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Wildland urban interface of the City of Cape Town 1990–2019

Sven Christ | **Nina Schwarz** | **Richard Sliuzas**

PGM Department, ITC Faculty, University of Twente, Enschede, The Netherlands

Correspondence
Sven Christ, PGM Department, ITC Faculty, University of Twente, 99 Hengellosses Straat, Enschede, Overijssel, The Netherlands.
Email: s.i.christ@utwente.nl

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Abstract

Wildfire affecting urban areas at the wildland urban interface (WUI) is a growing global concern, where management is important for urban residents as well as wildland vegetation. We used a socio-ecological system perspective to investigate the interactions of urban land with a fire-dependent wildland in South Africa's City of Cape Town (CoCT). We examined changes in population growth, land cover change and related WUI footprint, occurrence of large fires, and related policies over time. We used Landsat data to track changes over the period 1990–2019 in the formal and informal urban and wildland footprint, census data to track changes in population, and difference normalised burn ratio and MODIS burned area product to track large fires. The urban footprint has expanded greatly and through consolidation has led to the reduction of the WUI. Furthermore, evidence points to an increase in fire suppression, even though national policies ask for wildfires to run their course where possible and appropriate. As a result of pressure from urban residents, local managers prefer short term fire suppression to long term risk reduction for urban areas and ecological management of wildland. Framing the problem as a socio-ecological system enabled us to highlight how WUI management is a product of interaction between urban development, wildland type and policies. Our findings emphasise the point that wildland management is driven by urban residents and local municipalities, with national fire and disaster management policies not fully implemented.

KEYWORDS

City of Cape Town, fire-dependent ecosystems, fynbos, socio-ecological system, wildfire, wildland urban interface

1 | INTRODUCTION

Wildfires are an international concern. Many cause damage to property worth millions of dollars and result in loss of lives (Ashe et al., 2009; Buxton et al., 2011; Elia et al., 2016; Gorte, 2013; Richardson et al., 2012; Rodrigues et al., 2014). Many originate in fire-adapted and fire-prone wildlands (Bond & Keeley, 2005; Elia et al., 2016; Gorte, 2013; Keeley et al., 2012; Richardson et al., 2012). The problem is that urban expansion often meets wildlands at the urban edge, creating the so-called wildland urban interface (WUI). When vegetation at the WUI is fire-prone or fire-adapted it creates a fire hazard for neighbouring urban lands. Wildfires at the WUI pose risks to lives and homes, as well as other infrastructure, making it difficult to let wildfires run their course despite fire-dependent vegetation having an ecological requirement for recurring fires (Keeley et al., 2012; Radeloff et al., 2017).

Eradication of wildfire is neither always possible nor desirable since many ecosystems require repeated fires for regulation and survival, among them Mediterranean type ecosystems, boreal forests, eucalypt woodlands, shrublands, grasslands, and savannas (Bond & Keeley, 2005; Forsyth & Le Maitre, 2015; Keeley et al., 2012; Lavorel et al., 2007; Stephenson et al., 2013). Human activity has been counter-intuitively linked to increases in wildfire, even though built structures are usually most vulnerable to wildfire damages (Pechony & Shindell, 2010; Radeloff et al., 2017).

Adopting a socio-ecological system perspective means viewing wildfires within the WUI the result of interactions involving human agency, urban growth, and natural wildland processes. Fischer et al. (2013) focused on cultural and social structures that mediate interactions of groups and individuals with wildland forests in Oregon in the United States. Spies et al. (2014) studied WUI fire risk as a coupled human and environmental system, concluding that environmental responses to human interventions are well studied, although they found a knowledge gap exists in how decision makers respond to environmental change, the aim of their study was to investigate the management and public interaction in the system. They did not considered how the system operates or responds to stimuli in a multi-feedback system. In Mexico, Sheridan et al. (2015) investigated socio-ecological linkages with the development of a fire plan for a rural case study in a non-fire-dependent ecosystem. Their focus was on the social and institutional barriers to wildfire management and they found clear linkages within the system and forged a clear understanding of both the social and ecological systems, and the feedbacks between these is required for a fundamental understanding of the system. In turn, Fischer et al. (2016) viewed wildfire as a social and ecological system in which fire has a role in ecosystem management. They recognised that short term forest management strategies may result in long term damages; intense fires or ecosystem damage were highlighted as potential negative outcomes when not taking a holistic approach to WUI management. They also linked fire regime change to changes in social regimes.

These studies focused on a specific part of a system, on how governance responds to changes in the WUI, or on how wildland and urban residents respond in turn to governance changes. Steelman (2016) indicated that government systems respond slowly and Fischer et al. (2016) highlighted the point that the WUI system adapts faster than policy documents, and suggested a critical need to understand the system and its responses to change in order to develop effective management strategies. They described wildfire risk at the WUI as a socio-ecological pathology, and indicated that maladaptive feedbacks should be identified and understood if policy interventions that transform these feedbacks are to be developed. Most studies focused on fire-prone wildland WUIs; few studies investigated fire-dependent wildland WUIs that need fire for survival.

Key insights

Pressures and decisions from local groups dictate the management of wildland areas at the wildland urban interface (WUI). Long term fire safety and ecological health requirements of fire-dependent wildland are often overridden by short term fire protection strategies. There is a gap between urban centred local wildfire management strategies that are applied and more holistic approaches required by national government policies. A socio-ecological systems approach could be used to investigate management decisions and a seek a balance between long-term and short-term wildland management strategies.

The WUI includes wildland types and urban land and diverse types of formal and informal urban development. In this study, *formal* areas have official land rights and planned infrastructure. *Informal* settlements are groups of houses built on areas without formal land rights and areas with a high percentage of illegal backyard shacks, often lacking a planned structure (Barry & Ruther, 2005; Marais & Ntema, 2013).

The type of development at the WUI shapes how it affects and is affected by wildfire and it is important that the type of wildland is considered alongside the type of urban development. Usually residents of formal areas enjoy wider roads and low housing densities and are able to better mitigate against risk. (Kahanji et al., 2019; McFarlane et al., 2011). Informal areas are frequently accessed via disorganised, narrow roads that severely hinders emergency response access (Jones, 2017; Kahanji et al., 2019). Informal areas are also associated with an increase in fire ignitions (Kahanji et al., 2019). Whereas formal dwellings use more fire-resistant materials, informal dwellings are known to be built with highly flammable materials such as plastics, cardboard, and timber (ibid). While there is inequality in how wildfire may affect different homes, wildfire also links them, where one household not mitigating against wildfire poses a risk for itself and its neighbours (Collins & Bolin, 2009).

The combination of fire-dependent wildland and mixed urban areas makes it difficult to create a sustainable ecological environment and protect human settlements. Yet, no study has addressed a fire-dependent wildland with mixed urban development.

This study investigates the changes that occurred in a socio-ecological system comprising fire-dependent wildland and formal and informal urban areas in the WUI. Specifically, we ask: (1) How did the spatial extent of the WUI, urban areas, and burned areas change over time? (2) How are changes in policies potentially related to these spatial trends? (3) What are potential implications of these trends for sustainable development of wildland health and urban development? (4) What are implications of our study for future socio-ecological system studies on wildfires at the WUI?

We build on the findings of existing socio-ecological system frameworks (Section 2) to investigate the City of Cape Town (CoCT) as a case study (Section 3). We use a combination of spatial, policy, and climate data (Section 4) to describe (Section 5) and discuss (Section 6) changes in the socio-ecological system over 30 years, before sharing conclusions in Section 7.

2 | FRAMEWORK

We developed a framework for understanding interactions among different elements at the WUI, emphasising a fire-dependent wildland that suffers losses through either fire exclusion or an increase in fire frequency (Figure 1). We included actions among formal and informal residents and accounted for buildings they create at the WUI. Our framework is controlled by a governance system with policies and directives for how urban settlements and wildland should be interacting.

If the frequency of ignitions from urban areas is more than the minimum for fire-dependent species to reach reproductive maturity, wildland loss and degradation may occur (Kahanji et al., 2019; Narayanaraj & Wimberly, 2012). However, high frequencies of fire events in and around the WUI can stimulate requests for fire suppression.

WUI fire management based on largely fire suppression can lead to the loss of fire-dependent species and increase fuel loads, increasing the likelihood of large uncontrollable wildfires (Frost et al., 2018; Gorte, 2013; Westerling et al., 2006). The increase in fire suppression as a response to large fires has been described as maladaptive feedback (Fischer et al., 2016). Our third research question addresses wildfire patterns and their implications for WUI sustainability.

Governance incorporates local and national governments tasked with mediating how interactions in the system happen as, for example, in ecological and building/settlement policies. These policies may influence how the WUI is shaped by legislation that regulates urban and wildland growth and protection. Our second research question addresses this intersection by examining which policies govern and influence these interactions.

3 | STUDY AREA

We chose CoCT (2455 km^2) as a case study of a mixed urban system with a fire-dependent wildland. Wildfire frequently affects the Western Cape Province of South Africa, causing many losses over years (Payi, 2019; South African National Parks, 2018). CoCT (Figure 2), is situated in a Mediterranean-type climate that is home to the Cape Floristic region.

The Cape Floristic region is the smallest of six important floral regions globally, and the only one found in one country. Fynbos, the most extensive vegetation type in this floristic region, is fire-dependent and fire-prone (Brown, 1993; Van Wilgen, 2013). The ideal fire return interval for the fynbos biome is 10–20 years; intervals of

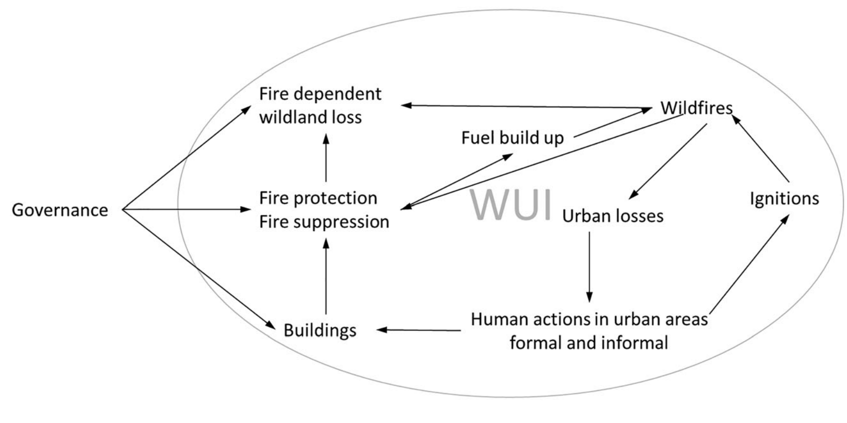

FIGURE 1 Socio-ecological system of a fire-dependent wildland WUI. *Source*: Authors, based on work by Fischer et al. (2016)

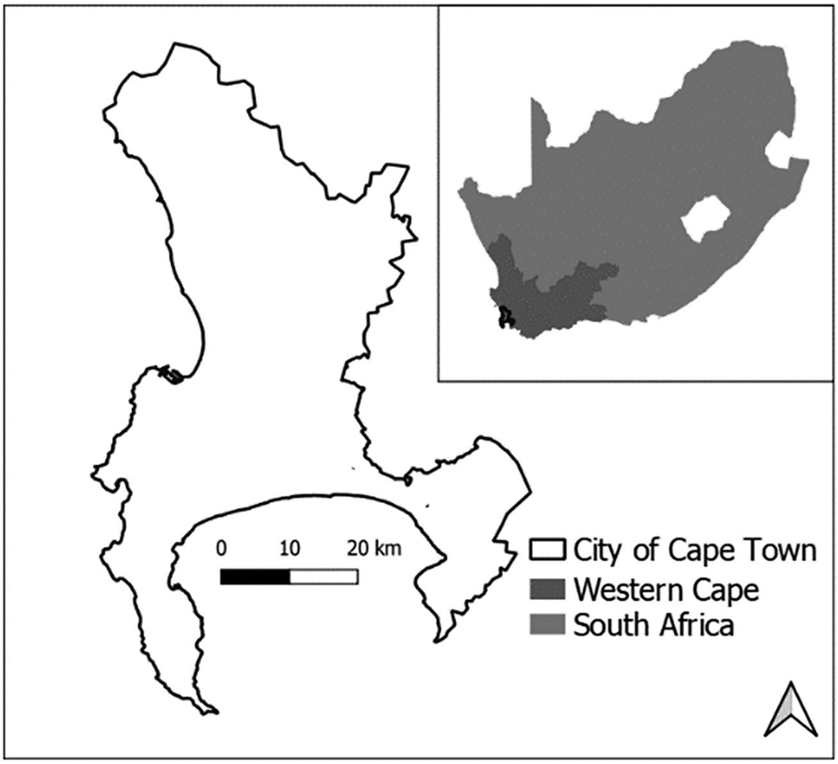

FIGURE 2 Location of the City of Cape Town situated in the Western cape in South Africa. *Source*: City of Cape Town, 2016

fewer than eight years or more than 30 years lead to species loss (Brown, 1993).

Increased human activity in CoCT may increase the number of fire ignitions, which can push the biome past its natural limits (Frost et al., 2018; Kruger & Bigalke, 1984; Payi, 2019). There is considerable interest in effective wildfire management because CoCT's population has grown from 2.5 million in 1996 to four million in 2016 (Small, 2017).

4 | DATA AND METHODS

This descriptive study investigates CoCT 1990–2019 with our framework, using various datasets: governance using literature and legislation; landcover change and wildfire patterns using remotely sensed spatial data; implications for wildland loss using literature on vegetation viability and reference to patterns of wildfire identified in the spatial data. Fuel build-up is considered implicit to a long interval between fires.

4.1 | Landcover data

Landsat 5 data were used to classify landcover datasets for 1990, 2001, and 2011 (U.S. Geological Survey, 2019a). Landsat 8 data (no pan sharpening) were used for the 2019 classification as Landsat 5 ended life (U.S. Geological Survey, 2019b). Level 1 processed Landsat datasets were downloaded from the Geological Survey (https://www.usgs.gov). Data were pre-processed to Top-OF-Atmosphere reflectance and atmospheric correction applied (DOS1) in QGIS (qgis.org) (Correia et al., 2018).

Data were classified into five classes: farm, formal (urban), informal (urban), wildland, and water, using the OpenCV Random Forest implementation in the SAGA software (Conrad et al., 2015). Random forest was chosen as an ensemble-based classification algorithm that outperforms approaches such as maximum likelihood, decision trees, and neural networks, allows multiple data sources to be used, is insensitive to outliers and overtraining, and is computationally fast (Feng et al., 2015; Ghosh et al., 2014).

Overall classification accuracy were between 78% and 80%, with a reduction to 75% for 1990. This outcome is partly due to low numbers of training sites for informal settlements in 1990 as there were few informal settlements under Apartheid. For technical details of the classification see Appendix A.

4.2 | Burned area data

Two types of burned area data were used: difference normalised burn ratio (dNBR) and MODIS Burned Area Product collection 6 (MCD64A1) (Giglio et al., 2015). dNBR was extracted from Landsat 5 (1990 to 2007) and

Landsat 7 (2008 to 2010) annually at 30 m spatial resolution (U.S. Geological Survey, 2019a, 2019b; see Appendix B for detailed processing information). Both the normalised burn ration (NBR) and dNBR have been used for burned area mapping. However, NBR presents a challenge for multi-aged burn scars in the same area (Axel, 2018). The multi-temporal dNBR, can help identify burned areas between specific dates (ibid.). dNBR has also been shown to be effective at burn scar detection after one year (Fornacca et al., 2018).

Monthly MODIS Burned Area Product collection 6 (MCD64A1) from 2001 to 2019 was downloaded at 500-m spatial resolution. dNBR has a better spatial resolution, but verification of the data was impossible especially for very old data (see also Strydom & Savage, 2016) and showed large and unpredictable deviation from MODIS when compared. An earlier MODIS product (MCD45A1) was found to have high user's accuracy but missed some burns in the Table Mountain region, possibly because of the reflective underlying surfaces in the region (De Klerk et al., 2012). A recent study within CoCT boundaries found that public records of many fires are not kept (Blanckenberg et al., 2019). Thus, in line with work by Strydom and Savage (2016), we also use MODIS as is.

The MODIS data were classified into fire season (October to April) and off-season (May to September) (Forsyth & Bridgett, 2004). The data were thus collated so that the period from October 2000 to April 2001 made up the 2001 fire season and May to September 2001 made up the 2001 off-season; this pattern characterised all years.

4.3 | WUI and burns in WUI data

WUI definitions vary based on region. In Europe, the WUI is based on the distance into settlement and distance into wildland from the contact zone where wildland meets urban development and varies between 50 to 400 m depending on country (Modugno et al., 2016). In the United States, the consensus is to split the WUI into intermix and interface, with *intermix* defined as houses and wildland intermingled with a density of 6.17 houses/km^2 and >50% of wildland and *interface* as areas with <50% wildland within 2.4 km of a densely populated vegetated area (at least 75% wildland wildland) and at least 5 km^2 in size (Radeloff et al., 2018; Stewart et al., 2007).

We adopted the WUI definition used in the fynbos biome of 100 m both sides of the contact zone (Forsyth & Le Maitre, 2015). Also, Kaval (2009) has found that creating a 100 m defensible (cleared land) zone into wildland from a home effectively reduces the risk of wildfire damage, highlighting it as an important zone for intervention at the WUI.

Using the generated landcover classification, wildland and urban land (formal and informal) were extracted to delineate the WUI. The wildland dataset was run through a sieve approximately 0.04 km^2, the smallest recommended reserve size to maintain healthy species diversity in fynbos (Cowling & Bond, 1991). To remove small areas of urban land that may be classification noise or single buildings, the urban dataset was run through a sieve of 0.009 km^2. Both datasets were then buffered by 100 m. The buffered area around the urban dataset that did not overlay wildland was removed; so was the wildland buffer that did not overlay urban land. The two datasets were merged, leaving the area that identifies all areas 100 m from the WUI boundary (contact zone).

4.4 | Temperature data

Temperature data for the central Cape Town International Airport were extracted from the National Centers for Environmental Information, National Oceanic and Atmospheric Administration dataset (ncdc.noaa.gov/cdo-web/) (Vose et al., 2014). We aggregated the daily average temperature into average and maximum temperature per fire season.

4.5 | Policy and census data

Literature on policies and the policy documents were considered. We consulted acts related to environmental management and to urban development pre- and post-Apartheid. Apartheid policies were examined as they influenced the morphology of CoCT in 1990 (Davenport, 1969; Department of Water Affairs and Forstry, 2005; Forsyth et al., 2010; Mabin & Smit, 1997; National Biodiversity Framework, 2009; Spinks, 2001; National Environmental Management Act, 1998; National Veld and Forest Fire Act, 1998).

For population numbers, a combination of the 1996 and 2001 Census data (Lehohla, 2012; Statistics South Africa, 1996) and a community survey for CoCT for 2016 (Small, 2017) were used due to updated census statistics being unavailable.

5 | RESULTS

In this section we present the spatial changes of urban areas and wildlands over four time periods chosen because of their connection to important political developments and their associated policy changes. We also consider how the observed changes related to population growth, wildland health, and the extent of burned areas.

5.1 | Before 1990: The Apartheid city

Apartheid segregated South Africa spatially and socially into groups based on race, religion, and origin country (Spinks, 2001). Before Apartheid, Cape Town showed the most residential integration across races. However, after Apartheid it was the country's most racially divided city, with only 6% of the population living outside racially designated areas (Spinks, 2001).

Apartheid resulted in distinct formal and informal settlement patterns (Davenport, 1969; Mabin & Smit, 1997; Muller, 2013; Spinks, 2001). Formal urban areas were designated for White residents only and Black residents were often relegated to informal settlements at the WUI (Mabin & Smit, 1997; Spinks, 2001).

To manage wildlands in the CoCT, in the 1970s prescribed burning was introduced in most fynbos conservation areas with some success (Van Wilgen, 2009). The frequency of planned burns was 12 to 15 years but was slowed by directives restricting burning to late summer/early autumn, which was detrimental for fynbos but safest for urban areas (ibid). By 1988, prescribed burns declined by 75%, also due to resistance from urban residents fearing property damage (Forsyth & Van Wilgen, 2008; Van Wilgen, 2009). The shift from protecting wildland to protecting urban land occurred before the end of Apartheid.

5.2 | 1990–2001: A new democracy begins

The land use of CoCT in 1990 was dominated by wildland and farmlands (Figure 3). Only 16% of the CoCT area was urban space; and of this, only 4% was informal, while the WUI was 346 km^2 (Figure 3); thus, wildland management would have an impact on wildfire hazard of a large urban area.

At the end of Apartheid, about 90% of non-Black South Africans were living in urban areas (Bakker et al., 2016; Mabin & Smit, 1997). Population increased by 13% from 1996 to 2001, while the share of the Black population in the CoCT rose after Apartheid (Figure 4).

Population growth is reflected in the expansion of urban landcover (Figure 3) by 4% to 23% in 2001. Informal urban areas accounted for 17% of the urban footprint. While farmland expanded by 1%, wildland decreased by 13%, most lost to urban growth. Further, the WUI expanded to 377 km^2, reflecting the expansion of the urban edge.

Figure 5 shows the (dNBR-based) CoCT burns and highlights the burned WUI. The total extent of burned area over this period is 1155 km^2 of which only 118 km^2 were WUI areas.

The average burns were about 115 km^2 per year, an area almost half the size of CoCT burned between 1990 and 2000 (Table 1). According to dNBR, 2000 had the largest burned area, three times larger than the next largest, 1991. Most burns occurred in farmlands and are not important for this study.

In this period, 31% of the WUI burned, wildland burned the most, followed by formal land and informal land, respectively (Table 2).

The new government addressed wildfire and the environment through national legislation. First, the 1998 National Veld and Forest Fire Act regulated the establishment of fire protection associations and the rights and responsibilities local municipalities and landowners have for fire safety and fire spread and restricts open fires when the fire hazard is high. Exemption may be granted to landowners from the requirement to create fire breaks. The 1998 National Environmental Management Act states that fire management should prevent harm to the environment, to property, and to humans (National Environmental Management Act, 1998).

5.3 | 2002–2011: City growth and shift in policies

The 2011 Census showed a further increasing population (3,740,026 people) and densification of CoCT (Figure 6). The Black population almost drew equal to the Coloured population, and the White population percentage marginally reduced (Figure 4).

The urban footprint grew to 24% of CoCT by 2011 (Figure 3), up 6% from 2001, indicating possible housing densification for the increased population. Informal areas reduced to 16% of the urban footprint. This corresponds with findings from the Socio-economic Rights Institute of South Africa (2018), that noted a rise and fall in people living in informal settlements between 2001 and 2011 nationally. In CoCT, literature also noted a reduction in non-backyard informal dwellings between 2001 and 2007 (The Housing Development Agency, 2012). There was a further small reduction in wildland (1%) and farmland (3%) since 2001.

According to the MODIS dataset for the period 2001–2010, 16% of CoCT burned with an average of 48 km^2 per year. Four years had off-season burns totalling 6 km^2 (4 km^2 in 2007), all in farmlands. In the fire season (2001–2011), 481 km^2 burned (Table 1), with 73 km^2 experiencing multiple burns, largely in farmlands. The

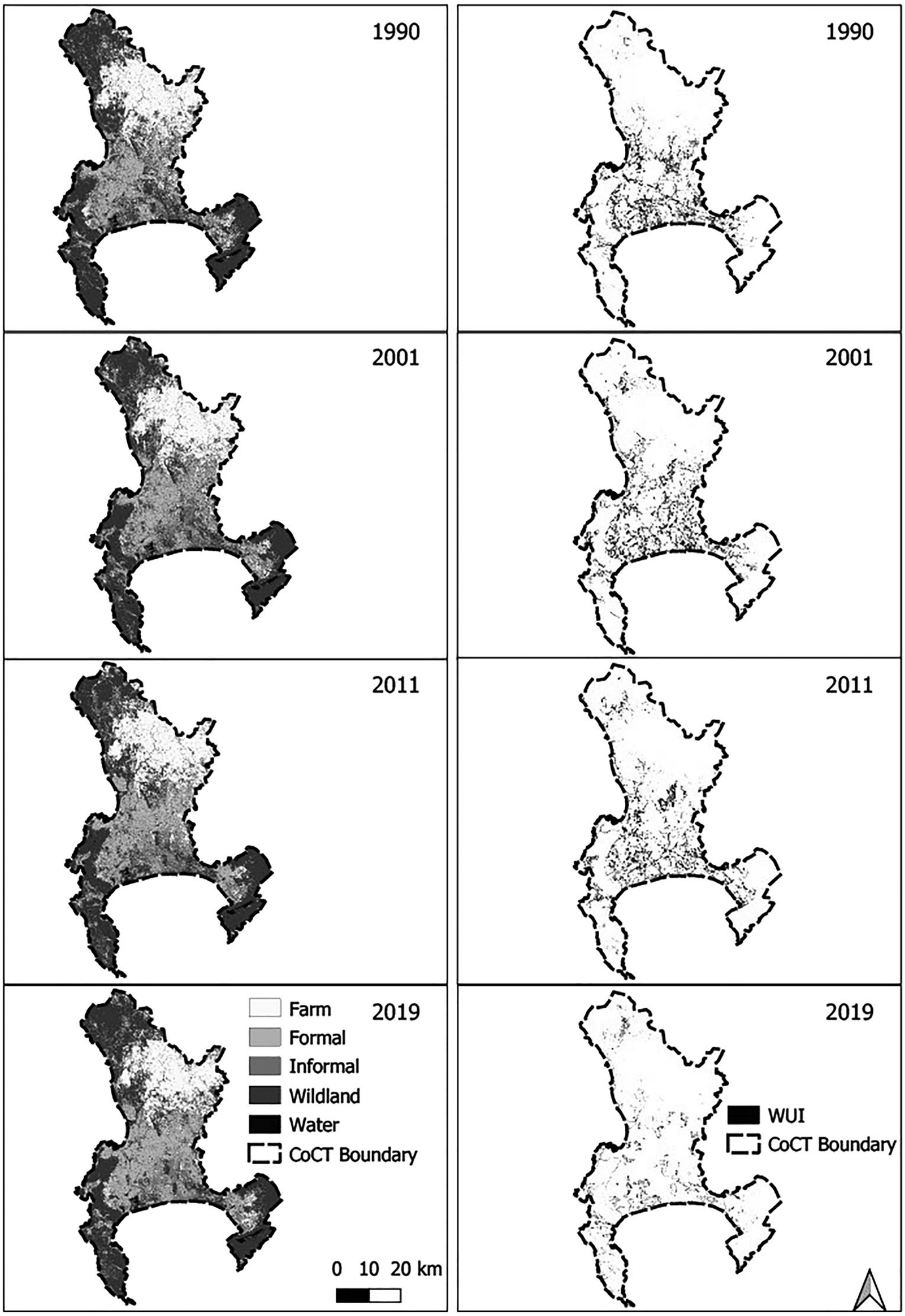

FIGURE 3 Landcover and WUI 1990, 2001, 2011, and 2019. *Source*: Authors, based on a classification using Landsat 5 (1990, 2001, 2011) and Landsat 8 (2019) datasets

2009 season saw a large burned area of 158 km^2, over a third of the total area burned in the decade. These large burns were followed by a decline in burned area in the following years until 2014, potentially due to the loss of combustible material in 2009.

According to the dNBR, a total of 924 km^2 burned (2001–2011), on average 92 km^2 per year, with 318 km^2 experiencing multiple burns. The years with the most burns indicated are 2006, 2007, 2010, and 2011 with between 165 and 214 km^2 burned (Figure 7). There is a large discrepancy between MODIS and dNBR; however, the patterns seen in (Figures 5 and 7) are similar in terms of peaks and lows, with the exception of the 2009 peak followed by the lows of 2010 and 2011 as per the MODIS dataset while the dNBR shows continued high annual burns over this period. The higher spatial resolution of the dNBR detects more small burn scars than the MODIS dataset, including smaller burns on farmlands.

By 2011, the WUI had shrunk to 333 km^2 (Figure 3), indicating that wildland pockets had been

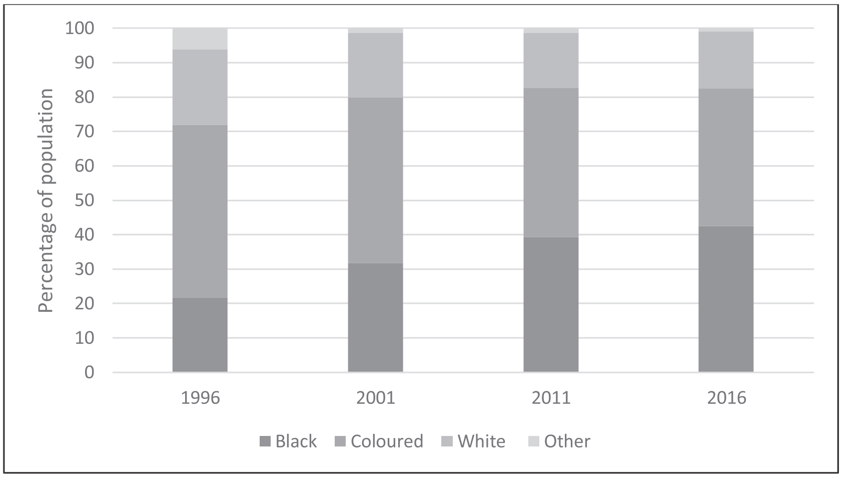

FIGURE 4 Racial percentage CoCT 1996, 2001, 2011, and 2016. *Source*: Lehohla (2012) and Small (2017)

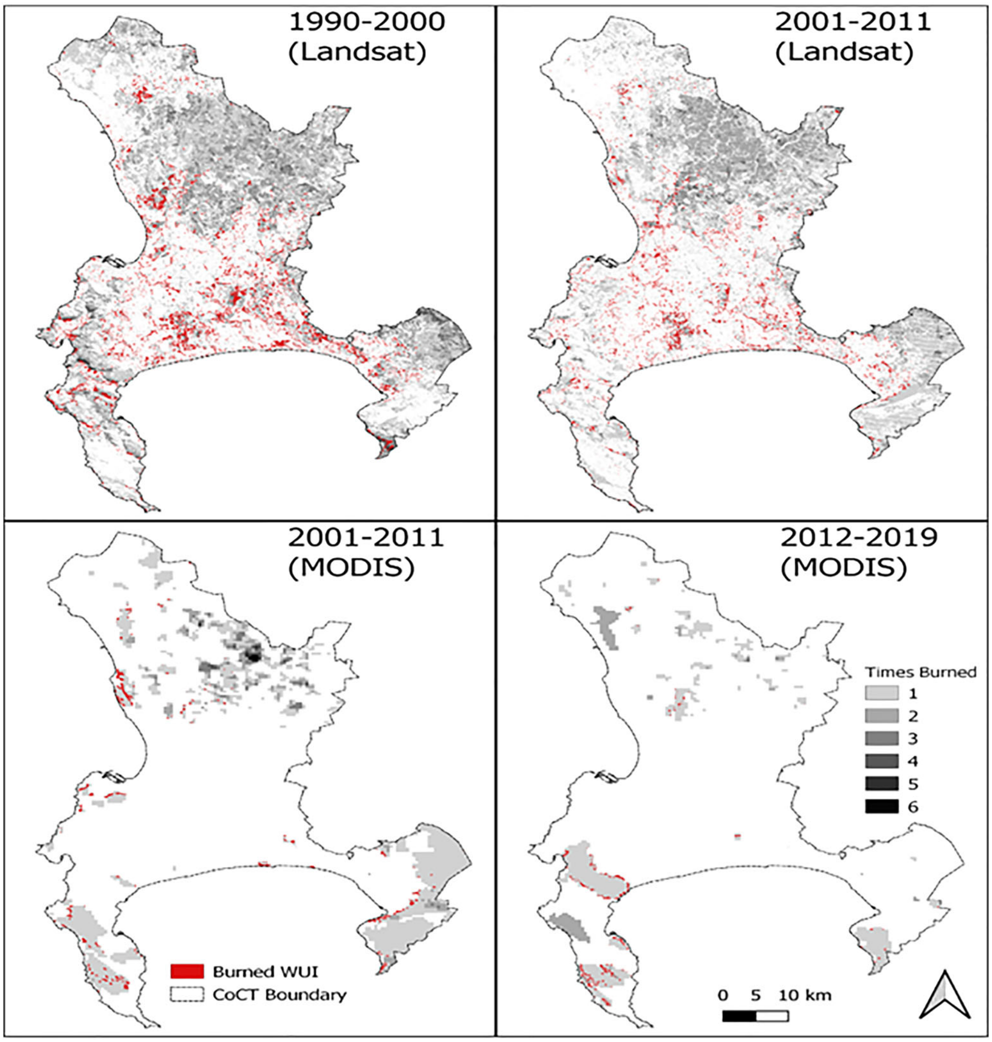

FIGURE 5 Burned area and WUI burned 1990–2000, 2001–2011, and 2012–2019 *Source*: Authors extracted burned area data from Landsat 5 and Landsat 7 for the Landsat burned area, and Giglio et al. (2015) for the MODIS burned area product

filled by urban development. Of this WUI area, 17 km^2 burned in MODIS detected burns and 76 km^2 in Landsat detected burns, about 5% and 22% of the WUI respectively (Table 2). For the MODIS dataset, the majority of burned WUI was formal land, and for the dNBR dataset it was wildland. From both datasets, the least burned WUI were informal areas. The WUI in this period was mostly affected by single period burns, with

TABLE 1 Total CoCT areas with multiple burns, 1990–2000, 2001–2011, and 2012–2019

Number of times specific area burned	Area burned in km² 1990–2000 (Landsat)	Area burned in km² 2001–2011 (Landsat)	Area burned in km² 2001–2011 (MODIS)	Area burned in km² 2012–2019 (MODIS)
1	687.7	616.8	407.7	189.0
2	335.1	257.5	49.4	41.6
3	102.7	44.1	17.0	0.6
4	24.9	5.6	3.5	0.0
5	4.4	0.3	1.9	0.0
6	0.3	0	1.1	0.0
Total	1155.1	924.3	480.6	231.2

Source: Authors, extracted from Landsat derived landcover classification, burned area product, and MODIS burned area product

TABLE 2 Burns in the WUI 1990–2000, 2001–2011, and 2012–2019

Years	Total extent of WUI (km²)	Wildland burned (Km²)	Formal burned (km²)	Informal burned (km²)	Total burned WUI (km²)
1990–2000 (Landsat)	377.0	72.2	36.3	9.8	118.3
2001–2011 (Landsat)	332.6	47.2	24.1	4.3	75.6
2001–2011 (MODIS)	332.6	6.7	9.6	1	17.3
2012–2019 (MODIS)	181.1	0.8	7.9	0.2	8.9

Source: Authors, extracted from Landsat derived landcover classification, and burned area product, and MODIS burned area product

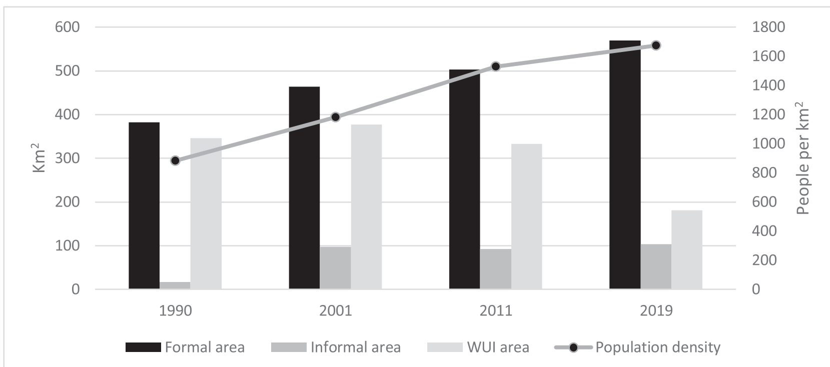

FIGURE 6 Urban growth, WUI size and population density, 1990, 2001, 2011 and 2019. *Source*: Authors, based on Landsat landcover classification and population data from Lehohla (2012) and Small (2017)

repeated burns occurring outside of the WUI (Figure 5). Of the fires that burned both wildland and urban areas, 70% affected only the 100 m of urban WUI as delineated.

Policy focused on disaster management and environmental management. The 2002 Disaster Management Act requires municipalities to plan, manage, and analyse actively for conditions of hazards and vulnerability that may lead to losses (human or environmental), including wildfires. Although the act provides a framework it lacks a concrete timeline for implementation (Forsyth et al., 2010).

Important for fynbos wildland is the 2003 National Environmental Management: Protected Areas Act that requires the identification and protection of all ecological areas (National Environmental Management Protected Areas Act, 2003). The 2004 Biodiversity Act sets a framework for the protection of species and ecosystems that warrant national protection (National Environmental Management Biodiversity Act, 2004).

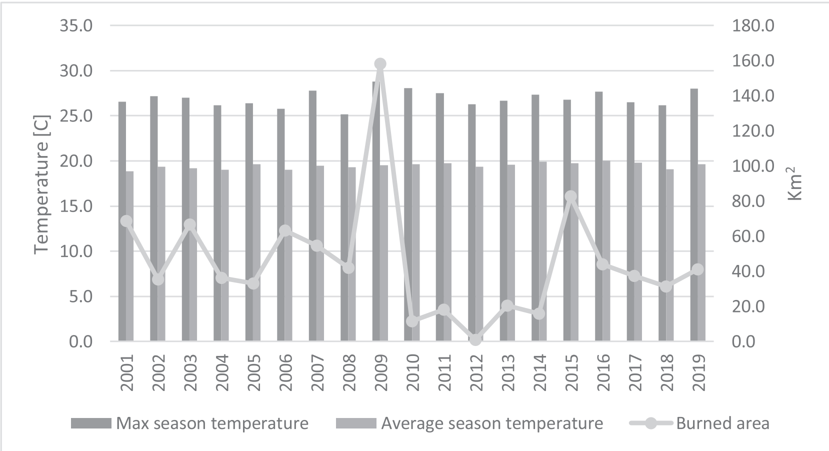

FIGURE 7 Fire season temperature in Celsius and burned area 1990–2019. *Source*: Authors Landsat and MODIS derived burned area products and temperature from Vose et al. (2014)

5.4 | 2012–2019: Recent developments

In 2016, the community survey estimated the CoCT population at 4,004,793, continuing the trend of growth and densification (Figure 6). The Black population increased the most (Figure 4), now forming the majority, the White population increased marginally, while the Coloured population percentage shrank (Small, 2017).

By 2019, the urban footprint (Figure 3) had grown to 673 km^2, including 104 km^2 informal areas (+13%), contrasting with the previous decline. Farmland declined by 11% and wildland by 1%. The total WUI again shrunk to 181 km^2.

With 231 km^2 burned area (Table 1, MODIS 2012–2019), there was less burned area than the previous period (Figure 5). Fewer areas burned more than once, at most three times. About 9 km^2 (5%) of the WUI burned once or more (Table 2) and most were formal areas. Although less of the CoCT burned, most of the largest burns affected the WUI, with 76% of these limited to the WUI area.

5.5 | Broad trends

Post-Apartheid there have been three important trends: the increase in urban area and population density, and the decrease in total burned area (Figure 6, Figure 5, and Table 2). While residents may be pleased with these trends, there is a growing hazard for larger wildfires and species loss in the wildland. This disconnect of reduced fires and increased hazard of larger fire is echoed by The Executive Council of the local government for environmental affairs and development planning that indicated 95% of wildfires in the Western Cape between April 2018 and March 2019 were extinguished in the first hour, but remaining fires were larger and more serious (IOL News, 2019). Rapid fire response is linked to the first principle of the Western Cape Wildfire Plan 2019–2020, which states that the protection of human life takes priority (Western Cape Government, 2019).

While the processes at the WUI are dynamic, the maximum and average temperatures for the fire season have remained relatively stable. Over the study period, the standard deviation of the maximum fire season temperature is 1.0 C, with the maximum deviation in 2009 with 2.4 C warmer than average (Figure 7). Otherwise, there appears to be little correlation with burned area and temperature in CoCT.

6 | DISCUSSION

The discussion addresses each of the research questions by discussing: urban growth and burn patterns overtime (6.1), the influences of urban policy (6.2), the implications of the current trends (6.3), and the limitations and implications a socio-ecological system approach has (6.4).

6.1 | Urban growth and burned area patterns

Investigating the WUI using our framework (Figure 1), human behaviour (governance and residents) in formal and informal urban areas is the core of how a socio-ecological system in a WUI with fire-dependent wildland interacts and changes. Rapid urbanisation of CoCT occurred after the abolition of Apartheid and by the 2000s increasing built-up areas meant a shrinking WUI, possibly relating to the reduction of the impact the WUI has on wildland burn patterns.

Fire, however, remains a persistent hazard at the WUI, though mostly in the fire season. Although scenarios for

Mediterranean climate regions indicate increased fire intensity and frequency due to urban growth (Blanckenberg et al., 2019; Narayanaraj & Wimberly, 2012; Pechony & Shindell, 2010), our results show little evidence for this before 2019.

Doerr and Santín (2016) noted that globally wildfires have remained constant over time and others have even seen reductions (Arora & Melton, 2018). One may argue that the reduction of the WUI due to urban consolidation has been a cause for the reduction in burns. However, we think that fire suppression efforts to protect urban residents has been a major contributor to the reduction of burns. This coincides with findings reported by Moreira et al. (2010) that higher population densities (Figure 6), decrease the likelihood of large burns despite increasing ignitions. While Jones (2017) and Kahanji et al. (2019) suggested that informal areas increase fires at a higher rate than formal areas, our research found more wildfires affecting formal areas (Table 2). Future studies should investigate this matter, but one reason may be that informal residents identify and address small wildfires earlier than formal dwellers.

6.2 | Ignitions, fire protection, and controlled burning

In our framework, ignitions, building patterns, and various fire management strategies directly interact at the WUI. Urban residents bringing an increase of ignitions are one of the most important factors of a growing urban system (Walls et al., 2019). Residents of CoCT suggest that arson and discarded cigarettes are often the cause of frequent small fires (Blanckenberg et al., 2019). The datasets used in this study, however, cannot track such small ignitions. The dNBR supported that smaller burns, whether through fire suppression or other management strategies, were less common with the reduction of the WUI. It is clear that there has been a reduction of larger burns over the years at the WUI and in the wildland, potentially due to fire management strategies.

As CoCT residents have historically been fire averse and resisted controlled burning to manage wildland and fuel loads, we agree with Forsyth and Van Wilgen (2008) that most wildland burns were unplanned.

Our findings agree with literature in the area that there has been a decrease in large burns in parts of CoCT with the increase in population (Van Wilgen, 2009). Our results also mirror those reported by Li et al. (2018) that increased population density and economic circumstances reduce fires due to suppression efforts. This interaction is captured in our framework by the indirect effect from the urban system at the WUI through fuel build-up, loss of wildland and increased hazard of large burns.

6.3 | Wildland health, fuel build-up, and climate

Our findings corroborate the view that high efficiency suppression, typical of development in fire-dependent ecosystems, can lead to species loss in these ecosystems (Bond & Keane, 2017; Forsyth & Le Maitre, 2015; Moritz et al., 2014; Shlisky et al., 2007). In CoCT, between 328 (MODIS and dNBR) and 771 km^2 (MODIS only) of wildland has not experienced wildfire, leaving a large area of Fynbos ecologically vulnerable. While disaster and biodiversity legislation ask for controlled fires and natural fires to be left to run their course where possible, to allow the survival of the natural wildland, these policies do not seem to be implemented as suppression strategies prevail (Bartel & Graham, 2016).

Unmanaged areas which have not experienced burns for a long period increase the fuel load, contributing to large uncontrollable fires. This increased hazard relates to the wildfire paradox, that wildfire suppression that is effective 95% to 98% of the time, will lead to large wildfires of higher intensity that can be impossible to suppress (Calkin et al., 2014). Thus, the current strategy may be more dangerous for urban areas, than a management strategy that supresses less wildfires.

An example of this effect was seen in the Knysna municipality during 2017, where warm windy days combined with areas of fynbos that had been excluded from burns for over 20 years created one of the largest uncontrolled burns in the Western Cape (Frost et al., 2018). Internationally, the trend of increased large wildfires due to fire suppression has been signalled. Ingalsbee (2017) suggests to shift from excluding fire towards restoring fire ecology processes through the integration of social and environmental needs, though as we, he acknowledges that achieving an integrated approach is a slow process.

6.4 | Implications for future research and limitations of this study

The socio-ecological system approach proved useful in identifying and documenting the interactions present in a fire-dependent wildland WUI. However, to improve understanding the WUI as a socio-ecological system, we suggest including data on ignitions and suppression efforts. These datasets are often not available, however the dNBR did prove useful and after better calibration may provide a higher-quality burned area product.

Investigation of human decisions around wildfire management would also greatly improve the understanding of the macro patterns identified.

The challenge of a socio-ecological system approach is to generalise relationships from detailed case specific events and factors. We started with a broad approach to the macro pattern, envisioning future work would build on our framework and add more detail.

7 | CONCLUSION

Wildfire at the WUI is a hazard with social and ecological origins and consequences. We examined the WUI of the CoCT with its fire-dependent wildland as a socio-ecological system. The local management strategy, strong fire suppression, is identified as a potential negative feedback that increases wildfire hazards. The socio-ecological system approach aids in re-emphasising how hazardous fire-suppression can be in the long-term for both fire-dependent vegetation and urban residents. Contrary to expectations, our findings suggest that the total burned area in CoCT decreased with the increase in urban size. Furthermore, an increase in informal areas has not shown an increase in large wildfires, emphasising the efficiency of the current suppression strategies.

Including WUI residents and creating more local knowledge is required to shift towards sustainable wildfire management as required by South African national policies. Understanding why residents request the current management strategy should be investigated in future research.

When evaluating future interventions and management strategies, we recommend that a socio-ecological system approach be used to evaluate and communicate the potential outcomes as it provides insights into decisions that are controversial in the short term but reduce long term wildfire hazards.

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CONFLICT OF INTEREST

None.

ETHICS STATEMENT

No ethical approval was sought for this study as there were no human participants, and all data are available in the public domain.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study were derived from the following resources available in the public domain: Landsat 5, 7, 8—https://earthexplorer.usgs.gov/; MODIS Burned Area Product collection 6—https://modis-fire.umd.edu/; DEM and City of Cape Town aerial imagery—https://web1.capetown.gov.za/web1/opendataportal/Default; National Oceanic and Atmospheric Administration (USA) Climate data—https://www.ncei.noaa.gov/access. Reference data derived from the aerial imagery are available from the corresponding author upon reasonable request. Information to how data was processed are available in the supporting information.

ORCID

Sven Christ https://orcid.org/0000-0003-0320-8571
Nina Schwarz https://orcid.org/0000-0003-4624-488X
Richard Sliuzas https://orcid.org/0000-0001-5243-4431

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APPENDIX A: LAND COVER CLASSIFICATION

The land cover classification of Landsat 5 and Landsat 8 data was processed using QGIS (3.4.3) and SAGA (7.5.0). The data was pre-processed and prepared in QGIS and classification was run in SAGA.

A.1 | Data pre-processing

Landsat data was converted to Top-OF-Atmosphere reflectance and atmospheric correction was applied (DOS1) in the QGIS SCP plugin (6.4.2) (Correia et al., 2018).

Texture layers were extracted from Landsat Bands 2, 3, 4, 5 using the r.texture in QGIS. Settings were a moving window of 3 and distance between samples of 1. All other boxes were left unchecked.

A 10 m digital elevation model (DEM) of the City of Cape Town (CoCT) was downloaded from https://web1.capetown.gov.za/web1/OpenDataPortal/.

A.2 | Training and accuracy assessment sites

The QGIS random points generator was used to create random training sites and accuracy assessment sites. Training and accuracy assessments sites were assigned their class using high resolution aerial photography obtained from the South African National Geospatial Information centre (cdngiportal.co.za/cdngiportal/) and the City of Cape Town (https://web1.capetown.gov.za/web1/OpenDataPortal/).

For the classifications, 436 training sites were created using high resolution aerial imagery of the area and 135 accuracy assessment sites in the 2019 classification. Both training and accuracy assessment sites were also used for earlier years, changing site, and site attributes only as required to maintain at least 30 sites for each class for the years 2019, 2011, 2001, and 1990. However, in 1990 only eight sites were possible for the informal class as there was not enough informal areas in the study area. Overall 1990 had less sites 416 training and 123 reference points, as the area was less developed.

A.3 | Classification

In SAGA, the OpenCV random forest classification tool was used with the following datasets:

- Input: bands 1–5 and 7;
- Texture layer: bands 2–5;
- 10 m COCT DEM.

A.1.1 | Settings

Using the training areas for the applicable year, the settings were for all years:

- Maximum tree depth: 100
- Minimum sample count: 2
- Maximum categories: 20
- Regression accuracy: 0.01
- Active variable count: 0
- Use 1SE rule and truncate pruned trees were deselected.

A.1.2 | Accuracy assessment results

TABLE A1 1990

	Training sites: 416	**Reference sites: 123**					**Input data:**
		Farm	**Formal**	**Informal**	**Truth Wildland**	**Total**	**Landsat 5 bands 1–5 and 7 Texture Landsat 5 bands 2–5**
Classification	Farm	22	4		4	30	DEM
	Formal (urban)	1	21	3	3	28	
	Informal (urban)		1	3	1	5	
	Wildland	3	8	3	46	60	
	Total	26	34	9	54	123	
	Overall accuracy [%]	74.8					
	Users accuracy [%]			**Producers accuracy [%]**			
	Farm	73.3		Farm	84.6		
	Formal	75.0		Formal	61.8		
	Informal	60.0		Informal	33.3		
	Wildland	76.7		Wildland	85.2		

TABLE A2 2001

	Training sites: 436	Reference sites: 137					Input data:
					Truth		Landsat 5 bands 1–5 and 7
		Farm	**Formal**	**Informal**	**Wildland**	**Total**	**Texture Landsat 5 bands 2–5**
Classification	Farm	23	1		6	30	DEM
	Formal (urban)		27	1	7	35	
	Informal (urban)		4	15	1	20	
	Wildland	4	2	3	43	52	
	Total	27	34	19	57	137	
	Overall accuracy [%]	78.8					
	Users accuracy [%]			**Producers accuracy [%]**			
	Farm	76.7		Farm	85.2		
	Formal	77.1		Formal	79.4		
	Informal	75.0		Informal	78.9		
	Wildland	82.7		Wildland	75.4		

TABLE A3 2001

	Training sites: 436	Reference sites: 133					
					Truth		Input data:
		Farm	**Formal**	**Informal**	**Wildland**	**Total**	**Landsat 5 bands 1–5 and 7**
Classification	Farm	23		1	5	29	Texture Landsat 5 bands 2–5
	Formal (urban)	2	23	1	5	31	DEM
	Informal (urban)		6	11		17	
	Wildland	1	7	1	47	56	
	Total	26	36	14	57	133	
	Overall accuracy [%]	78.2					
	Users accuracy [%]			**Producers accuracy [%]**			
	Farm	79.3		Farm	88.5		
	Formal	74.2		Formal	63.9		
	Informal	64.7		Informal	78.6		
	Wildland	83.9		Wildland	82.5		

TABLE A4 2019

	Training sites: 436	**Reference sites: 135**			**Truth**		**Data**
		Farm	**Formal**	**Informal**	**Wildland**	**Total**	**Landsat 8 bands 1–5**
Classification	Farm	20			4	24	Texture Landsat 8 band 2–5
	Formal (urban)	1	28	1	5	35	DEM
	Informal (urban)		5	11	1	17	
	Wildland	5	4		50	59	
	Total	26	37	12	60	135	
	Overall accuracy [%]	80.7					
	Users accuracy [%]			**Producers accuracy [%]**			
	Farm	83.3		Farm	76.9		
	Formal	80.0		Formal	75.7		
	Informal	64.7		Informal	91.7		
	Wildland	84.7		Wildland	83.3		

APPENDIX B: BURNED AREA CLASSIFICATION

Landsat data were chosen due to the temporal availability of these datasets. A remote sensing approach was used as it is difficult to manually identify burned areas in the large City of Cape Town region. This is made more difficult by the shrub like fynbos vegetation that dominates the area. Regrowth can be fast and upon manually comparing satellite data with known burn areas, many of these were missed by the naked eye.

The difference normalised burn ration (dNBR) was chosen as it gives a temporal view of burns between two image dates. The dNBR was calculated using Landsat 5 (1989–2007) and Landsat 7 (2007–2011) data using QGIS (3.4.3). The data was pre-processed and prepared in QGIS.

B.1 | Data pre-processing

Landsat data was converted to Top-OF-Atmosphere reflectance and atmospheric correction was applied (DOS1) in the QGIS SCP plugin (6.4.2) (Correia et al., 2018).

Before the Difference normalised Burn Ratio (dNBR) can be calculated, the normalised burn ration (NBR) first has to be calculated. NBR is a ratio between the Near Infra-Red (NIR) and Short Wave Infra-Red (SWIR) values (NIR − SWIR)/(NIR + SWIR) (United States Geological Survey, n.d.; Saputra et al., 2017). In both Landsat 5 and 7 NBR was calculated using the following formulae: NBR = (band 4 − band 7)/(band 4 + band 7) in raster calculator (ibid). Note must be given that Landsat 7 has a banding issue that leaves missing pixels throughout the years used 2008–2011.

The dNBR was calculated using the formulae, pre-fire NBR - post-fire NBR in the raster calculator (Kolden et al., 2012; Saputra et al., 2017).

B.2 | DNBR interpretation

The dNBR values fall within a range of −2000 to 2000, with the typical range falling between −200 and 1200 (Kolden et al., 2012).

For determining if an area burned in the past year we used the dNBR value of 0.2 or larger. This is in the middle range of the regularly interpreted value of 0.1–0.26 for low severity burns (Pepe & Parente, 2018). It is, however, in agreement with the value of 0.21 as suggested by Pepe and Parente (2018) and conforms best to a visual comparison of the Cape Nature all fires dataset, which is limited to only areas protected by Cape Nature.

A few anomalies appeared in the dNBR data with overestimation of burns that occurred. These years were 1991, 1997, 2000, 2006, and 2007. The cut-off for this was modified to a value of 0.4 before an area is classified as burned. This value also agreed best with the Cape Nature dataset and the MODIS burned area product when available.

Due to there being no Landsat product available for 2002, the 2003 dNBR cut-off was used at 0.1 as it compared best to the other burned area results between 2001 and 2003 from the Cape Nature dataset and the MODIS burned area product.