0.37
GABAM	1656.3	0.85	4334.4	0.93	14308.8	0.86
MCD14ML		0.94		0.70		0.78

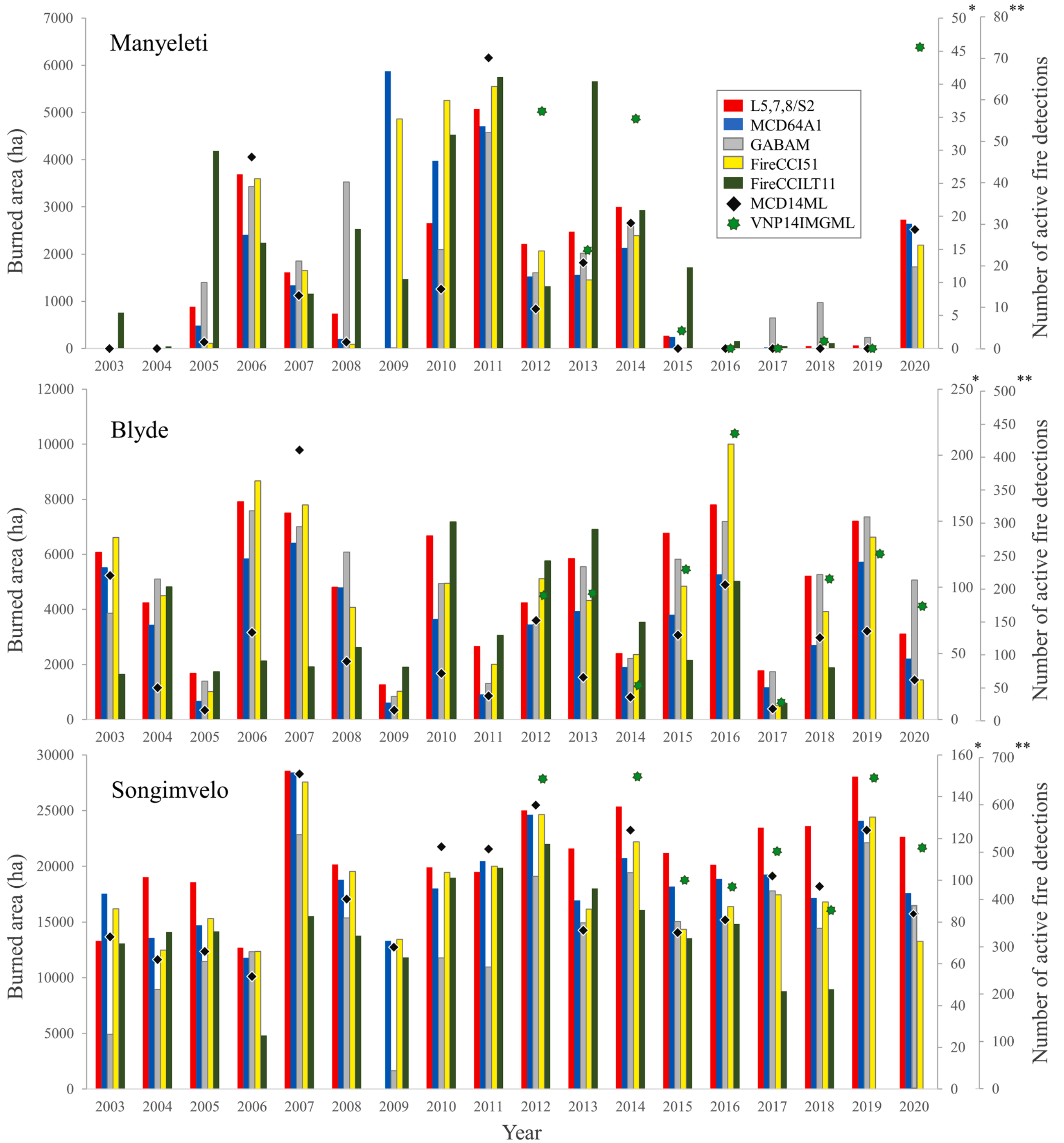

Fig. 3. A time series of annual burned areas accumulated over the calendar year detected within each of the three reserves using Landsat 5,7,8 and Sentinel-2 data and six fire products. * y-axis for MCD14ML, ** y-axis for VNP14IMGML.

and contributed to less than 0.05 % of the total BA.

Fig. 5 and Table 2 illustrate the proportion of individual fires detected by different fire products as a function of their size. VNP14IMGML accurately detected all large fires (>500 ha); 96 % were mapped by MCD64A1 and 93 % by FireCCI51 and MCD14ML. The readily available products' capability to detect fires drastically declined once fires below 200 ha were analyzed. Less than 6 % of very small fires were detected by all except the VNP14IMGML active fire product, which had the best capability to record fire detections at any size compared to other products. MCD14ML, on the other hand, was only superior to BA products when fires < 200 ha are considered; above this threshold, MCD64A1 detected more fire scars than the coarse resolution AF product. However, due to low detection rates of small fires, even VNP14IMGML only captured 35 % of the total fires observed from Landsat 8 and Sentinel-2 imagery, whereas, for FireCCI51, this number was as low as 12.7 %.

3.5. *Fire size vs seasonality*

Fig. 6 demonstrates that while small fires were observed throughout

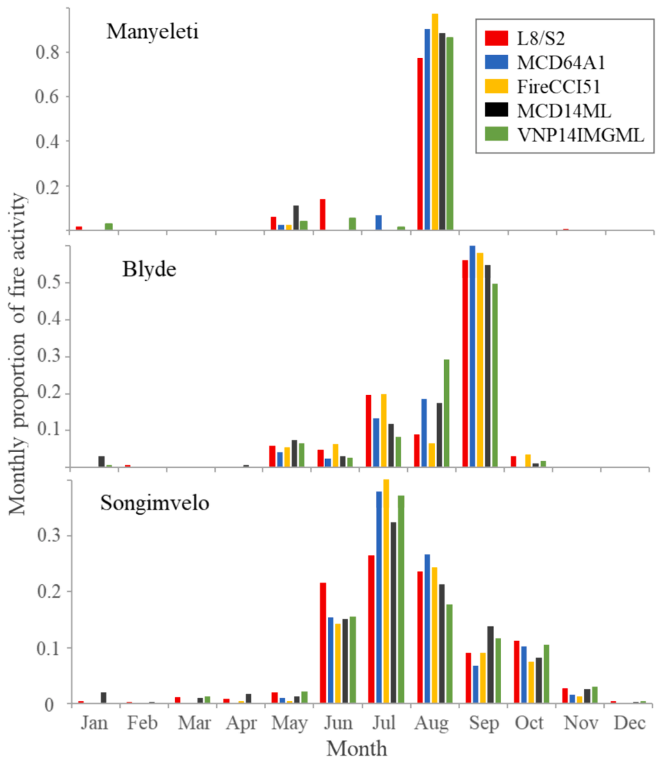

Fig. 4. Monthly distribution of fire activity (2018–2020) within three protected areas.

the year, fires larger than 500 ha occurred only during the main fire season. Months outside of the main fire season and its edge (one month before and after the main fire season) could be characterized by fires similar in size, predominantly very small (<25 ha).

All fire products showed very low capability in detecting fire outside of the fire season, regardless of the size of the individual fire scars. Specifically, both MCD64A1 and FireCCI51 omitted 100 % of the fires outside of the main and edge fire season, even fires 100–200 ha, more than a quarter of which BA products were able to detect when observed during the main fire season. Similarly, while detecting a negligible number of very small fires (2 %), FireCCI51 could only capture them during the main fire season. While AF products detected some fire activity before and after the fire season, their success rate depends strongly on the size of the individual fire scars. For example, VNP14IMGML detected 18 % of very small fires during the main fire season and only 6 % during the months before the edge of the fire season. However, when

Table 2
The number of individual fires detected by different fire products as a function of their size.

Fire size, ha	L8/S2	MCD14ML	MCD64A1	FireCCI51	VNP14ML
<10	238	13	9	3	27
10–25	151	9	1	5	31
25–50	113	14	9	9	38
50–100	66	13	9	9	42
100–200	52	23	14	15	38
200–500	42	23	23	22	38
500–1000	11	9	10	9	11
1000–2000	7	7	7	7	7
2000–3000	7	7	7	7	7
>3000	2	2	2	2	2

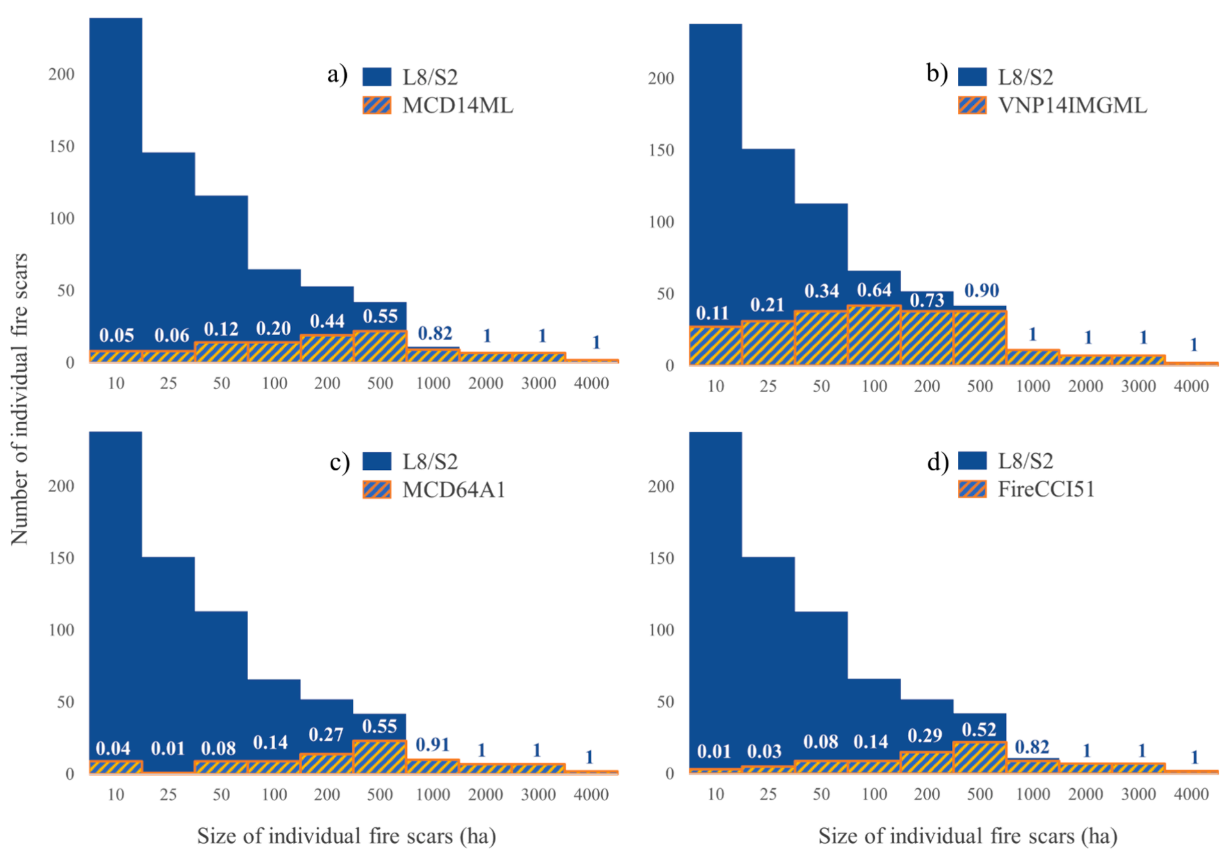

Fig. 5. Fire size distribution in all three protected areas combined based on Landsat 8 and Sentinel-2 imagery (blue) and four fire products (orange): MCD14ML (a), VNP14IMGML (b), MCD64A1 (c), and FireCCI51 (d). Numbers in bold indicate the proportion of fires detected by four fire products. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

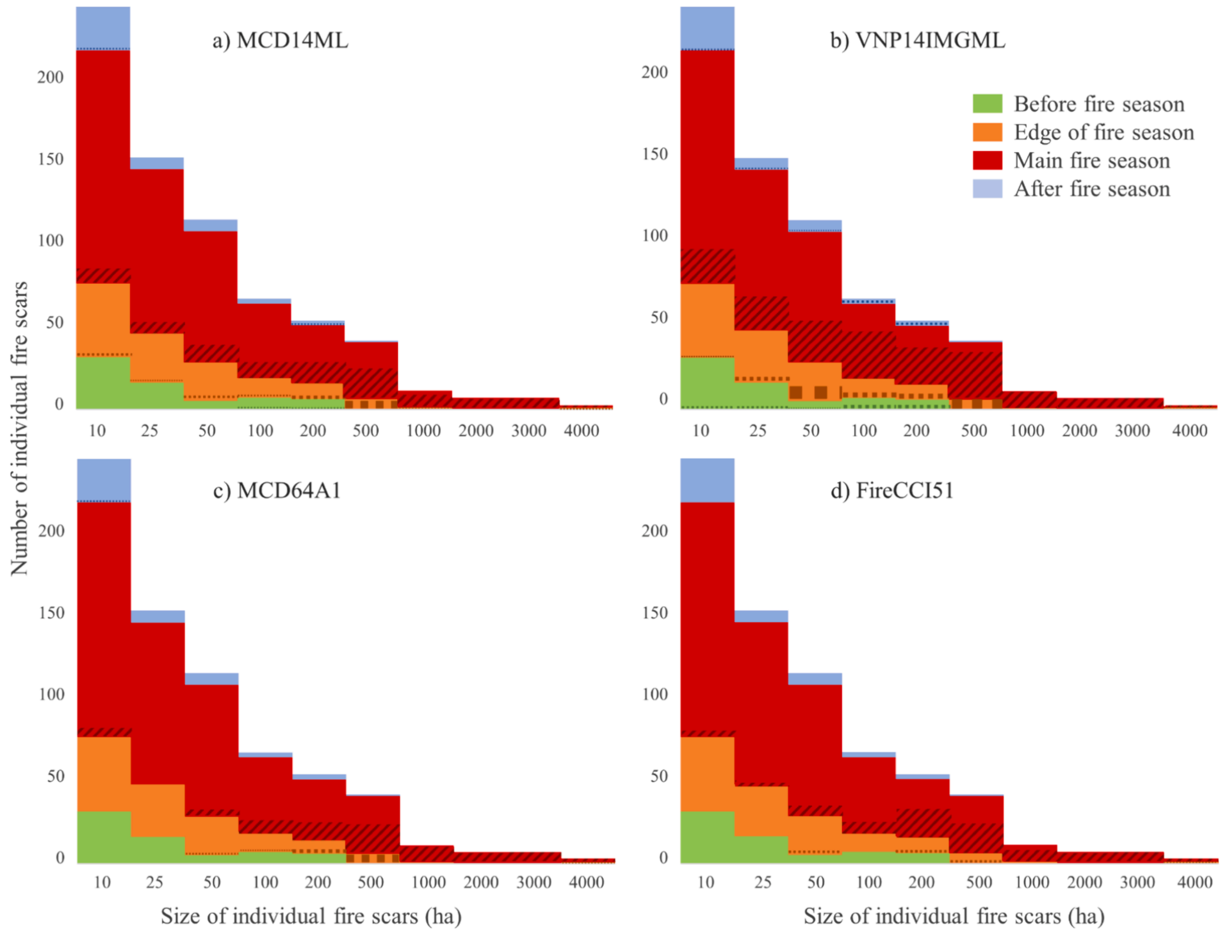

Fig. 6. Fire size distribution in all three protected areas combined based on Landsat 8 and Sentinel-2 imagery colored by fire season (solid bars) and four fire products (shaded subsets): MCD14ML (a), VNP14IMGML (b), MCD64A1 (c), and FireCCI51 (d). Each color represents one of the four periods of the fire season: red – main fire season (consecutive months with 80 % of the mean annual fire activity); orange – one month before and after the main fire season; green – months prior to the edge of the fire season; light blue – months after the edge of the fire season. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

larger fires were considered (100–200 ha), the success rate of their detection was not constrained by the timing of burning.

3.6. Accuracy estimates

Accuracy estimates of the MCD64A1 and FireCCI51 are presented for the entire study period (2003–2020) in Table 3. The accuracy results were quite different for two global BA products. Although MCD64A1 showed higher Oe especially within Manyeleti and Blyde, Ce of MCD64A1 were lower within all three protected areas when compared to FireCCI51.

4. Discussion

Our results support the general knowledge that dry savannas (<600 mm, Manyeleti) experience less fire activity with stronger inter-annual variability driven by rainfall compared to wet savannas (Daniau et al. 2012; Higgins et al. 2000). Manyeleti is, however, also subject to most grazing and herbivory that the other two reserves, which will reduce the availability of biomass to burn (personal communication). Additionally, Manyeleti was the only reserve with flat topography; therefore, the entire area was represented by similar climate and vegetation, which can all explain the homogeneity of fire activity in this region. Extreme changes in elevation within Blyde led to a number of microclimates that support a large variety of habitats and, consequently, a number of distinct fire regimes. The rugged nature of the terrain, with cliffs, acts as a firebreak in many areas. Moreover, while being protected areas, the surroundings can have strong influences on fire regimes within the reserves due to the lack of infrastructure to prevent escape fires from entering the reserve. Being adjacent to highly flammable grassland can increase fire reoccurrence in the protected areas. In contrast, commercial forestry neighboring Blyde, the topography of the canyon, mean annual precipitation being as high as 2770 mm, too frequent staff rotation to get acquainted with the reserve and fire behavior management, and the management being afraid to apply scheduled burns and fire application due to limited backup resources, together can explain

Table 3
Accuracy estimates [%] for the two global BA products.

—	Manyeleti		Blyde		Songimvelo	
	MCD64A1	FireCCI51	MCD64A1	FireCCI51	MCD64A1	FireCCI51
Oe	40.075	23.631	46.783	31.529	36.512	34.936
Ce	27.580	29.980	24.793	34.634	28.064	34.560

the absence of fire in many parts of the reserve (personal communication). Songimvelo is a unique reserve since rural communities are fenced in within the reserve, and they may farm with cattle. These communities light fires to provide fresh grazing and in the belief that it controls parasites such as ticks. Reserve management has no need to burn additional areas, and fire management is aimed at establishing firebreaks in priority areas. In the northern panhandle section of the reserve, the area is subject to uncontrolled fires originating from the adjacent Eswatini (personal communication).

The comparison of BA estimates from medium and coarse resolution fire products within the study area revealed a higher agreement than was previously reported in African savanna. According to Roteta et al. (2019), MCD64A1 detects only 20 % of fire activity in Africa that can be observed from Sentinel-2 imagery. On the contrary, we found that coarse resolution MCD64A1 product detected 70–89 % of the average annual BA retrieved from Landsat and Sentinel-2 data. Some might argue that our BA estimates might underrepresent the actual amount of fire activity due to the long revisiting time of Landsat compared to Sentinel-2. To test this hypothesis, we compared BA only from the last three years of the analysis when fire reconstruction was based on Landsat 8 and Sentinel-2 imagery. The restriction of the analysis to a shorter time interval had little effect on the omission error; MCD64A1 detected 68–93 % of the mean annual BA within three reserves. The omission error was comparable but smaller for FireCCI51 (<14 %) but substantially increased when a shorter time interval was considered (77–79 % of the mean annual BA was detected during 2018–2020). Admittedly, our analysis was restricted to the protected areas where, although the origin of fires might still be anthropogenic, the fire spread is less restricted by human activity. The lack of infrastructure and the absence of urban and agricultural areas in savanna ecosystems typically yield high biomass accumulation, coupled with unfragmented landscapes, creating ideal conditions for large, intense fires (Archibald et al. 2009; 2012). The specifications of the study area mentioned above can explain lower omission rates of the coarse resolution fire products than was previously reported (Boschetti et al. 2019, Franquesa et al. 2022).

In agreement with Roy et al. (2019), we found the spatial pattern of burnt areas to be similar among all the fire products. Meanwhile, the ability of coarse resolution products to accurately represent the year-to-year variability of fire activity has not been previously evaluated. Examination of the interannual variability illustrated good correspondence between fire datasets, with the exception of FireCCILT11. The coarsest resolution product analyzed in this study showed high inconsistencies in terms of the overall average BA (severely overestimated BA in one protected area and underestimated in others). It failed to accurately represent year-to-year fluctuation in fire activity, possibly due to the significant Advanced Very High Resolution Radiometer (AVHRR) orbit-drift artifacts that are present in this data set (Giglio and Roy 2022). Additionally, we found that FireCCILT11 was poorly correlated with the high-resolution fire maps created in this study and to FireCCI51, which was used as FireCCILT11 training data. Similar inconsistencies and low correlation between the FireCCI51 and FireCCILT11 products in Africa were previously reported by Giglio et al. (2022).

Unintuitively, the agreement between two medium-resolution products based on the same input data (Landsat), manually reconstructed BA and BA maps generated via an automated pipeline using Google Earth Engine (GABAM) was lower than between medium and coarse resolution data in two out of three reserves. In contrast, the two coarse resolution BA products derived from the same MODIS data produced the most coherent results ($r > 0.91$ in Manyeleti and Blyde). Our results are supported by Dalagnol et al. (2023), who also found a higher agreement between reference data and coarse resolution BA datasets (MCD64A1 and FireCCI51) than Landsat-based BA estimates (GABAM). Although, as expected, the finer spatial resolution of FireCCI51 yielded higher total BA estimates within two of the three reserves compared to MCD64A1, it did not lead to improved estimates of the inter-annual fluctuation of fire activity. A higher amount of BA reported by FireCCI51 can be explained not only by lower Oe but also by higher Ce compared to MCD64A1, which were reported within all three protected areas.

The high level of agreement between medium and coarse resolution datasets in terms of the overall amount of BA and its inter-annual variability within three protected areas confirmed that large fires (>100 ha) typically observed within the main fire season accounted for the majority of total BA estimates (van Wilgen et al. 2000; Forsyth and van Wilgen, 2008). These results are encouraging for researchers who require BA statistics to monitor large-scale fire dynamics, investigate fire impact, and estimate fire emissions. On the other hand, annual BA statistics alone cannot answer how well different management approaches are able to influence fire patterns (Hudak et al. 2004). Van Wilgen et al. (2004), after extensive research in the Kruger National Park, concluded that the management effect on total BA and its inter-annual variability is negligible as rainfall patterns mostly influence them. The ability of managers to control fire regimes consists mostly of regulating the timing and size of the individual fire scars. Unfortunately, fire products' capability to reproduce the seasonality and detect fires below a certain size is far from ideal. The only medium-resolution fire dataset, GABAM, offers neither monthly statistics nor information at the individual fire scar level. MCD64A1 was only capable of depicting the timing of the main fire season and the majority of individual fire events > 200 ha. In contrast, smaller fires remain predominantly undetected, similar to the finding of Ramo et al. (2021). Despite having a higher spatial resolution, ESA's coarse resolution BA product was found even slightly less suitable for detecting individual fire scars below 1000 ha and, similar to MCD64A1, failed to detect fire scars early or later in the fire year.

The inability of coarse resolution BA products to detect small fires outside of the fire season is a well-known issue (Laris 2005) that some suggested resolving by substituting BA for AF products such as MCD14ML (Earl and Simmonds 2018). In this study, we confirmed the higher capability of AF products to detect fires during all months of the year and most accurately represent fire seasonality within all three reserves. That being said, we did not find substantial improvement in capturing small burnings by MCD14ML compared to its BA analog. Our analysis showed that MCD14ML recorded 3 % more fires < 25 ha and 5 % more fire events 25–100 ha compared to MCD61A1. On the contrary, due to its higher spatial resolution, the VIIRS AF product proved to be the most reliable for small fire detection. Interestingly, more than a quarter of AF detections depicted by MODIS were omitted by VIIRS, possibly due to the morning overpass offered by Terra, which confirmed Nieman et al. (2021) suggestion to combine both AF products for a more complete representation of fire activity. While easy to implement, this suggestion severely restricts the length of the observation record since VIIRS started to collect data in 2012; therefore, both AF products cannot be used to evaluate different management approaches and changes in fire policies lasting longer than one decade.

We want to finish this discussion by acknowledging that while it appears that fire reconstruction based on several decades of Landsat imagery is the most ideal source of data for monitoring shifts in fire seasonality and size distribution, manually digitizing fire scars is extremely time-consuming and subjective (Hudak and Brockett 2004). Moreover, similar to other remotely sensed products, BA maps derived from Landsat are not immune to errors and uncertainties. First, as was mentioned earlier, the extent of several fires in 2010 in Manyeleti could not be mapped from Landsat imagery due to the high cloud cover occurring during much of the dry season. Similar but more extensive cloud cover in 2009 reduced the mapped region to zero within Manyeleti and Songimvelo. One might argue that an absence of one year of data would not be as detrimental as the systematic omission of small fires by coarse-resolution products, which would be true if the readily available medium-resolution annual BA product provided information to differentiate between unburnt and unmapped areas. According to GABAM, 2009 was not the year where insufficient data prevented accurate BA mapping, but the year least affected by fires in the past 20 years. Therefore, by selecting a fire product that conveniently offers several decades of BA maps with the highest resolution, one can erroneously interpret the fire frequency of the study area and come to a wrong conclusion regarding the main forces behind observed year-to-year variability in fire activity. Other than extensive cloud cover, other issues that yielded an underestimation of BA by GABAM and would potentially affect other products based on Landsat imagery included data gaps due to the failure of the Scan Line Corrector in the Landsat-7 ETM+instrument (can be observed in Fig. 2) and insufficient number of acquired scene to accurately reconstruct surface fires in tropical savannas where fire scar would remain undetected as a results of short post-fire signal persistence (Trigg and Flasse 2000). Nevertheless, GABAM reported a higher amount of BA than manually reconstructed maps within one out of three reserves. This inconsistency can be explained by BA commission errors due to non-fire related phenomena such as shadows or flooding, whose signals can appear similar to those of recently burnt areas (Roy et al. 2005b; 2019).

Moreover, persistent cloud cover or lack of frequently acquired images can not only reduce the ability to map individual fire scars but also accurately define their timing (Roy et al. 2005a), vital inputs for monitoring fire seasonality and size distribution. Precisely due to those constraints, part of the analysis presented in the study was restricted to the last three years by taking advantage of the high revisit frequency of the combination of Sentinel-2A, −2B, and Landsat 8 observations. To demonstrate, we calculated the annual number of individual fire scars during the entire study period (2003–2020) and found a significant upward trend within each reserve (Figure A3). If we chose to ignore data limitations, we could have concluded that changes in fire management within the last 18 years led to more burnings while the total average BA remained stable, with the exception of Songimvelo, where we detected a positive trend in the overall BA. In reality, the observed increase in the number of fire scars could be artificial, driven by the enhancement in temporal resolution of the input data and not past changes in fire regimes or fire management practices.

5. Conclusion

In this study, we reconstructed fire records of three protected areas in South Africa (Manyeleti, Blyde, and Songimvelo) by mapping fire scars through manual interpretation of medium-resolution Landsat 5,7,8 and Sentinel-2 imagery and calculated several fire regime metrics. By comparing manually derived fire statistics to six readily available fire products, four BA and two AF products, we observed a high level of agreement between products in terms of mapping spatial and temporal patterns of fire activity and total BA estimates. Considering an urgent need for consistent and efficient fire monitoring within protected areas in African savanna (Hudak & Brockett 2004) and a lack of higher accuracy alternatives, we recommend utilizing MCD64A1 product for examining the broad features of the past and current fire regimes (Nieman et al. 2021), specifically estimating the overall extent of the area affected by fire on a daily, monthly and yearly bases, and locating regions affected by the most extensive fires. Although the use of relatively fine-resolution data has obvious advantages by providing more detailed mapping of fire scars (Russell-Smith et al. 1997), this study highlighted a number of limitations of the only currently available medium-resolution annual BA product (GABAM) including flows in the fire classifications which led to substantial commission and omission errors, the absence of metadata which would help to illuminate to confusion between regions unaffected by fire and areas where automated classification could not be performed due to limited number of Landsat scenes, and the lack of temporal attributes which made data unsuitable for monitoring seasonal shifts in burning. Unexpectedly, the higher spatial resolution of ESA's FireCCI51 BA product compared to NASA's alternative did not lead to a higher detection rate of small fire scars or a more accurate depiction of the inter-annual variability of BA. On the other hand, the only coarse resolution fire product that offers nearly four decades of BA statistics globally, FireCCILT11, was unable to accurately capture any of the analyzed fire regime metrics at the scale of the study areas. Among all readily available multi-year fire datasets, the VIIRS AF product (VNP14IMGML) was the most suitable to study the temporal aspects of the fire regimes while also capturing the majority of fires 50 ha in size and larger, especially when combined with MODIS analog. Therefore, the current study confirmed that despite the limitations of the coarse resolution fire products (Zubkova et al. 2023), they can provide the managers with timely information on some aspects of fire regimes (overall BA and intra- and inter-annual variability) specifically, within protected areas where land fragmentation and agricultural practices are absent. This fire regime information is crucial for planning and monitoring prescribed burning and evaluating the effectiveness of conservation projects and policies, particularly when the data selection is based on addressing specific needs and involves clear understanding of the data uncertainties.

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CRediT authorship contribution statement

Maria Zubkova: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Mervyn Lötter:** Writing – review & editing, Conceptualization. **Frik Bronkhorst:** Writing – review & editing. **Louis Giglio:** Writing – review & editing, Validation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is available in Zenodo. the link is provided in the manuscript.

The data that support the findings of this study are openly available from the following repositories: MCD64A1: https://lpdaac.usgs.gov/products/; MCD14ML and VNP14IMGML: https://modis-fire.umd.edu/guides.html; FireCCI data: https://climate.esa.int/en/projects/fire/; GABAM: https://vapd.gitlab.io/post/gabam/.

Burned area maps created from Landsat 5,7,8 and Sentinel-2 imagery are available in Zenodo (https://doi.org/10.5281/zenodo.12745640).

Appendix

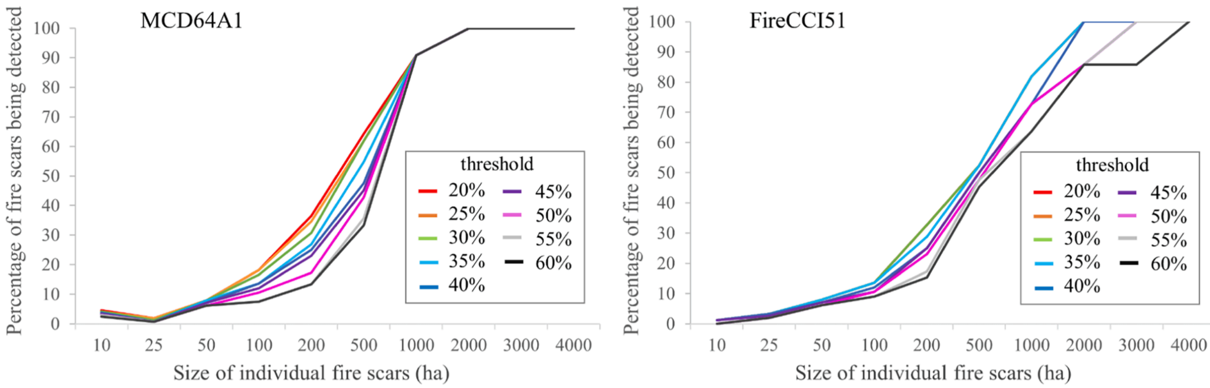

Fig. A1. Sensitivity analysis of the pre-selected threshold (20–60 %) for individual fire scars detection by two burned area products. The threshold is defined as the percentage of L8/S2 pixels within the fire scar perimeter that were classified as burned by the respective coarse resolution BA product.

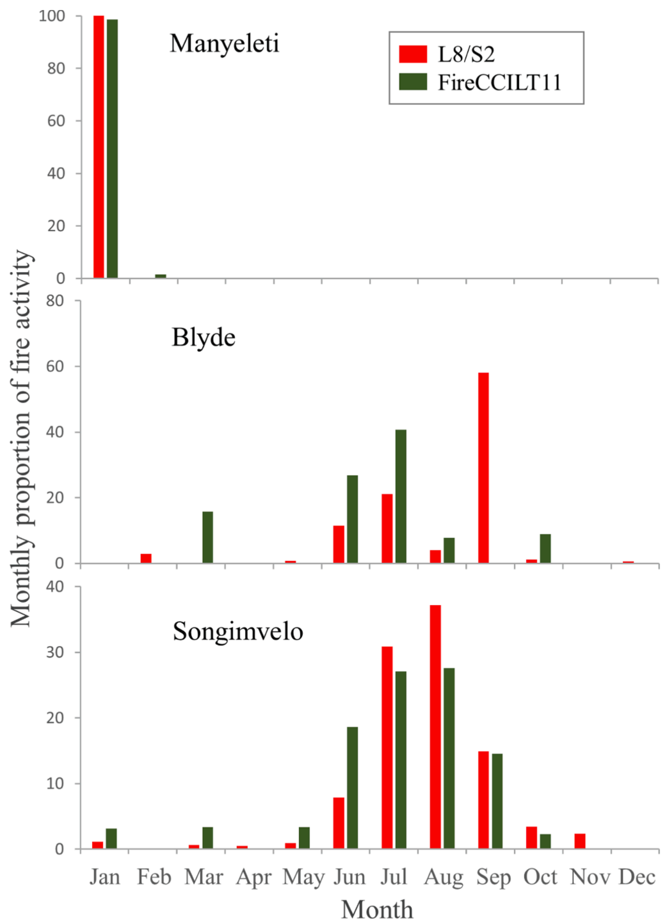

Fig. A2. Monthly distribution of fire activity (2018) within three protected areas.

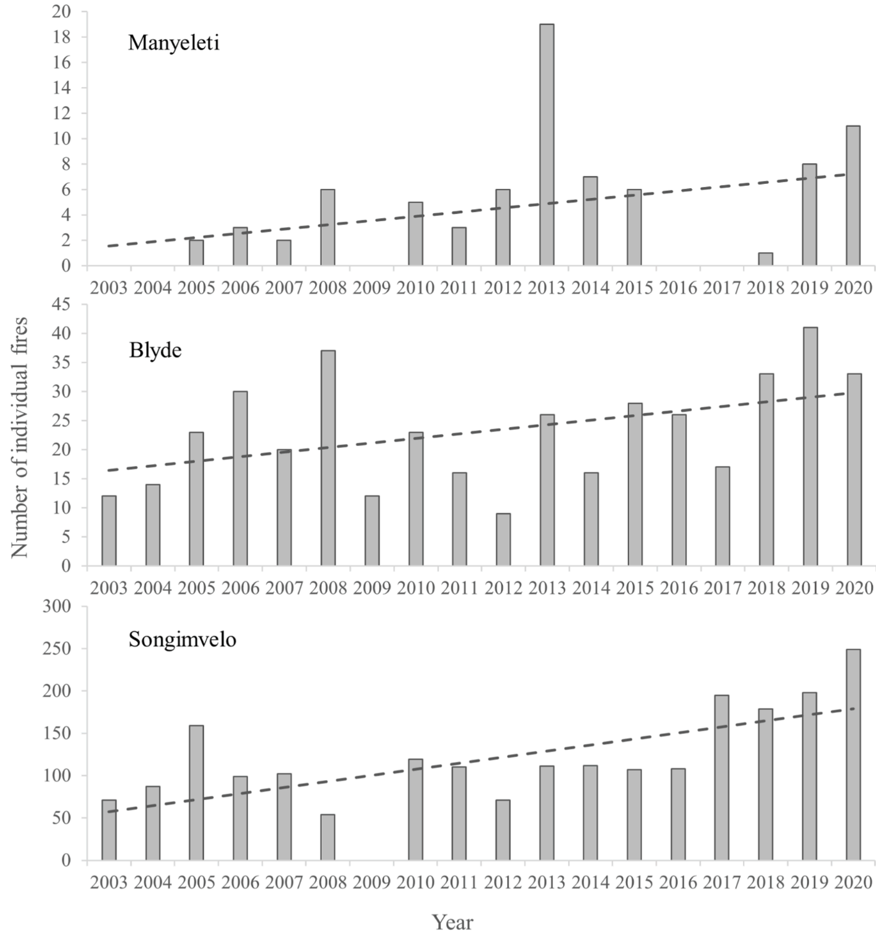

Fig. A3. A time series of the number of individual fire scars detected within each of the three reserves using Landsat 5,7,8 and Sentinel-2 data. Dashed lines represent linear trends. Note that for 2009 fire information was not available in Manyeleti and Songimvelo.

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