Received: 30 October 2020 | Revised: 14 April 2021 | Accepted: 12 May 2021

DOI: 10.1002/cli2.8

Climate Resilience and Sustainability
Interdisciplinary Approaches Towards Solutions for Climate Change
Open Access
RMetS

ORIGINAL ARTICLE

South American fires and their impacts on ecosystems increase with continued emissions

Chantelle Burton[1] | **Douglas I. Kelley**[2] | **Chris D. Jones**[1] | **Richard A. Betts**[1,3] | **Manoel Cardoso**[4] | **Liana Anderson**[5]

[1] Met Office Hadley Centre, Met Office, Exeter, UK

[2] UK Centre for Ecology & Hydrology, Wallingford, Oxfordshire, UK

[3] Laver Building, Global Systems InstituteUniversity of Exeter, North Park Road, Exeter, UK

[4] Earth System Sciences, National Institute for Space Research, São José dos Campos, São Paulo, Brazil

[5] National Center for Monitoring and Early Warning of Natural Disasters —Cemaden, São José dos Campos, São Paulo, Brazil

Correspondence
Chantelle Burton, Met Office Hadley Centre, Met Office, Exeter EX1 3PB, UK.
Email: chantelle.burton@metoffice.gov.uk

Funding information
Newton Fund; UK Earth System Modelling Project (UKESM), Grant/Award Number: NE/N017951/1; São Paulo Research Foundation, Grant/Award Numbers: 2015/50122-0, 2017/22269-2, 2016/02018-2; National Council for Scientific and Technological Development, Grant/Award Numbers: 314016/2009-0, 442650/2018-3, 309247/2016-0; Inter-American Institute for Global Change Research, Grant/Award Number: SGP-HW 016

Abstract

Unprecedented fire events in recent years are leading to a demand for improved understanding of how climate change is already affecting fires, and how this could change in the future. Increased fire activity in South America is one of the most concerning of all the recent events, given the potential impacts on local ecosystems and the global climate from the loss of large carbon stores under future socio-environmental change. However, due to the complexity of interactions and feedbacks, and lack of complete representation of fire biogeochemistry in many climate models, there is currently low agreement on whether climate change will cause fires to become more or less frequent in the future, and what impact this will have on ecosystems. Here we use the latest climate simulations from the UK Earth System Model UKESM1 to understand feedbacks in fire, dynamic vegetation, and terrestrial carbon stores using the JULES land surface model, taking into account future scenarios of change in emissions and land use. Based on evaluation of model performance for the present day, we address the specific policy-relevant question: how much fire-induced carbon loss will there be over South America at different global warming levels in the future? We find that burned area and fire emissions are projected to increase in the future due to hotter and drier conditions, which leads to large reductions in carbon storage, especially when combined with increasing land-use conversion. The model simulates a 30% loss of carbon at 4°C under the highest emission scenario, which could be reduced to 7% if temperature rise is limited to 1.5°C. Our results provide a critical assessment of ecosystem resilience under future climate change, and could inform the way fire and land-use is managed in the future to reduce the most deleterious impacts of climate change.

KEYWORDS
burned area, carbon sink, climate change, emissions, fire

1 | INTRODUCTION

Record fire events in recent years across the Arctic (Witze, 2020), Europe, western USA (Higuera & Abatzoglou, 2020), Australia (Boer et al., 2020) and Brazil's rainforest and wetland biomes (Lizundia-Loiola et al., 2020; Mega, 2020) are leading to questions about how climate change is affecting fire regimes, and how this could change in the future. For example, temperature, fuel, and moisture availability are key drivers of burned area, which are all projected to change as the climate changes, although there is still much uncertainty around how and when these changes will occur. Already at 1°C of warming above pre-industrial (PI) levels, fire season length has increased by an average of 33 days over the last 35 years in South America (Jolly et al., 2015).

Today, fires in South America are mainly focused across Brazil's Cerrado region, where conditions are hot and dry, particularly over the June-October fire season. Vegetation in this region is heterogeneous fire-adapted paths of woodlands, mixed with more sparse vegetation dominated by small trees, shrubs and grasses (Ratter et al., 1997). Historically fire has not been considered a major threat across the Amazon rainforest, with high moisture levels and very few natural ignition sources. However, the risk of fires may increase over wider areas in the future due to warming and drying over the next century as the climate continues to change (Ciais et al., 2013). It is estimated that currently, 58% of the Amazon is too humid to support fires, but climate change may reduce this area to 37% by 2050 (Ciais et al., 2013; Le Page et al., 2010), potentially introducing fires to a region of the Amazon where trees are more vulnerable to burning (Staver et al., 2020).

At particular risk is South-east Amazonia, where most models project longer and more intense dry seasons in the future (Malhi et al., 2008; 2009), which could result in instability in this area by the end of the century (Staal et al., 2020). In higher emission scenarios, fires may increase in frequency and duration, burning up to 28 times more forest by the end of the century compared to present day (Le Page et al., 2017). Drought years could increase fire danger further on top of this climate change signal, as was the case in the recent 2015/16 El Niño (Anderson et al., 2015; Burton et al., 2020), and in such times the net Amazon carbon sink can change to a source of carbon (Aragão et al., 2018). Future burned area in South America will depend on both anthropogenic and climatic factors. Fires in this region are primarily ignited by people, through land-use change and deforestation activities. In some future scenarios, land-use change is projected to increase, either for increased food production or for increased use of biofuels, and these expanding frontiers can increase forest fragmentation and ignitions (Armenteras et al., 2013). If climate and land use change scenarios for the end of the century are combined, fire risk could increase by 21% to 113% in Amazonia by the end of the century (Fonseca et al., 2019).

As greenhouse gases increase, CO_2 fertilisation may help offset some species' vulnerability to future drought and speed up recovery post-disturbance through increased photosynthesis, carbon uptake and water use efficiency (Castanho et al., 2016; Keenan, 2015). However, this may be limited by nutrient availability and increased parasitic vegetation growth, and there is still a high degree of uncertainty around the magnitude of these potential changes due to the current lack of field observations (Ciais et al., 2013). Because natural fires are infrequent in rainforest ecosystems, the vegetation in Amazonia is not adapted to fire disturbance which leads to low resilience of the forest, and vulnerability to any changes in the fire regime (Malhi et al., 2008). Possible outcomes could include transitioning to a seasonal forest or savannah-like ecosystem (Lovejoy & Nobre, 2018; Malhi et al., 2009; Settele et al., 2014). IPCC AR5 concluded that large-scale dieback due to climate change alone is unlikely by the end of this century. However, there is evidence of critical ecological thresholds and positive feedbacks whereby drought, land-use change and fire could catalyse a self-reinforcing transition to low-biomass, fire-adapted vegetation (Brando et al., 2014; Settele et al., 2014).

There is currently low agreement across models on whether climate change will cause fires to become more or less frequent in the future. The complexity of interactions and feedbacks, a lack of proper representation of fire biogeochemistry in climate models (Kloster & Lasslop, 2017; Settele et al., 2014), and difficulty capturing the root-cause of fire occurrence, which encompasses socio-economic-political and cultural activities, results in widely varying methods used for representing fire (Rabin et al., 2017). Confidence in the magnitude of biogeochemical feedbacks on the climate from fire is also low, with fire emissions contributing greenhouse gases and aerosols to the atmosphere and changes in the land surface altering albedo and carbon sinks (Arneth et al., 2010). Based on limited studies using wide-ranging modelling techniques, we cannot yet be sure even of the sign of radiative forcing from fire (Ciais et al., 2013).

Moritz et al. (2012) project a decrease in fire danger across most of the Southern Hemisphere by the end of the century, using a statistical model based on CMIP3 climate projections. However, these models show little agreement on the direction of change in the nearer term to 2040, and low agreement in some regions such as across the east of Brazil by 2100. Other studies have projected increases in fire in the future. Betts et al. (2015) show that the McArthur Forest Fire Danger Index (FFDI) increases in all future emission scenarios, especially across eastern

Amazonia under RCP8.5. Liu et al. (2010) project higher fire danger by the end of the century across South America, mainly due to warming and drying using the KBDI and four GCMs including HadCM3. Kloster et al. (2012) use CLM with climate projections from ECHAM5/MPI-OM and CCSM to show a projected increase in fire emissions over South America, and a 17–68% increase in global annual fire emissions in 2075–2099 compared to present day. There are added complexities associated with diagnosing burned area that are not represented by indices of fire danger such as the FFDI, including fuel availability and anthropogenic influences such as ignition and fire suppression. Therefore risk varies strongly by region (Ciais et al., 2013). To be able to represent all of these factors, a fire-enabled dynamic land surface or Earth System Model is required (Kelley & Harrison, 2014).

There is also large disagreement across models concerning how precipitation will change by the end of the century, in particular over South America (Chadwick et al., 2016), predominantly related to changes in sea surface temperatures (SSTs) and land-sea temperature differences, which cause shifts in convection and convergence (Kent et al., 2015). However, while CMIP3 projections showed an increase in wet season precipitation and a decrease in the dry season across the Amazon in the future, there is a stronger consensus across the more recent CMIP5 and CMIP6 models towards a decrease in precipitation in both wet and dry seasons (Joetzjer et al., 2013), and the mean trend indicates a drying in Amazonia (Parsons, 2020). One of the key drivers of this is plant physiology (Chadwick et al., 2017; Richardson et al., 2018), whereby plant stomata open less under elevated levels of CO_2, which leads to reduced evapotranspiration (ET), and local warming and drying (Betts et al., 2008). Another explanation is the Walker circulation shifts relating to decreasing tropical Pacific SST gradients (Parsons, 2020).

Here we use new results from the latest Earth System Model (ESM) UKESM1 (Sellar et al., 2019) climate to drive the coupled fire-vegetation model JULES-INFERNO (Burton et al., 2019; Clark et al., 2011; Mangeon et al., 2016), to understand how changes in climate, land-use and vegetation may impact burned area and fire emissions in South America in the future. This configuration enables us to fully represent fuel availability through dynamic vegetation and temporally and spatially varying land-use, anthropogenic and natural ignitions, and fire weather, to understand fire-vegetation feedbacks under changing climate and land-use. The model simulates varying soil moisture in response to vegetation changes, which feeds back onto fire, and represents resultant changes in evapotranspiration. We focus here on South America as a key region of interest given the multiple pressures from fire, deforestation and climate change, as well as high uncertainty in projections and a large potential source of carbon in Amazonia. We start by describing the model set up for the study, then move on to an evaluation of the model at present day compared to observations to verify the model. We present results for three different future scenarios using the Shared Socioeconomic Pathways SSP126, SSP370, and SSP585 (Riahi et al., 2017) as used in CMIP6 (O'Neill et al., 2016). Results are split into climate and land-use drivers, burned area and fire emission impacts, and vegetation impacts. The discussion and conclusion provide a critical assessment of ecosystem resilience under future climate change by addressing our primary research question: how much fire-induced carbon loss will there be over South America at different global warming levels in the future?

2 | METHODS

JULES (Joint UK Land Environment Simulator) is a land surface model which simulates surface fluxes of water, energy and carbon, along with the state of terrestrial hydrology, vegetation and carbon stores (Best et al., 2011; Clark et al., 2011). Vegetation and the carbon cycle is represented in JULES through a coupled scheme of leaf photosynthesis and stomatal conductance by the DGVM (Dynamic Global Vegetation Model) TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics, Cox, 2001; Cox et al., 2000), which simulates the distribution of plant functional types (PFTs) according to species competition, agricultural fraction, carbon uptake (including CO_2 fertilisation) and mortality. In JULES, the agricultural fraction is prescribed as the total land area (gridbox fraction) that is either crop or pasture as opposed to natural vegetation, here using the land use projections provided as part of the CMIP6 driving data (Hurtt et al., 2020). In these areas, only C3 and C4 crops/pasture is able to grow, with the area of C3/C4 determined by TRIFFID (Burton et al., 2019; Sellar et al., 2019). JULES forms the land surface component in the Met Office Unified Model for Numerical Weather Prediction and the latest climate and Earth System Models of the Hadley Centre family, including HadGEM3 (Senior et al., 2016) and UKESM1 (Sellar et al., 2019). JULES can also be used as a stand-alone offline model. The fire model INFERNO (INteractive Fire and Emission algoRithm for Natural envirOnments) was implemented in JULES in version 4.5 (Mangeon et al., 2016), and simulates burned area via the following equation:

$$BA_{pft} = I_T F_{pft} \overline{BA_{pft}}$$

where BA_{pft} is the burnt area fraction for each PFT, I_T is the number of ignitions (from lightning and population density), F_{pft} is the flammability (calculated from fuel, temperature, saturation vapour pressure, relative humidity, precipitation, soil moisture), and $\overline{BA}_{pft}$ represents an average burnt area for each PFT. Additional developments documented in Burton et al. (2019) coupled fire to dynamic vegetation and soil, giving a feedback on the land surface from burned area through fire mortality and carbon reduction. UKESM1 is a complete Earth System Model, simulating processes and feedbacks between the atmosphere, ocean, ice and land surface using the latest developments in terrestrial carbon and nitrogen cycles, ocean biogeochemistry, a unified troposphere-stratosphere chemistry model and a multi-species aerosol scheme (Sellar et al., 2019). In the first implementation of UKESM1 for CMIP6, fire feedbacks are not included, and so to understand these feedbacks on the land surface requires JULES to be run offline.

For this study we use 3-hourly driving data from UKESM1 to provide climate conditions to the offline land surface model JULES, including temperature, precipitation, shortwave and longwave radiation, air pressure, wind, and specific humidity. We use the latest JULES-ES configuration at version 5.7, which simulates 17 land cover tiles (Sellar et al., 2019), and coupled fire-vegetation feedbacks as described in Burton et al. (2019) to represent the feedback of fire with fuel from vegetation and litter pools, and additional developments which allow us to vary mortality by PFT. The representation of crop and pasture as separate PFTs now enables us to reduce burning (via the $\overline{BA}_{pft}$ parameter) in crop areas, which gives a more realistic representation of fire activity as shown in Andela et al. (2017) and Bistinas et al. (2014), allowing us to capture global trends in fire (Table S3, Supporting Information). Here we use values for fire mortality as per Burton et al. (2020), and reduce the background disturbance rate accordingly (values listed in Table S1, Supporting Information).

We use monthly LIS-OTD (Lightning Imaging Sensor—Optical Transient Detector) observations for 2013 from NASA (Christian et al., 2003; Mangeon et al., 2016) for lightning ignitions, and population density data from HYDE 3.2 (Klein Goldewijk et al., 2017a, b) for the historical anthropogenic ignitions, and keep these constant for the future runs. JULES-INFERNO simulates flammability using temperature, precipitation and calculated relative humidity from the driving data, and fuel density, soil moisture and saturation vapour pressure simulated internally by JULES. The model is run at a spatial resolution of N96 (1.25° latitude x 1.875° longitude). We use multiple observations of burned area and fire emissions from FireMIP (Hantson et al., 2020), focussing on GFED4.1s (Global Fire Emissions Database, including small fires; van der Werf et al., 2017) for the majority of our comparison with the model at present day. We spin up the model for 1600 years, and then run the historical simulation from 1860–2014, and use three SSP scenarios to assess how climate might vary over the coming decades from 2015–2100.

TABLE 1 Global Warming Levels and corresponding dates for each SSP scenario

	SSP126	SSP370	SSP585
1.5°C	2023 (2013–2033)	2024 (2014–2034)	2021 (2011–2031)
2.0°C	2030 (2020–2040)	2030 (2020–2040)	2030 (2020–2040)
3.0°C		2050 (2040–2060)	2047 (2037–2057)
4.0°C		2069 (2059–2079)	2062 (2052–2072)

For the analysis we use Global Warming Levels (GWLs) for the future period, which are defined as a specific value of UKESM global mean surface air temperature above the pre-industrial mean. Here we use the period 1850–1900 for the pre-industrial mean, and to limit the influence of short-term variability we use a 21-year mean centred on the first year that the GWL is reached. Table 1 shows the GWLs and corresponding years. We use 1994–2013 for present day, except where otherwise stated. We evaluate burned area at all GWLs for all SSPs, and for the rest of the analysis we use results from SSP370 to assess GWL impacts on all variables.

For evaluating the performance of the model at present day, we assess the model compared to observations, and use the scoring system from the FireMIP protocol (Hantson et al., 2020) based on the benchmarking process outlined in Kelley et al. (2013, 2019). Annual average burnt area, LAI and vegetation carbon was assessed using the normalised mean error step 3 (NME3) metric. To calculate NME3, we sum the difference between the simulation and observations over all cells, correct for differences in the mean and absolute variance between simulation and observations, and then normalise by the average distance from the mean of observations (see Supplementary Information). The same method was also used to compare climatological grid cell-based linear trends on logistic transformed burned area. Tree cover comparisons used the Manhattan Metric (MM), the mean difference between simulation and observation in fractional and non-fraction tree covers.

2.1 | SSP scenario drivers: CO_2 and land-use change

The SSP scenarios used here represent a subset of the latest future pathway scenarios as used in CMIP6, replacing

Climate Resilience and Sustainability
Interdisciplinary Approaches Towards Solutions for Climate Change
Open Access
RMetS

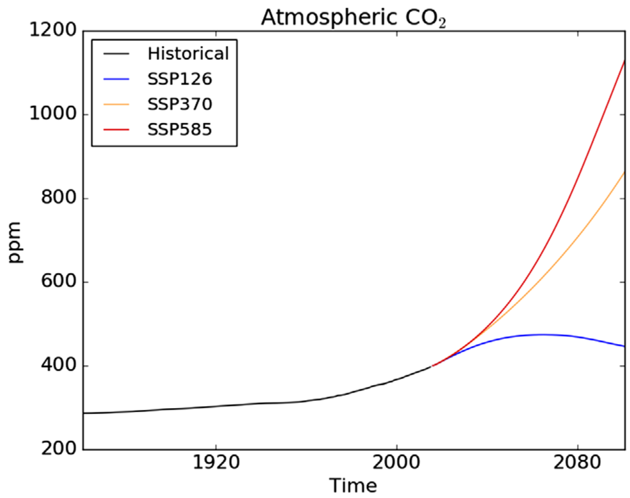

FIGURE 1 Time series of global mean atmospheric CO_2 (parts per million)

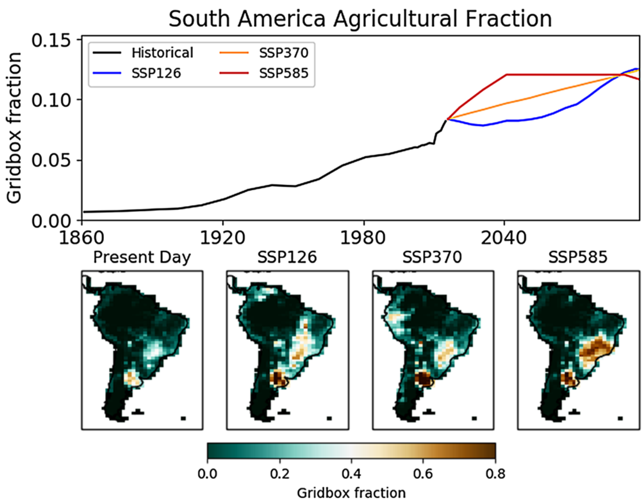

FIGURE 2 Land-use change in South America. Top: Time series of historical and projected mean agricultural fraction over time. Bottom: Maps of land-use change at present day and 2090s for three SSP scenarios

the RCP scenarios used in CMIP5, where SSP126 is a sustainability scenario, SSP370 is a scenario with high challenges to mitigation and adaptation with higher emissions, and SSP585 is a fossil-fuelled development scenario (Riahi et al., 2017). According to the SSP scenarios, CO_2 concentration continues to increase rapidly over the 21st century in the fossil-fuelled development scenario SSP585 (Figure 1). SSP370 has a steadier but still increasing trajectory, whereas atmospheric CO_2 peaks around 2050 and then declines in the sustainability scenario SSP126.

Also included into the SSP scenarios are assumptions about how land use will change in the future, accounting for factors such as changing population, dietary requirements, and urbanisation. Under a sustainability scenario (SSP126), agricultural fraction initially declines in South America after present-day (Figure 2) due to more sustainable land-use practises, lower population levels and low-meat diets, but then increases towards the end of the century with increases in bioenergy production (Popp et al., 2017). High population growth, low agricultural productivity and little environmental protection results in pressure on land-use in SSP370, and continued expansion of crop and pasture reduces forest cover over the 21st century (Riahi et al., 2017). According to SSP585, meat-rich diets and slow declines in deforestation (Popp et al., 2017) result in increasing land-use change until around 2040, and then stabilised levels to the end of the century to reach a similar level as in the other two scenarios. The spatial pattern of land-use change also varies in each scenario, with SSP126 and SSP585 being focused more on agriculture across the SE of the continent, whereas in SSP370 change also occurs over the far west (Figure 2). There is some spread of agriculture into the southern Amazon in SSP370 and eastern Amazon in SSP126, but otherwise the Amazon forest stays mainly intact throughout the century.

3 | MODEL EVALUATION

Compared to CRU observations of temperature, there is a slight warm bias over the Amazon region, and over Chile and Argentina in driving data from UKESM1 (Figure 3a). Elsewhere across the continent there is a slight cool bias. The model simulates too little precipitation over northeast Brazil compared to CMAP observations, and elsewhere precipitation is higher than the observations (Figure 3b). The fire-vegetation model responds appropriately to the NE Brazil dry bias, with a decrease in biomass compared to JULES simulations driven with observed climate (see Burton et al., 2019), and burned area higher than observations (Figure 4a,b). This also leads to a negative bias in vegetation carbon (Figure 3c) which is amplified by fire (Figure 3d). The cooler, wetter region across southern Brazil leads to too much biomass in the model, alleviated here by the inclusion of fire (Figure 3d). This gives an indication of the likely impact on biogeochemistry in this region when fire is fully coupled into future versions of UKESM.

Across the rest of the continent the spatial pattern of burned area is well represented compared to observations (Figure 4 a,b), and benchmarking scores show the model outperforms the null models (Table 2). As the model framework does not perform as well at simulating high and low burnt areas (step 1 scores in Table S2, Supporting Information), our results focus on changes in fire and resultant

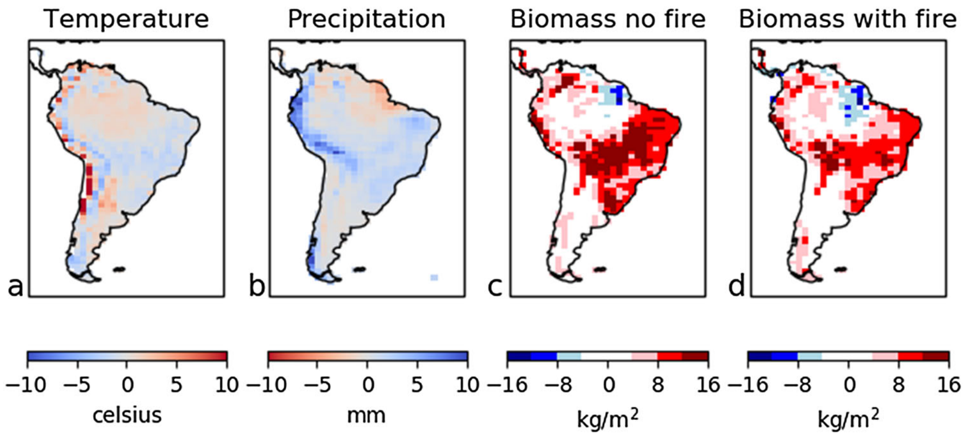

FIGURE 3 Present day modelled bias (against observations) in temperature (CRU, 1980–2013), precipitation (CMAP, 1980–2013), and biomass (Global Carbon, 1996–2005) with and without fire for South America

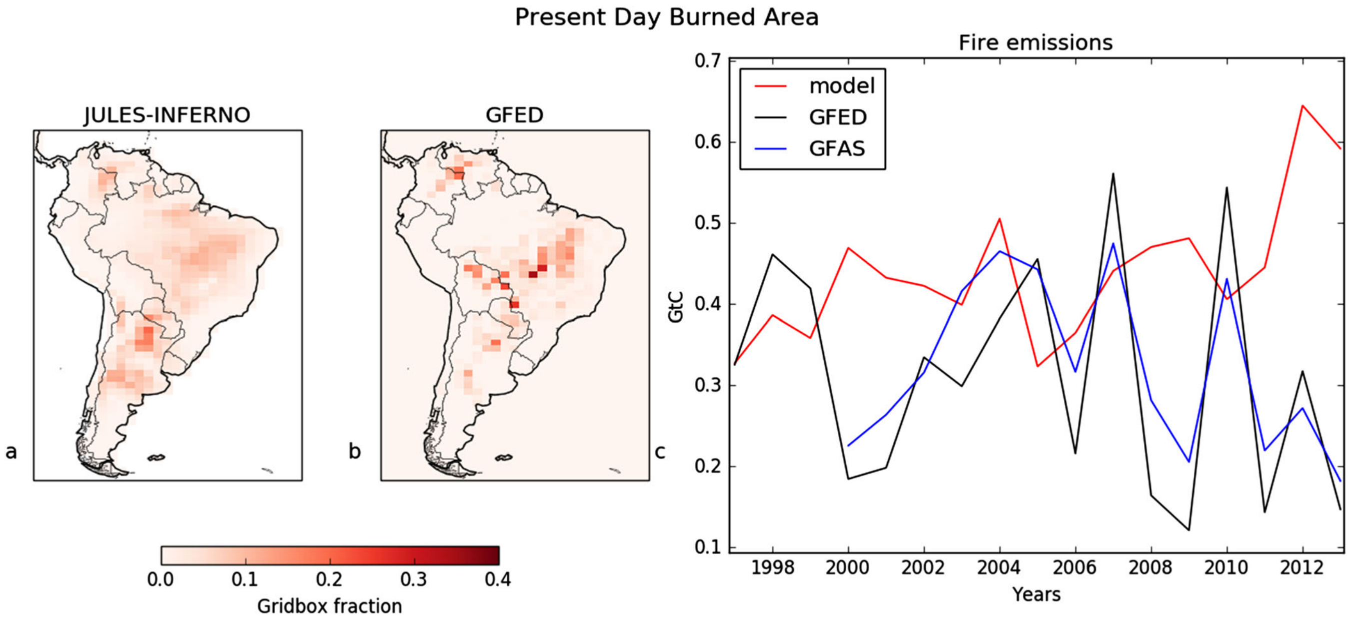

FIGURE 4 Maps of burned area fraction at present day (1997–2013) modelled by (a) JULES-INFERNO and from (b) GFED4.1s observations. (c) Time series of present day (1997–2013) carbon emissions from fire as modelled by JULES-INFERNO (red), and from GFED4.1s observations (black) and GFAS observations (blue, 2000–2013) for South America

vegetation carbon compared to present day. There is a slight decline in the observed emissions trend from GFED and GFAS, except for peaks in 2007 and 2010 which have been linked to deforestation across the Amazon (Morton et al., 2008), and drought driven by the Atlantic Multidecadal Oscillation (Chen et al., 2011) and a tropical North Atlantic warming anomaly (Marengo & Espinoza, 2016) respectively (Figure 4c). The decline has been shown to be unrelated to climate (Kelley et al., 2020), and is likely driven by strict land-use change policies implemented after 2004 that curbed deforestation and associated fires across Brazil (Aguiar et al., 2016; Aragão et al., 2018), which are not fully captured in the current version of the model. Instead, without the influence of land-use policy, emissions are simulated to increase over the period driven by climate and population trends.

Overall, burned area and emissions are reasonably well represented by JULES-INFERNO, and the simulation of vegetation carbon and LAI is improved in the present day by the addition of fire (Table 2), showing the model is fit for purpose for use in this study. Globally, JULES-INFERNO performs very well in all measures (See Table S3, Supporting Information). The dry bias in NE Brazil should be noted, however this is mitigated to some extent by assessing change in GWLs from present-day in the results presented herein.

TABLE 2 Benchmarking scores for South America using NME3. Lower scores from the simulation signifies better performance. Colours indicate how many null models the configuration outperforms: blue is for all; green is for all but one; yellow indicates only one; red indicates none

			Null models			JULES-INFERNO	
Comparison	**Observations**	**Time period**	**Median**	**Mean**	**Randomly resampled**	**Fire-Off**	**Fire-On**
Tree cover	CCI	2010	0.53	0.53	0.68 +/− 0.024	0.45	0.41
Wood cover	VCF	2002–2012	0.54	0.55	0.7 +/− 0.02	0.50	0.43
	CCI	2010	0.49	0.49	0.64 +/− 0.018	0.38	0.37
Vegetation carbon	Avitabile et al., 2016		1.00	1.00	1.26 +/− 0.018	0.86	0.79
LAI	MODIS	2002–2012	1.00	1.00	1.33 +/− 0.039	0.79	0.74
	AVHRR	1997–2005	0.99	1.00	1.31 +/− 0.037	0.92	0.91
Spatial burned area	GFED4s	1997-2014	0.83	1	1.26 +/− 0.013	-	0.88
	GFED4	1997–2014	0.75	1	1.23 +/− 0.0024	-	0.92
	MODIS CCI	2000–2014	0.76	1	1.23 +/− 0.032	-	0.97
	MCD45	2001–2008	0.75	1	1.21 +/− 0.0043	-	0.88
	MERIS	2006–2009	0.74	1	1.2 +/− 0.042	-	1.02
Spatial trend in burned area	GFED4s	1997–2014	0.97	1	1.48 +/− 0.015	-	1.06
Spatial fire carbon emissions	GFAS	2000–2009	0.87	1	1.27 +/− 0.024	-	0.86
Spatial trend in fire carbon			0.96	1	1.37 +/− 0.023	-	0.99

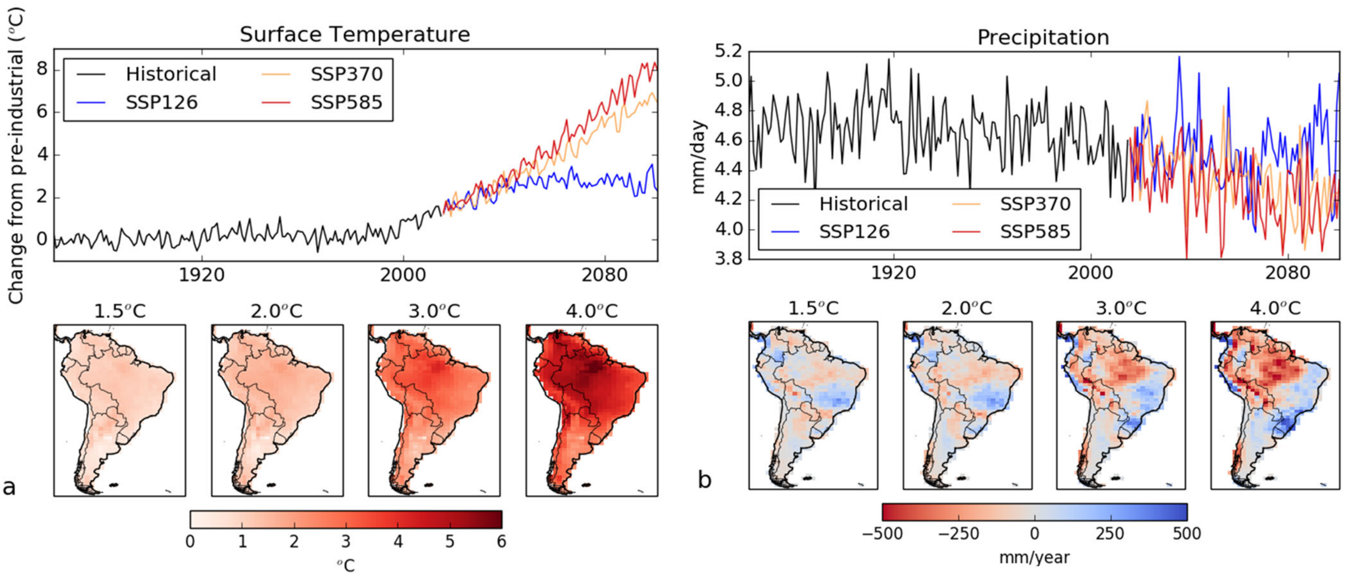

FIGURE 5 Top row: Modelled time series of (a) mean temperature (°C above pre-industrial 1860–1900) and (b) precipitation (mm day^{-1}) over South America. Bottom row: maps of change in (a) mean temperature (°C) and (b) precipitation (mm $year^{-1}$) above present day at four GWLs for SSP370

4 | RESULTS

4.1 | Climate drivers

UKESM projects a global temperature increase in all scenarios in the future in line with CO_2 (Figure 5a), although in SSP126 temperature stabilises by around 2040 and remains at around 2.0°C above pre-industrial. Warming is not homogeneous across the region, with higher rates of warming simulated in the centre and far north of the continent. South American precipitation generally declines in the future although with continued variability. In general there is greater drying in SSP585, followed by SSP370, and precipitation stays approximately the same as

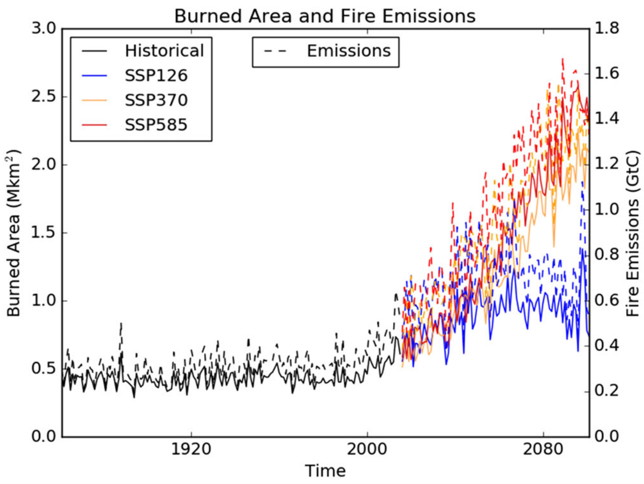

FIGURE 6 Time series of burned area (Mkm^2, solid line) and fire emissions (GtC, dashed line) for South America

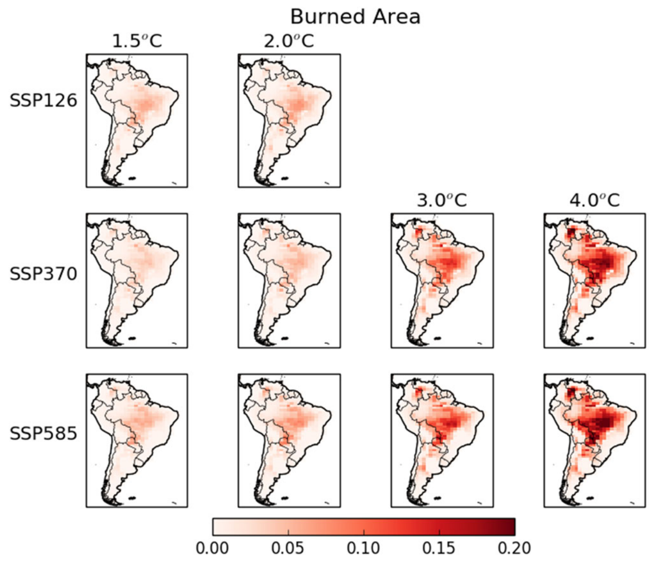

FIGURE 7 Change in burned area fraction compared to present day at four GWLs for SSP126 (top row), SSP370 (centre row) and SSP585 (bottom row) for South America

present-day SSP126 although with greater extremes (Figure 5b). In all scenarios, further drying is projected over the Amazon region and along the SW border of Brazil, with more intense drying in central Amazonia and across the northwest in SSP370. Conversely there is a trend towards increased precipitation for the south which also increases with the scenarios, although the change is smaller than the drying over the north.

4.2 | Burned area and fire emissions

Both burned area and fire emissions are projected to increase in the future (Figure 6), following a similar trend to increased temperature and decreased precipitation (Figure 5). SSP585 leads to a substantial rise in burned area and emissions by the end of the century, closely matched by SSP370 (Figure 6). The increase in SSP126 is more moderate, remaining stable for most of the latter half of the century, but with a potential increase towards the end of the century. Through the dynamic vegetation model, vegetation continues to regrow following disturbance, and faster growing PFTs such as grasses and shrubs can still be available to burn even in frequently disturbed areas. Burned area and emissions can therefore continue to increase, not just from the initial burning of forests but from continued annual burning of natural vegetation where climate conditions allow.

The increase in burned area is primarily centred across the southern Amazon, Cerrado, and northern Amazonia regions across all SSPs (Figure 7). At 1.5°C this mainly remains in the current region of burned area, increasing moderately compared to present day, but at higher GWLs the burned area expands and the burned fraction increases right across the southern Amazon, the Pantanal, and into Columbia and Venezuela. The impacts of each scenario overlap initially (e.g., see Figures 5 and 6); it is only towards the middle of the century when very distinct differences between the pathways emerge and at this point the anomalies compared to present day are larger than the differences between the scenarios at the same GWLs. At lower GWLs, burned area increases more in SSP126 and SSP585 than SSP370, although at higher temperatures the difference is minimal. Differences between scenarios at the same GWL may be caused by the variance in timing at which each GWL is reached, or the assumptions made in each scenario for example around land-use.

4.3 | Vegetation impacts

In present day, observed vegetation cover across South America is mainly a mixture of trees and grasses (Figure 8a). In the model, tree fraction decreases with warming level, and at higher levels of burned area some tree cover is replaced by grasses and a small increase in agriculture (Figure 8). There is also a slight reduction of vegetation at higher levels of precipitation, indicating a shift towards more drying.

Over the historical period, vegetation carbon levels remain quite stable over the 1800s/early 1900s, but start to decline after 1920 when land-use change starts to increase (Figure 9a). Considering the change over the 21st century, in all scenarios vegetation carbon decreases from present day. When fire is not represented in the model, vegetation carbon is higher in the historical period, and

Climate Resilience and Sustainability
Interdisciplinary Approaches Towards Solutions for Climate Change
Open Access
RMetS

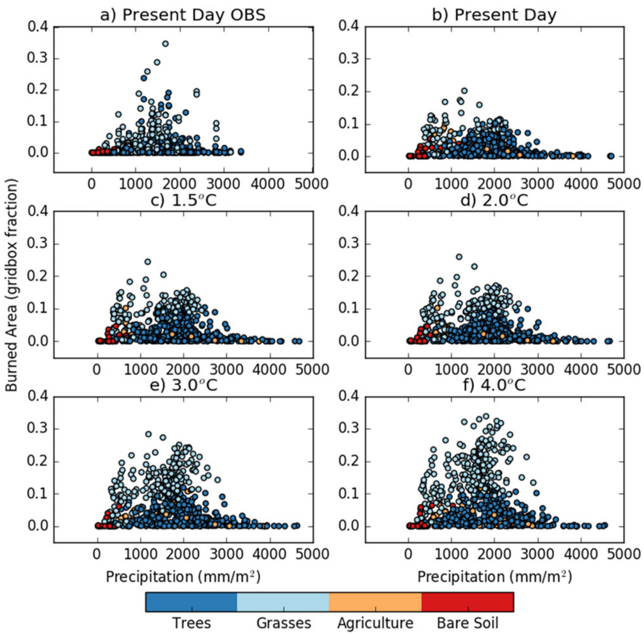

FIGURE 8 Dominant land cover types over South America categorised into trees, grasses and shrubs, agriculture (crop and pasture), and bare soil, shown according to precipitation and burned area for (a) observed present day, and (b) modelled present day, (c) 1.5°C, (d) 2.0°C (e) 3.0°C and (f) 4.0°C for SSP370 (20 year mean, each dot is a gridpoint for each land cover type). Observations used are the same as those for Figures 3 (precip) and 4 (burned area), and ESA CCI, 2010 land cover

declines in the future in line with the SSP scenarios with an initial stronger decline in SSP585, a steady decline in SSP370 and a slight increase before declining in SSP126 (Figure 9a). However by the end of the century vegetation carbon is approximately the same in all SSP scenarios (around 200GtC), and slightly higher in SSP585 as CO_2 fertilisation mitigates the loss of carbon and land-use change starts to decline (Figure 2), enabling carbon levels to begin to recover. When fire is included, the trends shift to much sharper declines in all scenarios, and importantly the CO_2 fertilisation in higher emissions scenarios does not mitigate the additional carbon loss as a result of the increase in fire. There is a much larger difference between the scenarios, which increases over the century to around 40GtC by 2100. Spatially, the loss of carbon without fire is focused mainly in southeast Brazil over the Atlantic Forest, resulting from land-use change (Figure 4), although there is some loss over central Amazonia in higher GWLs (Figure 9b). The substantial carbon loss simulated at higher GWLs across Amazonia, the Cerrado and the Pantanal are therefore almost entirely due to changes in burned area and fire feedbacks, which have not previously been represented in the model.

Productivity is also lower when fire is accounted for, although the difference over the historical period is minimal at around 0.9GtC on average (Figure 10a). Future projections however show a large difference when fire is included; the increase in productivity seen in SSP585 and SSP370 without fire over the 21st century (approximately 10GtC and 7GtC respectively) due to increased CO_2 is counteracted by the increase in fire, so that all scenarios remain at approximately the same level of Gross Primary Production (GPP) in the future with fire. With fire, soil carbon increases over the historical period, and continues to increase in SSP126 contrary to fire-off, as uncombusted vegetation is added to the soil pools. Carbon levels drop steeply in SSP585 and SSP370 however, with the trend staying the same for fire-on and fire-off.

There is an overall decrease in total annual precipitation over South America in the future, with greater reductions of up to 7% at higher GWLs (Figure 11a). Evapotranspiration (ET) mostly decreases with GWL as well, with the highest reduction with fire of around 7% at 4°C in SSP585 (Figure 11b). Limiting temperature rise to 1.5°C reduces the impacts to a 1–2% reduction in ET. In all scenarios, burned area increases with warming in the future, with increases of over 150% simulated at GWL of 4°C. Due to the warming, drying and additional feedbacks with fire, vegetation carbon also reduces with GWLs, with 27% reduction projected in SSP370, and 30% in SSP585 at 4°C. Limiting temperature rise to 1.5°C can reduce vegetation loss to less than 10% (7% in SSP126, 8% in SSP370 and 9% SSP585).

5 | DISCUSSION

In this paper we have posed a specific policy-relevant question: how much fire-induced carbon loss will there be over South America at different global warming levels in the future? Using our most advanced representation of the Earth system to date, we have shown that burned area is projected to increase in the future with GWLs in all SSP scenarios, driven by an increase in temperature and decrease in moisture availability. This results in substantial vegetation carbon loss across the continent, including Amazonia, the boundary with the Cerrado, and the Pantanal. Together with land-use change further south, loss of vegetation carbon is projected to be up to 30% in the highest emission scenario at 4°C of warming, but could be limited to 7% if temperatures are kept to 1.5°C above PI in lower emission scenarios. The feedbacks with fire play an important role in how ecosystems will respond to future change, where increased fire activity diminishes any benefit of CO_2 fertilisation in higher emissions scenarios, leading to a shift from a forest-dominated ecosystem to more grasses and shrubs.

Many models, including UKESM1, do not yet fully represent fire processes, and the results here show that the

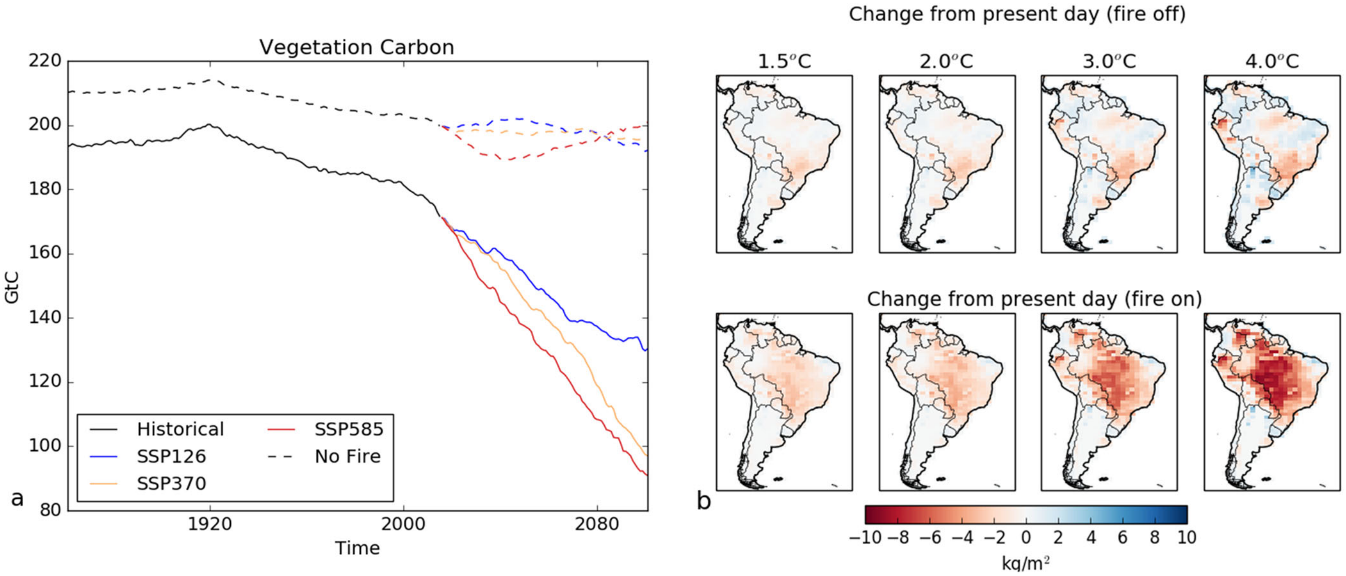

FIGURE 9 (a) Time series of vegetation carbon (GtC) with (solid lines) and without (dashed lines) fire. (b) Maps of vegetation carbon change from present day at 4 GWLs (kg m^{-2}) with fire off (top row) and fire on (bottom row) for SSP370 for South America

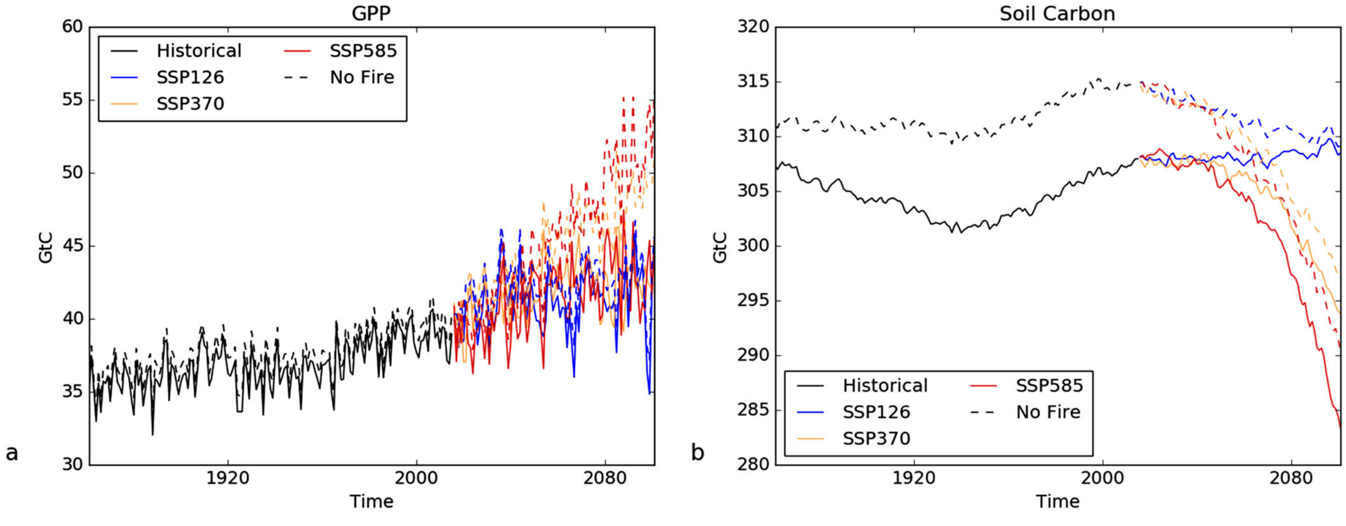

FIGURE 10 Time series of (a) GPP and (b) soil carbon (GtC) with fire (solid lines) and without fire (dashed lines) for South America

impacts of changes in climate and land-use on fire and vegetation could lead to large carbon losses in the future that may not be fully accounted for. Drought and increased temperatures can lead to more fires, and together with deforestation and edge effects can create a positive feedback from reduced evapotranspiration (Lovejoy & Nobre, 2018; Silva Junior et al., 2020). Although additional feedbacks on to the climate are not represented here, the further reduction in ET resulting from the fire-vegetation coupling suggests that there could be enhanced drying in this region when fire is coupled to the atmosphere. This is of particular concern over Amazonia, where ET and moisture recycling is a significant source of precipitation (Spracklen et al., 2012).

Multiple opposing factors act to both increase and decrease vegetation cover, type and carbon content across the SSP scenarios in the future. CO_2 fertilisation promotes vegetation growth, especially in the higher emissions scenarios, whereas land-use change and fire decrease vegetation cover, and high levels of warming and drying can also increase mortality particularly in drought-sensitive vegetation. Climate projections unanimously show that temperatures will increase in the future with continued emissions of greenhouse gases. There is much higher uncertainty around future projections of rainfall, and this can be an important driver in how burned area is projected to change in the future. Here we have considered one model outcome of future climate; future studies could include an

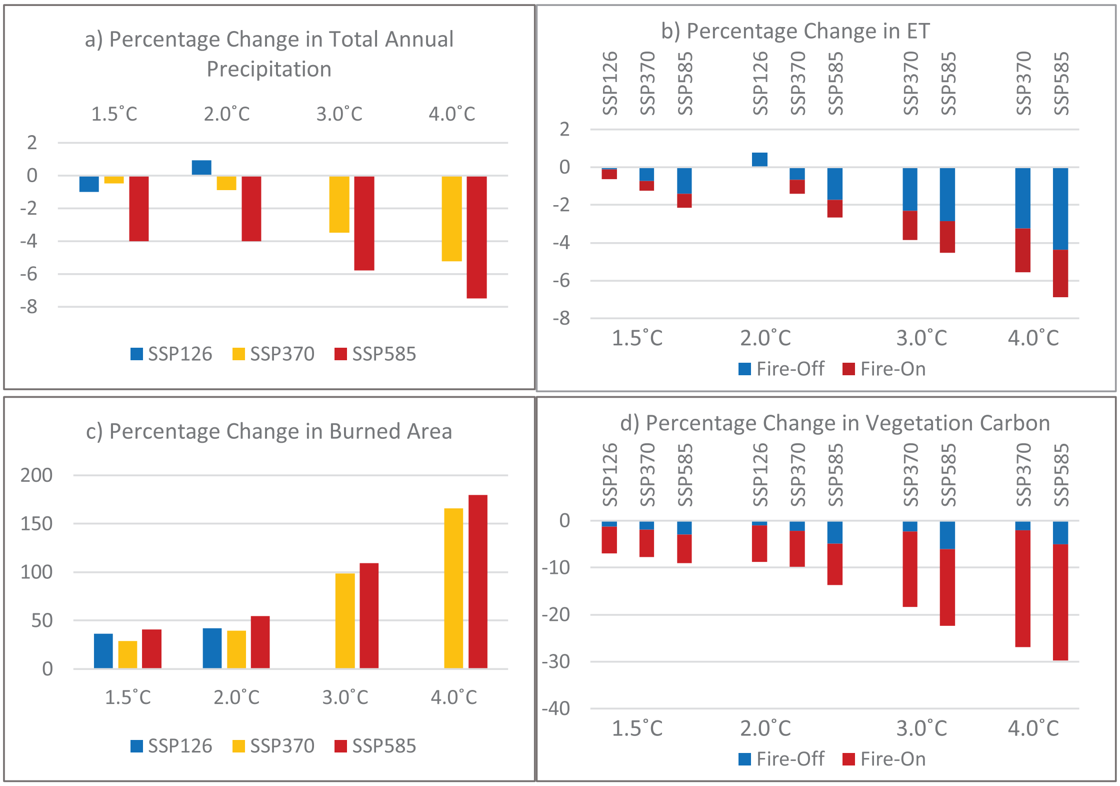

FIGURE 11 Summary of percentage change from present day for South America for (a) total annual precipitation, (b) evapotranspiration (ET), (c) burned area and (d) vegetation carbon for three SSP scenarios and four GWLs. ET and vegetation carbon show changes with fire on and fire off

assessment of uncertainty by considering the projected range across a number of ESMs. We also note that our results only represent one fire model within a range of available representations and parameterisations of fire (Andela et al., 2017; Rabin et al., 2017), and further studies could address the uncertainty across a range of fire models. However, as climate models start to include more complexity such as the representation of physiological processes and the nitrogen cycle, there is a stronger consensus across CMIP5 and CMIP6 towards future drying over NE South America (Chadwick et al., 2016; Parsons, 2020). UKESM1 results are in line with the model means across these multi-model studies, giving confidence in the simulations that have been used in this study.

Through the model evaluation, we identified a particular area of drying over NE Brazil in UKESM1 in the present day, which impacts the simulation of burned area and vegetation (Figures 3 and 4). A number of other ESMs also show a dry bias in this region (Parsons, 2020). Ongoing work to understand this bias in UKESM1 has suggested a number of possible contributing factors, including a bias in the representation of SSTs, the prescribed extent of lake-fraction over the Amazon river being too large and inundation too small, and soils being too shallow in the land surface model, leading to higher water stress in the vegetation than observed. In future studies it could be useful to address this through a standard bias correction method, such as that employed by ISIMIP (the Inter-Sectoral Impact Model Intercomparison project, Lange, 2019). We have moderated the impact of this bias in our results by considering the change at specific GWLs compared to present day. Given the uncertain nature of current vegetation-fire modelling, we propose this as a template for identifying policy-relevant questions that fire models have the ability to answer now.

With recent developments of the representation of fire in JULES-INFERNO, we can now account for the reduction of fire in cropland areas, based on global trends identified in studies such as Bistinas et al. (2014), and Kelley et al. (2019), and varying mortality across different PFTs. Like most fire models, ignitions are also based on global-scale relationships of population density (Hantson et al., 2016), developed by early fire modelling studies (e.g., Mangeon et al., 2016; Venevsky et al., 2002). However, these global-scale trends have not been parameterised on regional scales for different biomes, and more information is needed at local scales to improve the representation of mortality, links with land-use change, and the role of anthropogenic ignitions for South American ecosystems. Ignitions in this region for example, may be better linked with escaped fire from deforestation activity (Cano-Crespo et al., 2015) or distance to roads (Cardoso et al., 2003) than with population density. In this study we used present day population and lightning ignition for the future scenarios. Further work could look at how population levels are projected to change and what impact this could have on fire, which could tie in with further development work around the representation of ignitions for this region.

As fire-vegetation feedbacks are not currently represented in UKESM1, we have used the capability of the offline land surface component here to model the feedbacks between burned area and dynamic vegetation. We have shown that the representation of fire is an important factor in future ecosystem resilience, and higher levels of warming beyond the Paris agreements 1.5°C and 2°C targets could lead to further fire-induced carbon loss. Similar studies across a number of land-surface and fire models in the future could help to reduce the uncertainty in future projections of fire and the impacts on global ecosystems.

6 | CONCLUSIONS

In this paper we have shown that under high warming, high emissions scenarios, additional feedbacks from increased fire over South America in the future could lead to significant loss of tree cover, vegetation carbon and productivity. Climate model output projects increasing warming and drying over South America over the 21st century, especially under high emissions scenarios, but this could stabilise under stringent mitigation efforts. Changes in climate drive large impacts on regional ecosystems, with fire-vegetation feedbacks being an important mechanism that is not currently represented in many ESMs including UKESM1. Through an assessment of these additional processes, we find large increases in future burned area which drives significant losses in tree cover, productivity and carbon stores. Changes in vegetation cover are also driven by future land-use and GWL, which has important implications for local fire and land management policies as well as global-scale climate action.

Our results suggest that the resilience of ecosystems across the region could be undermined by increased temperature, drying, land-use and burned area. There is a potential for a 30% loss of vegetation carbon if global warming reaches 4°C by the end of the century. However, keeping temperatures to the Paris Agreements target of 1.5°C can help reduce the worst impacts, keeping vegetation carbon losses to 7%. This study adds to our understanding of future fire impacts for this region, and what this could mean for these globally-important ecosystems.

ACKNOWLEDGEMENTS

The UKESM data used to drive JULES in the simulations used in this paper were produced by Richard Ellis and Alistair Sellar. The authors would like to sincerely thank Richard and Alistair for their significant contribution to UKESM1, and for their kind permission to use these datasets in this study. The authors would also like to thank Karina Williams for her help and advice in processing the driving data for JULES. This work and its contributors (Chantelle Burton, Richard A. Betts, and Chris D. Jones) were supported by the Newton Fund through the Met Office Climate Science for Service Partnership Brazil (CSSP Brazil). The contribution by Douglas I. Kelley was supported by the UK Natural Environment Research Council through The UK Earth System Modelling Project (UKESM, grant no. NE/N017951/1). Manoel Cardoso acknowledges the support from the São Paulo Research Foundation (FAPESP, Processes 2015/50122-0 and 2017/22269-2), and the Brazilian National Council for Scientific and Technological Development (CNPq, Process 314016/2009-0). Liana Anderson acknowledges the support from the São Paulo Research Foundation (FAPESP, Process 2016/02018-2), the Brazilian National Council for Scientific and Technological Development (CNPq, Process 442650/2018-3, and 309247/2016-0), and Inter-American Institute for Global Change Research (IAI), process: SGP-HW 016.

REFERENCES

Aguiar, A., Vieira, I., Assis, T., Dalla-Nora, E., Toledo, P., Santos-Junior, R., et al. (2016) Land-use change emission scenarios: Anticipating a forest transition process in the Brazilian Amazon. *Global Change Biology*, 22, 1821–1840. Available from: https://doi.org/10.1111/gcb.13134

Andela, N., Morton, D., Giglio, L., Chen, Y., van der Werf, G., Kasibhatla, P., et al. (2017) A human-driven decline in global burned area. *Science*, 356, 1356–1361.

Anderson, L., Aragão, L., Gloor, M., Arai, E., Adami, M., Saatchi, S., et al. (2015) Disentangling the contribution of multiple land covers to fire-mediated carbon emissions in Amazonia during the 2010 drought. *Global Biogeochemical Cycles*, 29, 1739–1753. Available from: https://doi.org/10.1002/2014GB005008

Aragão, L.E.O.C., Anderson, L.O., Fonseca, M.G., Rosan, T.M., Vedovato, L.B., Wagner, F.H., et al. (2018) 21st century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature Communications*, 9, 536.

Arneth, A., Harrison, S., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P.J., et al. (2010) Terrestrial biogeochemical feedbacks in the climate system. *Nature Geosci*, 3, 525–532. Available from: https://doi.org/10.1038/ngeo905

Armenteras, D., González, T.M. & Retana, J. (2013) Forest fragmentation and edge influence on fire occurrence and intensity under different management types in Amazon forests. *Biological Conservation*, 159, 73–79. Available from: https://doi.org/10.1016/j.biocon.2012.10.026

Avitabile, V., Herold, M., Heuvelink, G.B.M., Lewis, S.L., Phillips, O.L., Asner, G.P., et al. (2016) An integrated pan-tropical biomass map using multiple reference datasets. *Glob Change Biology*, 22, 1406–1420. Available from: https://doi.org/10.1111/gcb.13139

Best, M., Pryor, M., Clark, D., Rooney, G., Essery, R., Menard, C., et al. (2011) The Joint UK Land Environment Simulator (JULES), model description—Part 1: Energy and water fluxes. *Geoscientific Model Development*, 4, 677–699.

Betts, R.A., Golding, N., Gonzalez, P., Gornall, J., Kahana, R., Kay, G., et al. (2015) Climate and land-use change impacts on global terrestrial ecosystems and river flows in the HadGEM2-ES Earth system model using the representative concentration pathways. *Biogeosciences*, 12, 1317–1338.

Betts, R.A., Malhi, Y. & Roberts, J.T. (2008) The future of the Amazon: New perspectives from climate, ecosystem and social sciences. *Philosophical Transactions of the Royal Society B-Biological Sciences*, 363, 1729–1735.

Bistinas, I., Harrison, S.P., Prentice, I.C. & Pereira, J.M.C. (2014) Causal relationships versus emergent patterns in the global controls of fire frequency. *Biogeosciences*, 11, 5087–5101. Available from: https://doi.org/10.5194/bg-11-5087-2014.

Boer, M.M., Resco de Dios, V. & Bradstock, R.A. (2020) Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, 10, 171–172. Available from: https://doi.org/10.1038/s41558-020-0716-1

Brando, P.M., Balch, J., Nepstad, D., Morton, D., Putz, F., Coe, M., et al. (2014) Abrupt Amazonian tree mortality. *Proceedings of the National Academy of Sciences*, 111(17), 6347–6352. Available from: https://doi.org/10.1073/pnas.1305499111

Burton, C., Betts, R., Cardoso, M., Feldpausch, T.R., Harper, A., Jones, C.D., et al. (2019) Representation of fire, land-use change and vegetation dynamics in the Joint UK Land Environment Simulator vn4.9 (JULES). *Geosci. Model Dev.*, 12, 179–193. Available from: https://doi.org/10.5194/gmd-12-179-2019.

Burton, C., Betts, R.A., Jones, C.D., Feldpausch, T.R., Cardoso, M. & LO, A. (2020) El Niño driven changes in global fire 2015/16. *Front. Earth Sci.*, 8, 199. Available from: https://doi.org/10.3389/feart.2020.00199

Cano-Crespo, A., Oliveira, P.J.C., Boit, A., Cardoso, M. & Thonicke, K. (2015) Forest edge burning in the Brazilian Amazon promoted by escaping fires from managed pastures. *Journal of Geophysical Research, Biogeosciences*, 120, 2095–2107. Available from: https://doi.org/10.1002/2015JG002914.

Cardoso, M., Hurtt, G., Moore, B., Nobre, C. & Prins, E. (2003) Projecting future fire activity in Amazonia. *Global Change Biology*, 9, 656–669.

Castanho, A.D., Galbraith, D., Zhang, K., Coe, M.T., Costa, M.H. & Moorcroft, P. (2016) Changing Amazon biomass and the role of atmospheric CO2 concentration, climate, and land use. *Global Biogeochemical Cycles*, 30, 18–39. Available from: https://doi.org/10.1002/2015GB005135.

Chadwick, R., Douville, H. & Skinner, C.B. (2017) Timeslice experiments for understanding regional climate projections: Applications to the tropical hydrological cycle and European winter circulation. *Climate Dynamics*, 49, 3011–3029. Available from: https://doi.org/10.1007/s00382-016-3488-6

Chadwick, R., Good, P., Martin, G. & Rowell, D.P. (2016) Large rainfall changes consistently projected over substantial areas of tropical land. *Nature Climate Change*, 6, 177–181.

Chen, Y., Randerson, J.T., Morton, D.C., DeFries, R.S., Collatz, G.J., Kasibhatla, P.S., et al. (2011) Forecasting fire season severity in South America using sea surface temperature anomalies. *Science*, 334, 787–791

Christian, H.J., Blakeslee, R.J., Boccippio, D.J., Boeck, W.L., Buechler, D.E., Driscoll, K.T., et al. (2003) Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *J. Geophys. Res.-Atmos.*, 108, 4005. Available from: https://doi.org/10.1029/2002JD002347

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., et al. (2013) *Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, T. F., D. Qin, G. - K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (eds.)]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Clark, D., Mercado, L., Sitch, S., Jones, C., Gedney, N., Best, M., et al. (2011) The Joint UK Land Environment Simulator (JULES), model description - Part 2: Carbon fluxes and vegetation dynamics. *Geoscientific Model Development*, 4, 701–722.

Cox, P.M. (2001) Description of the "TRIFFID" Dynamic Global Vegetation Model, Tech. Note 24. Bracknell, UK: Hadley Centre, Met Office, p. 16.

Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A. & Totterdell, I.J. (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, 408, 184–187

ESA CCI (2010) Climate change initiative: Land cover map. Available at: https://maps.elie.ucl.ac.be/CCI/viewer/ [Accessed 4th January 2019].

Fonseca, M.G., Alves, L.M., Aguiar, A.P.D., Arai, E., Anderson, L.O., Rosan, T.M., et al. (2019) Effects of climate and land-use change scenarios on fire probability during the 21st century in the Brazilian Amazon. *Global Change Biology*, 25, 2931–2946. Available from: https://doi.org/10.1111/gcb.14709

Hantson, S., Arneth, A., Harrison, S., Kelley, D., Prentice, I., Rabin, S., et al. (2016) The status and challenge of global fire modelling. *Biogeosciences*, 13, 3359–3375.

Hantson, S., Kelley, D.I., Arneth, A., Harrison, S.P., Archibald, S., Bachelet, D., et al. (2020) Quantitative assessment of fire and vegetation properties in simulations with fire-enabled vegetation models from the Fire Model Intercomparison Project. *Geoscientific Model Development*, 13, 3299–3318. Available from: https://doi.org/10.5194/gmd-13-3299-2020.

Higuera, P.E. & Abatzoglou, J.T. (2020) Record-setting climate enabled the extraordinary 2020 fire season in the western United States. *Glob Change Biol*. 27, 1–2. Available from: https://doi.org/10.1111/gcb.15388

Hurtt, G.C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B.L., Calvin, K., et al. (2020) Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6. *Geoscientific Model Development*, 13, 5425–5464. Available from: https://doi.org/10.5194/gmd-13-5425-2020.

Joetzjer, E., Douville, H., Delire, C. & Ciais, P. (2013) Present-day and future Amazonian precipitation in global climate models: CMIP5 versus CMIP3. *Climate Dynamics*, 41, 2921. Available from: https://doi.org/10.1007/s00382-012-1644-1

Jolly, M., Cochrane, M., Freeborn, P., Holden, Z., Brown, T., Williamson, G., et al. (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, 6, 7537. Available from: https://doi.org/10.1038/ncomms8537

Keenan, R.J. (2015) Climate change impacts and adaptation in forest management: A review. *Annals of Forest Science*, 72, 145–167.

Kelley, D.I., Bistinas, I., Whitley, R., Burton, C., Marthews, T.R. & Dong, N. (2019) How contemporary bioclimatic and human controls change global fire regimes. *Nature Climate Change*, 9(9), 690–696.

Kelley, D.I. & Harrison, S.P. (2014) Enhanced Australian carbon sink despite increased wildfire during the 21st century. *Environmental Research Letters*, 9, 104015.

Kelley, D.I., Prentice, I.C., Harrison, S.P., Wang, H., Simard, M., Fisher, J.B., et al. (2013) A comprehensive benchmarking system for evaluating global vegetation models. *Biogeosciences*, 10, 3313–3340. Available from: https://doi.org/10.5194/bg-10-3313-2013.

Kelley, D., Burton, C., Huntingford, C., Brown, M., Whitley, R. & Dong, N. (2020) Technical note: Low meteorlogical influence found in 2019 Amazonia fires. *Biogeosciences*, 18, 787–804.

Kent, C., Chadwick, R. & Rowell, D.P. (2015) Understanding uncertainties in future projections of seasonal tropical precipitation. *J. Climate*, 28, 4390–4413. Available from: https://doi.org/10.1175/JCLI-D-14-00613.1

Klein Goldewijk, K., Beusen, A., Doelman, J. & Stehfest, E. (2017a) Anthropogenic land use estimates for the Holocene – HYDE 3.2. *Earth Syst. Sci. Data*, 9, 927–953. Available from: https://doi.org/10.5194/essd-9-927-2017.

Klein Goldewijk, K., Dekker, S.C. & van Zanden, J.L. (2017b) Per-capita estimations of long-term historical land use and the consequences for global change research. *Journal of Land Use Science*, 12, 313–337. Available from: https://doi.org/10.1080/1747423X.2017.1354938.

Kloster, S. & Lasslop, G. (2017) Historical and future fire occurrence (1850 to 2100) simulated in CMIP5 Earth System Models. *Global and Planetary Change*, 150, 58–69. Available from: https://doi.org/10.1016/j.gloplacha.2016.12.017

Kloster, S., Mahowald, N.M., Randerson, J.T. & Lawrence, P.J. (2012) The impacts of climate, land use, and demography on fires during the 21st century simulated by CLM-CN. *Biogeosciences*, 9, 509–525. Available from: https://doi.org/10.5194/bg-9-509-2012.

Lange, S. (2019) Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). *Geoscientific Model Development*, 12(7), 3055–3070. Available from: https://doi.org/10.5194/gmd12-3055-2019.

Le Page, Y., Morton, D., Hartin, C., Bond-Lamberty, B., Pereira, J., Hurtt, G., et al. (2017) Synergy between land-use and climate change increases future fire risk in Amazon forests. *Earth System Dynamics*, 8, 1237–1246.

Le Page, Y., van der Werf, G.R., Morton, D.C. & Pereira, J.M.C. (2010) Modeling fire-driven deforestation potential in Amazonia under current and projected climate conditions. *Journal of Geophysical Research, Biogeosciences*, 115, G03012.

Liu, Y., Stanturf, J.A.,& & Goodrick, S.L. (2010) Trends in global wildfire potential in a changing climate. *Forest Ecology and Management*, 259, 685–69. Available from: https://doi.org/10.1016/j.foreco.2009.09.002

Lizundia-Loiola, J., Pettinari, M.L. & Chuvieco, E. (2020) Temporal anomalies in burned area trends: Satellite estimations of the Amazonian 2019 fire crisis. *Remote Sensing*, 12(1), 151.

Lovejoy, T.E. & Nobre, C. (2018) Amazon Tipping Point. *Science Advances*, 4, eaat2340. Available from: https://doi.org/10.1126/sciadv.aat2340

Malhi, Y., Aragão, L., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., et al. (2009) Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, 106(49), 20610–20615. Available from: https://doi.org/10.1073/pnas.0804619106

Malhi, Y., Roberts, J.T., Betts, R.A., Killeen, T.J., Li, W. & Nobre, C.A. (2008) Climate Change, Deforestation, and the Fate of the Amazon. *Science*, 319(5860), 169–172. Available from: https://doi.org/10.1126/science.1146961

Mangeon, S., Voulgarakis, A., Gilham, R., Harper, A., Sitch, S. & Folberth, G. (2016) INFERNO: A fire and emissions scheme for the UK Met Office's Unified Model. *Geoscientific Model Development*, 9, 2685–2700. Available from: https://doi.org/10.5194/gmd-9-2685-2016.

Marengo, J.A. & Espinoza, J.C. (2016) Extreme seasonal droughts and floods in Amazonia: Causes, trends and impacts: EXTREMES IN AMAZONIA. *International Journal of Climatology*, 36(3), 1033–1050.

Mega, E. (2020) 'Apocalyptic' fires are ravaging the world's largest tropical wetland. *Nature*, 586, 20–21. Available from: https://doi.org/10.1038/d41586-020-02716-4

Moritz, M., Parisien, M., Batllori, E., Krawchuk, M., Van Dorn, J., Ganz, D., et al. (2012) Climate change and disruptions to global fire activity. *Ecosphere*, 3, 1–22.

Morton, D.C., Defries, R.S., Randerson, J.T., Giglio, L., Schroeder, W. & Van Der Werf, G.R. (2008) Agricultural intensification increases deforestation fire activity in Amazonia. *Global Change Biology*, 14(10), 2262–2275.

O'Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., et al. (2016) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9, 3461–3482. Available from: https://doi.org/10.5194/gmd-9-3461-2016.

Parsons, L.A. (2020) Implications of CMIP6 projected drying trends for 21st century Amazonian drought risk. *Earth's Future*, 8, e2020EF001608. Available from: https://doi.org/10.1029/2020EF001608

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., et al. (2017) Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, 42, 331–345.

Rabin, S.S., Melton, J.R., Lasslop, G., Bachelet, D., Forrest, M., Hantson, S., et al. (2017) The Fire Modeling Intercomparison Project (FireMIP), phase 1: Experimental and analytical protocols with detailed model descriptions. *Geoscientific Model Development*, 10, 1175–1197. Available from: https://doi.org/10.5194/gmd-10-1175-2017.

Ratter, J.A., Ribeiro, J.F. & Bridgewater, S. (1997) The Brazilian Cerrado vegetation and threats to its biodiversity. *Annals of Botany*, 80(3), 223–230. Available from: https://doi.org/10.1006/anbo.1997.0469

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., et al. (2017) The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153–168. Available from: https://doi.org/10.1016/j.gloenvcha.2016.0

Richardson, T.B., Forster, P.M., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., et al. (2018) Carbon dioxide physiological forcing dominates projected eastern Amazonian drying. *Geophysical Research Letters*, 45, 2815–2825. Available from: https://doi.org/10.1002/2017GL076520

Sellar, A.A., Jones, C.G., Mulcahy, J.P., Tang, Y., Yool, A., Wiltshire, A., et al. (2019) UKESM1: Description and evaluation of the U.K. Earth System Model. *Journal of Advances in Modeling Earth Systems*, 11, 4513–4558. Available from: https://doi.org/10.1029/2019MS001739

Senior, C.A., Andrews, T., Burton, C., Chadwick, R., Copsey, D., Graham, T., et al. (2016) Idealized climate change simulations with a high-resolution physical model: HadGEM3-GC2. *J. Adv. Model. Earth Syst.*, 8, 813–830. Available from: https://doi.org/10.1002/2015MS000614.

Settele, J., Scholes, R., Betts, R., Bunn, S., Leadley, P., Nepstad, D., et al. (2014) Terrestrial and inland water systems. In: Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P.R. Mastrandrea, & L. L. White (Eds.) *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, pp. 271–359.

Silva Junior, A., Aragão, L., Anderson, A., Fonseca, M., Shimabukuro, Y., Vancutsem, C., et al. (2020) Persistent collapse of biomass in Amazonian forest edges following deforestation leads to unaccounted carbon losses. *Science Advances*, 6, 1–9. Available from: https://doi.org/10.1126/sciadv.aaz8360.

Spracklen, D., Arnold, S. & Taylor, C. (2012) Observations of increased tropical rainfall preceded by air passage over forests. *Nature*, 489, 282–285. Available from: https://doi.org/10.1038/nature11390

Staal, A., Fetzer, I., Wang-Erlandsson, L., Bosmans, J.H., Dekker, S.C., van Nes, E.H., et al. (2020) Hysteresis of tropical forests in the 21st century. *Nature Communications*, 11(1), 1–8.

Staver, A.C., Brando, P.M., Barlow, J., Morton, D.C., Paine, C.T., Malhi, Y., et al. (2020) Thinner bark increases sensitivity of wetter Amazonian tropical forests to fire. *Ecology Letters*, 23(1), 99–106.

van der Werf, G.R., Randerson, J.T., Giglio, L., van Leeuwen, T.T., Chen, Y., Rogers, B.M., et al. (2017) Global fire emissions estimates during 1997–2016. *Earth Syst. Sci. Data*, 9, 697–720. Available from: https://doi.org/10.5194/essd-9-697-2017.

Venevsky, S., Thonicke, K., Sitch, S. & Cramer, W. (2002) Simulating fire regimes in human-dominated ecosystems: Iberian Peninsula case study. *Global Change Biology*, 8, 984–998. Available from: https://doi.org/10.1046/j.1365-2486.2002.00528.x.

Witze, A. (2020) The Arctic is burning like never before — and that's bad news for climate change. *Nature News*, 585, 336–337. Available from: https://doi.org/10.1038/d41586-020-02568-y

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Burton, C., Kelley, D. I., Jones, C. D., Betts, R. A., Cardoso, M., & Anderson, L. (2021) South American fires and their impacts on ecosystems increase with continued emissions. *Climate Resil Sustain*, e8. https://doi.org/10.1002/cli2.8