The need for multifaceted approaches when dealing with the differing impacts of natural disasters and anthropocentric events on air quality

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Abstract

Air pollution associated health issues are increasing globally. This is due to both anthropogenic sources, such as traffic, and natural sources, such as bushfires. Natural disasters, such as bushfires, impact air quality by releasing large concentrations of pollutants affecting respiratory health. However, another recent global event has also had severe impacts on the environment and health, the global COVID-19 pandemic. Global pandemics, such as COVID-19, can also influence air quality by altering human activity, resulting in its own associated health impacts. This study aimed to investigate the impact of a natural disaster and global pandemic on outdoor ambient air pollution by quantifying and comparing the spatial distribution of two air pollutants, nitrogen dioxide (NO_2) and particulate matter (PM_{10}), during the different periods across the Greater Sydney region, Australia, while correcting for anthropogenic sources and meteorological influences such as temperature and rain. COVID-19 and bushfire affected periods were compared to a control period when both of these influences were absent. We found that NO_2 was significantly higher during the COVID-19 pandemic than during the control period and the recent 2019 bushfires. Conversely, PM_{10} was significantly lower during the COVID-19 pandemic than the bushfire and control periods. The spatial distribution of both pollutants and influencers also varied across the study site. These results suggest that both events markedly impacted air quality, although they impacted the air pollutants differently. These findings further demonstrate a greater need to understand the impact of natural disasters and anthropocentric events on air pollution as multifaceted, spatially relevant policies are required to address these events, particularly if they increase in frequency or severity in the future.

1. Introduction

Air pollution is increasing as emissions from anthropogenic sources, such as industry, transport, and agriculture, intensify (Shaddick et al. 2020). Reduced air quality has negative health consequences, and air pollution poses one of the most substantial risks to human health (Zalakeviciute et al. 2018). It is estimated that ambient air pollution kills more than 8.8 million people annually (3, 4) and this figure is expected to increase as 90% of the global population are exposed to air quality standards below the WHO Air Quality Guidelines (World Health Organisation 2016). Studies have shown that exposure to air pollutants, such as particulate matter with a diameter of less than 10µm (PM_{10}) and gaseous pollutants such as nitrogen dioxide (NO_2), are associated with respiratory and cardiovascular mortality (Cai et al. 2016, Li et al. 2017).

Natural sources of air pollution, such as bushfires, also have the ability to increase air pollution concentrations (Dong et al. 2020). An example of this was the 2019–2020 'Black Summer' Australian bushfire season, which was a period of abnormally severe bushfires throughout Australia, with New South Wales (NSW) being the worst affected state (BBC 2020). During these bushfires, Canberra and Sydney were considered to have the worst air quality of any city in the world (8, 9). Many sporting events and festivals were cancelled in Canberra and Sydney due to public health concerns (Boland &Sas 2020). Canberra experienced levels of $PM_{2.5}$ pollution that were approximately 100 times the levels considered safe (Australian Institute of Health Welfare 2020). Simultaneously, Sydney experienced periods where air pollution was approximately 11 times greater than the levels deemed hazardous to human health,, while experiencing hazardous levels of air pollution for at least 30 days during the bushfires (Morton 2019). These bushfires impacted air quality by releasing significant amounts of pollutants through the burning of vegetation, contributing an estimated 20% to NO_X emissions globally (Dong et al. 2020). Horsley *et al.* (2019) found bushfire smoke was positively correlated to asthma hospitalisations, while outdoor urban air pollution of NO_2 and PM has also been associated with greater hospital admissions for asthma and heart disease (Dean &Green 2018). Smoke from extreme bushfires has previously been proven to increase mortality rates (Bel &Holst 2018), with the 2019-2020 bushfire event causing an estimated 3151 cardio-respiratory hospitalisations and 417 premature deaths in eastern Australia alone (Jalaludin et al. 2020).

Months following the bushfires saw a significant decrease in anthropogenic activity due to the COVID-19 pandemic and associated lockdowns and travel restrictions. During March-May 2020, residents remained at home and in isolation unless necessary. Subsequently, there was a drastic decline in transport and other activities as restrictions were imposed by the Australian Government (Beck &Hensher 2020). Literature published early in the pandemic suggested more lives were saved by reducing air pollution-related mortality than deaths from COVID-19 (Dutheil et al. 2020, Isaifan 2020). Despite the global death toll from COVID-19 totalling over 650,000 at the time (World Health Organisation 2020a), the usual annual death toll associated with air pollution was 8.8 million (Burnett et al. 2018, Lelieveld et al. 2020, World Health Organisation 2020b, World Health Organization 2015). Simultaneously, NSW's COVID-19 death toll was only 56 from the first case in January until December 31st 2020 (Department of Health 2020), while premature deaths associated with air pollutants across Sydney have been estimated to be 643 – 1,446 annually (Parker 2006).

Vehicular emissions, such as particulate matter of different sizes ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NO_X) and sulfur dioxide (SO_2), normally contribute to 23% of air pollutants produced globally (Bel &Holst 2018, Shrestha et al. 2020). Thus traffic-related or road-based variables are commonly incorporated in spatial studies of air pollution (Douglas et al. 2019, Gilbert et al. 2005, Madsen et al. 2011, Ross et al. 2005, Ryan &LeMasters 2007). In particular, traffic count has been positively correlated with air pollutant concentrations, with Douglas *et al.* (2019) finding that traffic count was the strongest predictor for pollutant concentration variability for Sydney (Douglas et al. 2019). Kalisa *et al*. (2018) also found that both pollutants included in the current study increased in urban areas due to traffic congestion (Kalisa et al. 2018). Furthermore, in Sydney, approximately 71% of total NO_X emissions are caused by vehicles, and peak concentrations of NO_2 occur near busy roads (Cowie et al.

2016). Hence, traffic metrics need to be included in air quality studies for Sydney to ensure differences in traffic during the different periods do not influence other effects.

Meteorological conditions also have an effect on air pollutant concentrations and their impacts. Elminir (2005) found NO_2 increased with temperature and Li *et al.* (2017) found extremely high temperatures significantly increased cardiovascular mortality caused by PM_{10} (Elminir 2005, Li et al. 2017). Further, a recent study by Coker *et al.* (2020) examined the relationship between air pollution and COVID-19, and found a positive association between ambient $PM_{2.5}$ concentration and excess COVID-19 related mortality. Their study found a one μg/m^3 increase in $PM_{2.5}$ concentration was associated with a 9% increase in COVID-19 related mortality (Coker et al. 2020). Additionally, a positive relationship between air pollution and COVID-19 mortality was detected in Mexico City that increased with age and was mainly driven by long-term pollution exposure (López-Feldman et al. 2021).

Rainfall also has the potential to have significant effects on the concentrations of many atmospheric pollutants. Precipitation events can cause significant decreases in major air pollutants through wet scavenging and washout processes which remove the pollutants from the atmosphere (Yoo et al. 2014). For example, Kwak *et al.* (2017) revealed that PM_{10} concentrations decrease during rainfall, with the effect of rain washout being so great that it outweighs the increased traffic pollution from slower moving traffic during rain. Kwak *et al.* (2017) also found that the inverse of this washout relationship was true for NO_2, as the increase in traffic outweighed the washout effects by rain (Kwak et al. 2017). Thus, these were included as covariates in the current work to account for their potential influence on air quality and to correct for seasonal variance in meteorological effects.

This spatio-temporal study was conducted using a Geographic Information System (GIS) based method to ensure that variability in weather, traffic and air quality across Greater Sydney were accounted for. These methods have been found to be particularly useful when meteorological variables, such as rainfall or temperature, have high variability within a region (Yoo et al. 2014) or across a city (Zhang et al. 2011). Additionally, the variability in traffic-related variables such as congestion, road length, and traffic density within an urban environment leads to variability in intra-urban air quality (Dasgupta et al. 2020).

This study aimed to investigate the impact of a natural bushfire disaster and the COVID-19 pandemic on air pollution by quantifying and comparing the spatial distribution of two air pollutants, nitrogen dioxide (NO_2) and particulate matter (PM_{10}), during the different periods across the Greater Sydney region while correcting for anthropogenic and meteorological influences. This was achieved by interpolating daily concentrations of NO_2 and PM_{10} from the peak months of these events and a control month and statistically comparing them. The effects of traffic count, temperature, and rainfall, were accounted for to correct any potential confounds. It was hypothesised that there would be significantly higher concentrations of these pollutants during the bushfires than the COVID-19 period. The outcomes of this study builds on previous studies by furthering our understanding of the impacts of natural disasters and anthropocentric events on air pollution.

2. Methods

2.1 Study area

The area of interest for this study was the Greater Sydney region (Figure 1A). This was selected as it was the most frequently applied boundary for COVID-19 restrictions in NSW (New South Wales Government 2021). Additionally, Sydney is the most populated city in Australia with over 5 million people (Dean &Green 2018) and is located in a geographical basin, which limits pollutant dispersal and acts as a pollutant trap due to the surrounding elevated terrain to the west and the Pacific Ocean to the east (Crawford et al. 2016).

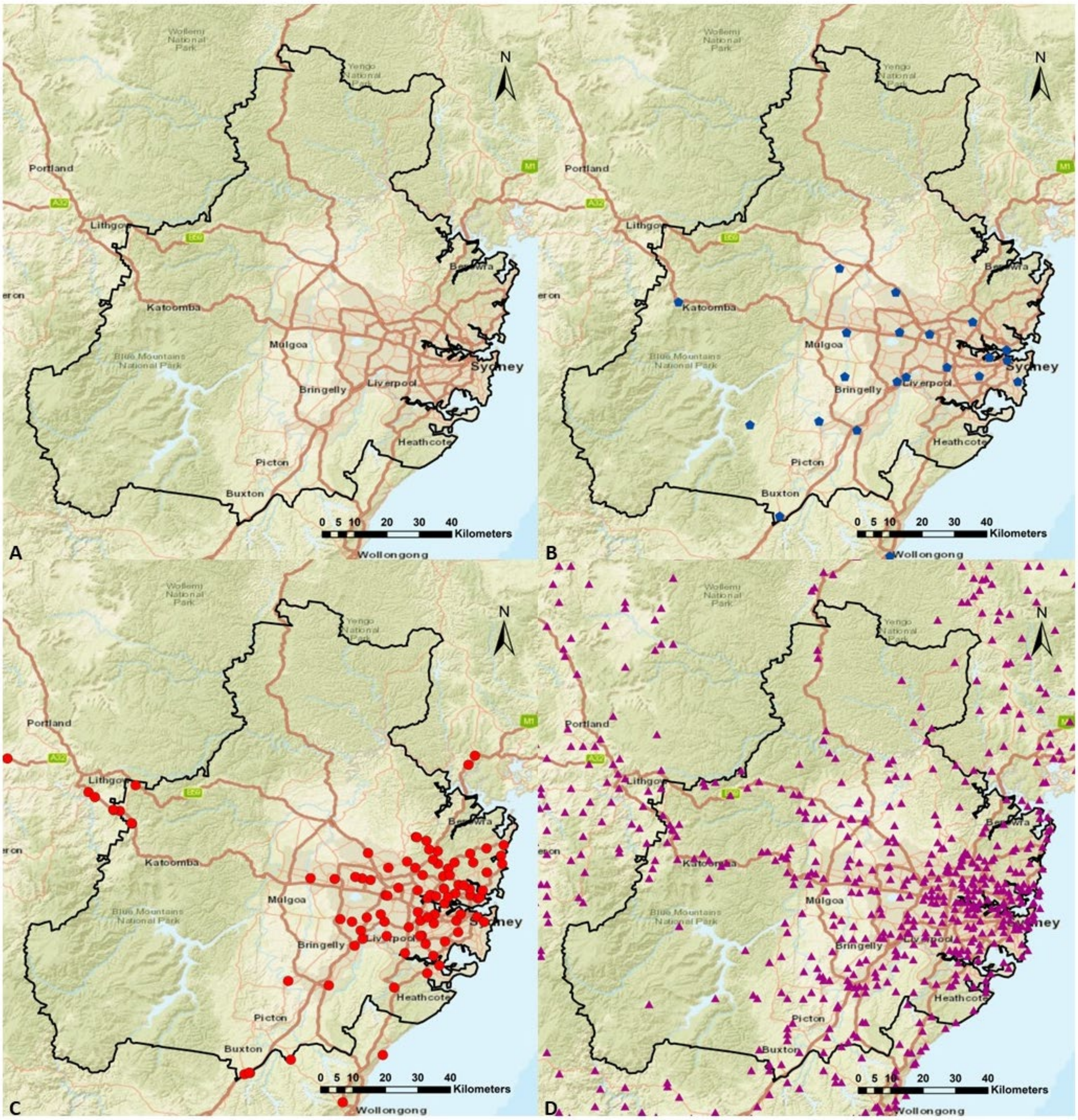

Figure 1. A. *The Greater region of Sydney study area (Australian Bureau of Statistics 2009).* ***B.*** *Office*

of Environment and Heritage monitoring stations are shown by the blue pentagons (Office of Environment and Heritage 2020). ***C.*** *Transport for NSW monitoring stations are represented by the purple triangles (Transport for NSW 2020).* ***D.*** *Bureau of Meteorology rainfall stations are depicted by the red circles (Bureau of Meteorology 2020).*

2.2 Data collection and variables

The data collected covered three different periods, each consisting of 30 days, with each period representing a different event. The natural disaster bushfire period ran from 16 December 2019 to 14 January 2020. This period was selected as it was representative of the conditions prevalent within the peak bushfire season (Australian Institute of Health Welfare 2020, Richards et al. 2020). The local first pandemic period ran from 15 March to 13 April 2020. This period was selected due to the increased enforcement of lockdown measures and travel and industry restrictions that occurred during COVID-19 (Storen &Corrigan 2020). The reference control period ran from 1 February to 1 March 2020 wand was representative of the normal conditions that would occur during this time of the year. Sydney experienced the natural and pandemic disasters within a short time frame interspersed with a period of normal conditions, ensuring environmental conditions and seasonality were similar. It was confirmed that the control period was representative of a normal time period and was not influenced by the bushfires or COVID-19 through comparison with the same time periods during the previous year.

2.2.1 Office of Environment and Heritage monitoring – Temperature and air pollutants

Daily air pollutant concentrations and hourly temperature (°C) data were obtained from 55 Office of Environment and Heritage (OEH) monitoring stations within the study region (Figure 1B, (Office of Environment and Heritage 2020). The air pollutant data incorporated in this study included ambient concentrations of NO_2 (pphm) and PM_{10} ($\mu g/m^3$). NO_2 was chosen to represent gaseous pollutants, and PM_{10} was selected to represent particulate matter during the three time periods.

2.2.2 Transport for New South Wales monitoring – Daily traffic

Traffic count data from the 157 traffic counting stations shown in Figure 1C was obtained from the Traffic Volume Viewer provided by Transport for New South Wales (Transport for NSW 2020). The daily average traffic counts included all vehicles types and all directions of travel. The traffic counts for the bushfire period were calculated by averaging the 2019 and 2020 average counts as the sample ran across the two years. The traffic counts for the control and COVID-19 periods used only the 2020 yearly counts from each station.

2.2.3 Bureau of Meteorology – Daily rainfall

Daily rainfall data from monitoring stations located in or around the study region was obtained from 643 Bureau of Meteorology (BOM) stations (Figure 1D, (Bureau of Meteorology 2020).

2.3 Analysis

If the data was not already provided as daily averages, it was converted prior to processing. ArcGIS version 10.6 (Esri, 2018) was used to spatially transform and join the data, create maps and perform all spatial data analyses. Microsoft Excel 2016 (Microsoft Corporation, 2016) was used for data handling and processing, while SPSS version 26 (IBM Corporation, 2019) was used for statistical transformation and analysis. All tabular data was joined to the relevant spatial layer to ensure accurate spatial representation, and all spatial layers were transformed to the Geocentric Datum of Australia 1994, which is the Australian coordinate system (Geoscience Australia 2006).

Spatial interpolations for the Greater Sydney region were conducted for each variable and covariable, with a spatial resolution of approximately $500m^2$. This process was completed for each day in all three time periods for each variable, and then spatially overlaid and joined. Once all variables and covariables were spatially joined, the combined dataset was transformed and analysed in SPSS. To ensure that all assumptions were met for the repeated measures analyses of covariances (ANCOVAs), NO_2 was transformed using a square root transformation, and the PM_{10} data was natural log-transformed.

The data was analysed using repeated measures ANCOVAs for NO_2 and PM_{10}. Bonferroni's *post hoc* test was used for each air pollutant to produce pairwise comparisons and help control the high Type 1 error rate likely to arise from the large sample sizes resulting from the fine spatial resolution used in this analysis. The three covariables (temperature, rainfall, and traffic count) were incorporated into the analysis to ensure air pollution during both events was accounted for. The Greenhouse-Geisser correction was used to determine significance in cases where sphericity could not be assumed. All comparisons were confirmed by producing estimated marginal means (EMMs) of the concentrations from the repeated measures ANCOVAs and verified by confirming that the 95% confidence intervals for the EMMs did not intersect with the EMM from another time period.

3. Results

All measurements for NO_2 were within the maximum ambient concentrations set by the Department of Planning, Industry and Environment (Department of Planning Industry and Environment 2020). However, the daily set limit of 50 $\mu g/m^3$ for PM_{10} (Department of Planning Industry and Environment 2020) was exceeded at one or more stations on all 30 days during the bushfire period, 17 days of the normal period, and four days during the COVID-19 period.

Spatial differences across the study site were detected for NO_2 and PM_{10} (Figures 2–4). NO_2 concentrations were CBD-centred during the normal period and generally lower during the bushfire period across the area (Figure 2, Figure 3). Interestingly, increased NO_2 concentrations were higher and more widespread during the COVID-19 period (Figure 4). Contrastingly, PM_{10} was concentrated to the west of the study during the bushfire period, as this area was closer to the fire areas (Figure 2). PM_{10} concentrations were low across the study area during the COVID-19 lockdown period (Figure 4), though slightly elevated across the cityscape during the normal period.

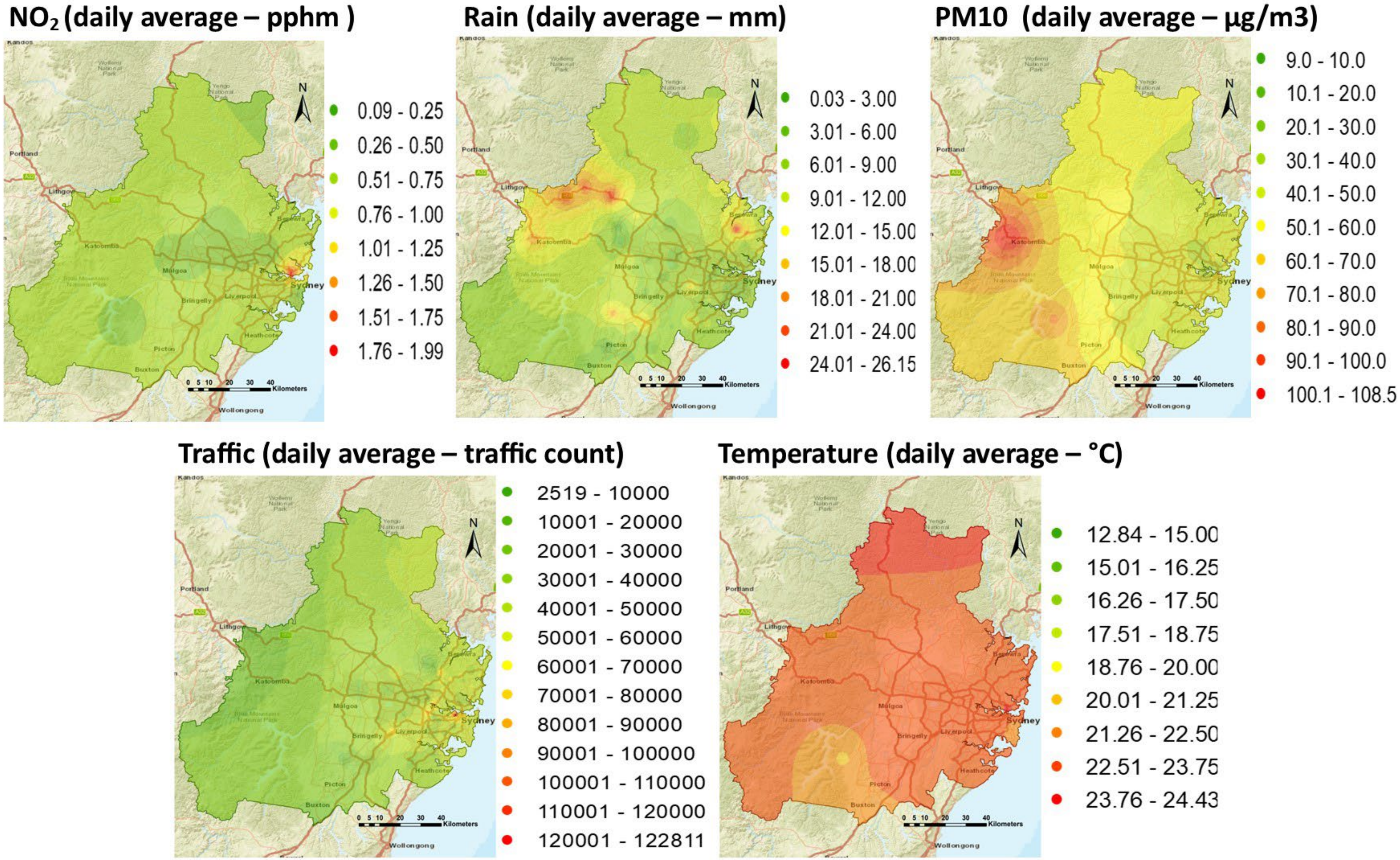

Figure 2. *Spatial distribution for the daily average of all five variables across the study site, Sydney, during the bushfire period.*

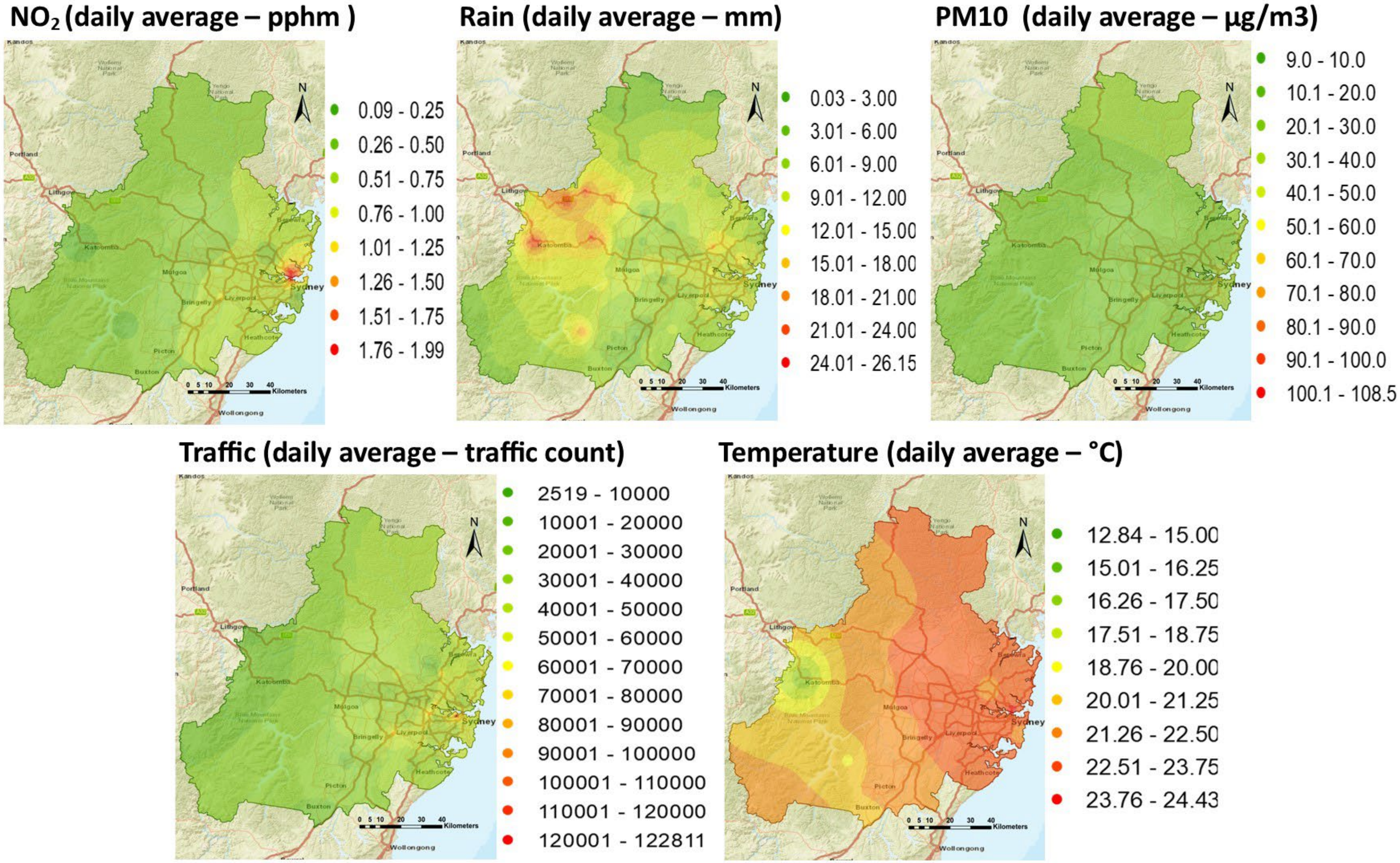

Figure 3. *Spatial distribution for the daily average of all five variables across the study site, Sydney, during the normal period.*

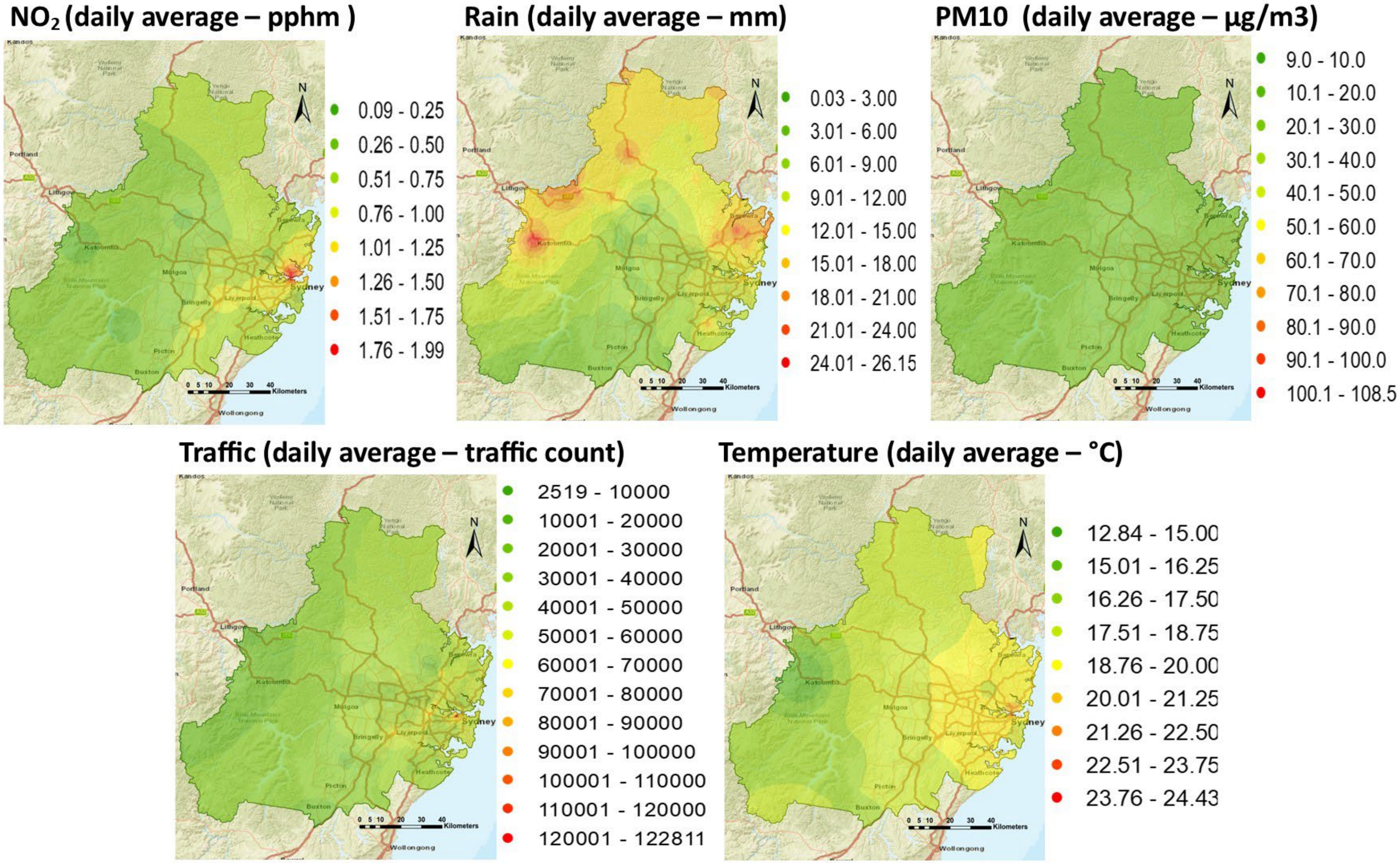

Figure 4. *Spatial distribution for the daily average of all five variables across the study site, Sydney, during the COVID-19 period.*

When the effects of the covariables were accounted for by the repeated measures ANCOVAs with Bonferroni's *post hoc* test, the pairwise comparisons revealed significant differences amongst the three time periods for both NO_2 and PM_{10} amongst the bushfire control and COVID-19periods ($p<0.05$, Figure 5, Figure 6).

The results shown in Figure 5 show that ambient NO_2 concentrations were significantly lower during the bushfires and significantly higher during the COVID-19 pandemic. The inverse is true for PM_{10}, with significantly lower concentrations during COVID-19 restrictions and significantly higher levels during the bushfire period (Figure 6). The significant differences were also confirmed aby the absence of overlap between any group's EMM 95% confidence intervals.

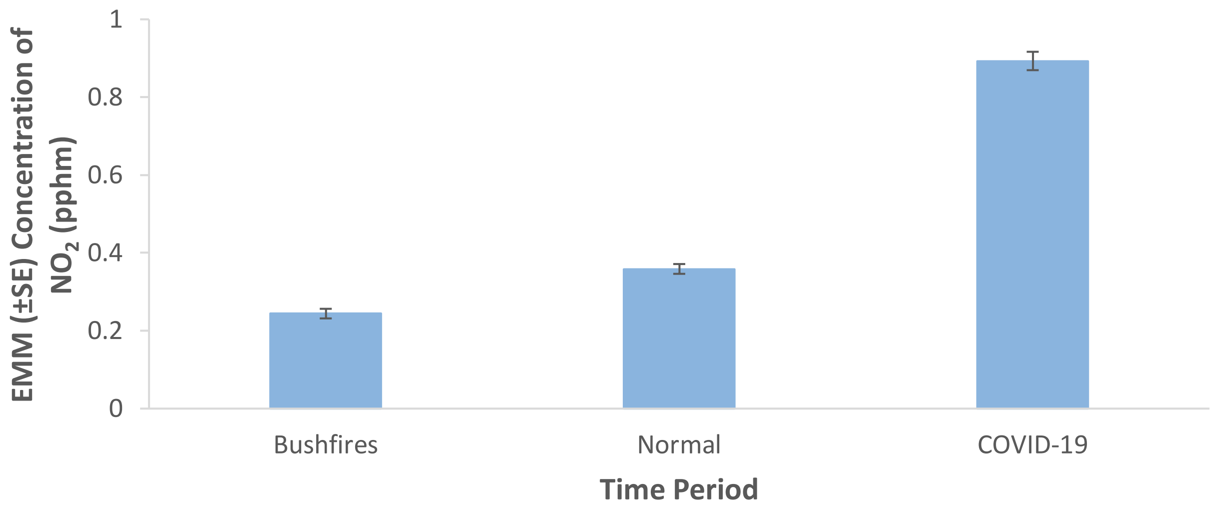

Figure 5. *Ambient NO_2 (pphm) concentrations for the bushfire, control and COVID-19 periods. Data shown is the corrected estimated marginal means (EMM ± SEM).*

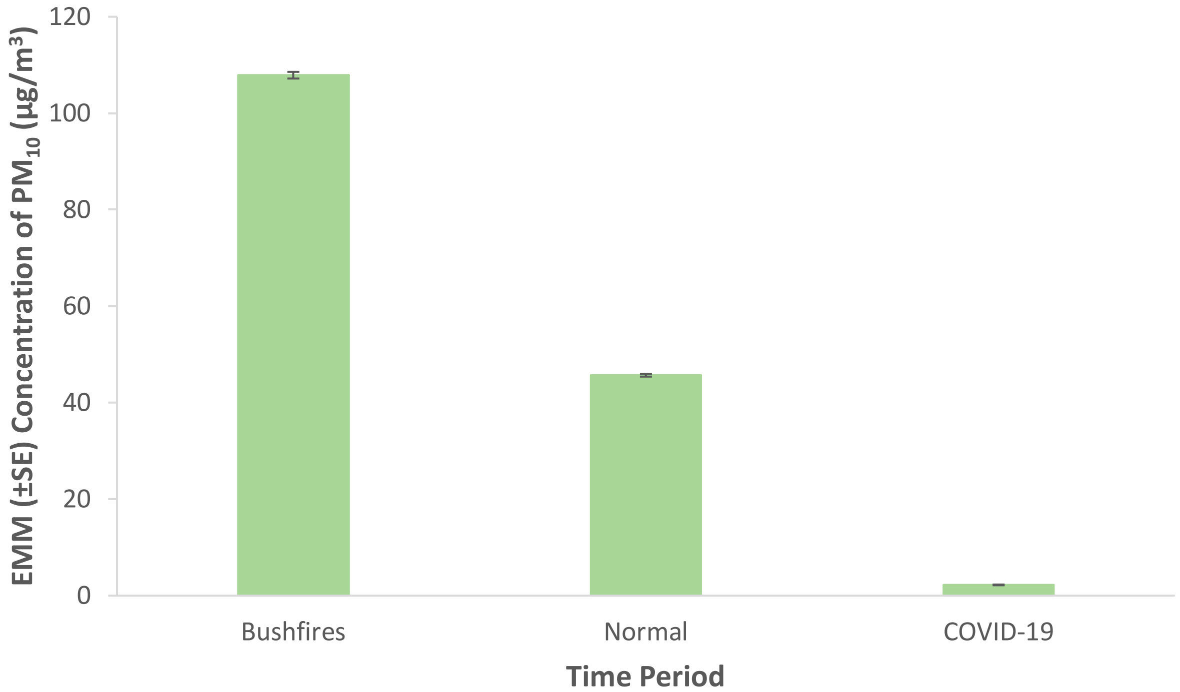

Figure 6. *Ambient PM_{10} ($\mu g/m^3$) concentrations for the bushfire, control and COVID-19 periods. Data shown is the corrected estimated marginal means (EMM ± SEM).*

Our findings demonstrate that the impacts of bushfires and the COVID-19 lockdown on air quality are not always obvious or have an equal impact on air pollution (Figure 7). The percentage change between the bushfire and COVID-19 and normal periods are shown in Figure 7. Between the bushfire and normal periods there was a decrease in NO2, but PM10 experienced an increase. The opposite was true for both pollutants when comparing the COVID-19 period to the normal period (Figure 7).

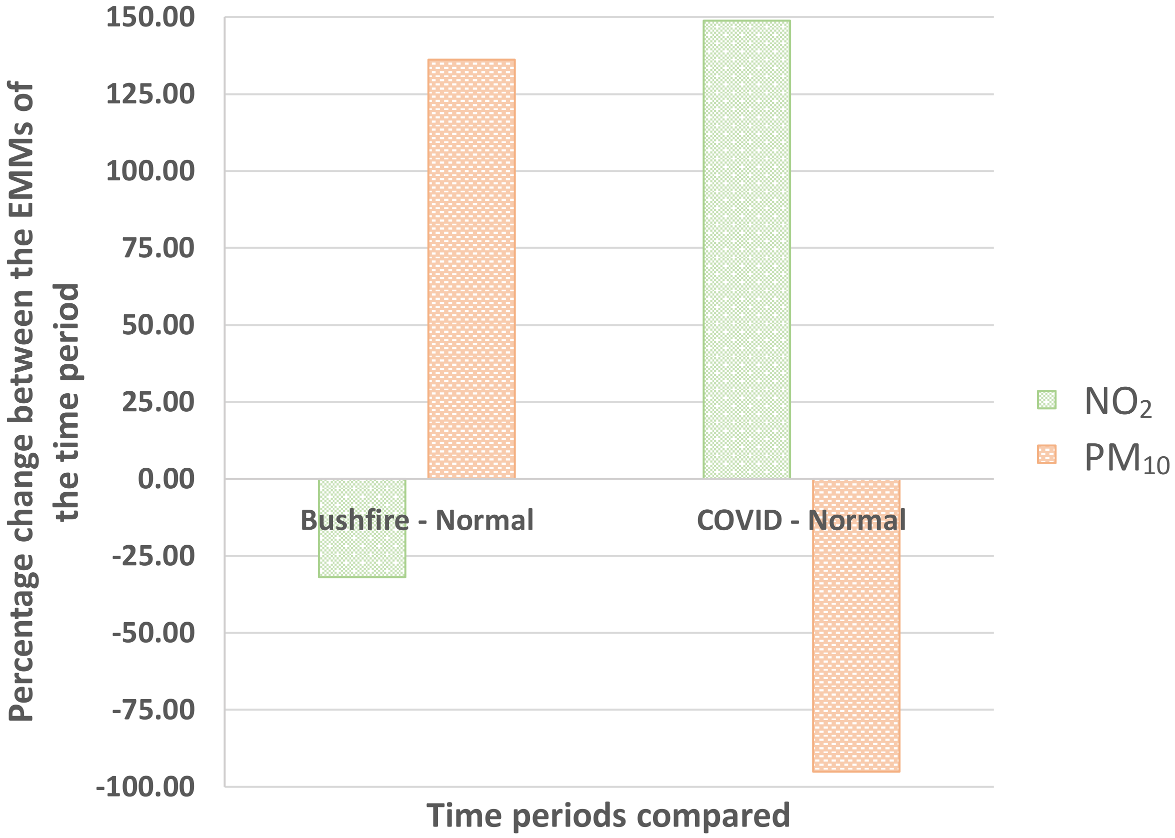

Figure 7. *Percentages changes of estimated marginal means NO_2 and PM_{10} between the three time periods, bushfires, COVID-19 and normal.*

4. Discussion

This study aimed to investigate the impacts of a natural disaster and global pandemic on air quality across the Greater Sydney region whilst controlling for environmental and anthropogenic variables. It builds on previous studies by furthering our understanding of natural disasters and anthropocentric events on air pollution and also explores the spatial patterns in two criteria air pollutant concentrations during these events across a cityscape. The results show that both the bushfires and COVID-19 pandemic had significant impacts on air quality, though the impact of each event differed. Interestingly, the hypothesis that lower air pollutant concentrations would occur during the pandemic was only true for PM_{10}, as there were significantly reduced concentrations of particulate matter in the Greater Sydney region in the period affected by COVID-19 in comparison to the bushfires and the control (Figures 4, 6, 7). However, ambient NO_2 was unexpectedly higher during the pandemic (Figures 4, 5, 7). As the normal period occurred between the bushfires and COVID-19, it represented as a transition time with intermediate concentrations of both pollutants.

This current findings are in contrast to those of other publications that assessed NO_2 concentrations during COVID-19, as they were higher during the global pandemic and lower during the bushfires (Figures 5, 7). Otmani *et al.* (2020) found there was a 96% reduction in NO_2 concentrations in Morocco during COVID-19, while Cadotte (2020) found significant declines in NO_2 in areas of China during government restrictions in early 2020 when compared to pre-COVID-19 levels in 2019 (Cadotte 2020, Otmani et al. 2020). Conversely, Iran experienced no reductions in NO_2 levels during the lockdown, and no significant NO_2 changes occurred in the period before or after the lockdown (Bauwens et al. 2020). The same was observed for most sites in Greece, with no reduction in air pollution mostly attributed to the meteorological conditions that prevailed during the time (Varotsos et al. 2021a). The greater concentrations and wider distribution of NO_2 during COVID-19 (Figure 4) could have been driven by multiple factors. The reduction in the use of public transport during the pandemic and a switch in preference to commuting using private vehicles (Aloi et al. 2020, De Vos 2020, Scorrano &Danielis 2021), particularly as commuters feared public transport could act as a vector for COVID-19 (Restrepo 2021), may have influenced this.

The shift in vehicles types on Australia roads would have also impacted the air pollution experienced during these time periods as the larger vehicles with a greater polluting potential, such as SUV and light commercial vehicles, experienced increased sales in both 2019 and 2020 (Federal Chamber of Automotive Industries 2020, 2021). SUVs equated to 49.6% of the sales in 2020 and 22.4% for light commercial vehicles (Federal Chamber of Automotive Industries 2020, 2021). While smaller passenger vehicles sales decreased in both 2019 and 2020 (Federal Chamber of Automotive Industries 2020, 2021). There additional changes in traffic experienced during COVID, characterised by the increased reliance on and movement of long-haul trucks, local fleet delivery and heavy vehicles as online purchases, deliveries and transportation of goods increased (Bureau of Transportation Statistics 2021, Transurban 2020) would also influence air pollution. Subsequently, these large polluting vehicles were the least impacted by COVID and remained consistent or increased compared to passenger/personal use vehicles, potentially equating to increased NO_2 levels (Bureau of Transportation Statistics 2021, INRIX 2021, Transurban 2020). This was further supported by the elevated concentrations of NO_2 across the city centre and the along the traffic corridors across western and Greater Sydney during COVID, while overall traffic counts remained relatively consistent (Figure 5).

However, vehicle transportation may be a secondary driver of NO_2 air pollution, as Wang *et al.* (2020) found the presence of industry was more strongly correlated with air quality issues including atmospheric NO_2 across China during lockdown than motor vehicles (Wang et al. 2020). Additionally, Kerr *et al.* (2021) found that more localised and regional changes to NO_2 concentrations could be due to factors other than vehicle use, such as industrial emissions (Kerr et al. 2021). Therefore, these differences across the published literature and in this current study could be driven by the strength and severity of lockdown restrictions, transportation requirements and types, and the presence of alternative sources such as industry. Furthermore, NO_2 has a shorter atmospheric lifetime limiting its ability to disperse and accumulate, so higher NO_2 concentrations will only be observed in close proximity to bushfires (Yin et al. 2020). This may explain why this study found NO_2 was lower during the bushfires across our area of study (Figure 2).

During the bushfire time period, the daily set limit of 50 µg/m^3 for PM_{10} (Department of Planning Industry and Environment 2020) was exceeded at one or more stations on every day of the sample period. The PM produced from these natural fires would have surpassed anthropogenic sources as the primary contributing pollutant source (Yin et al. 2020). They would have also increased as the number and extent of burning fires increased, ensuring higher concentrations of PM_{10} across the study area with increased concentrations occurring in the west of the study area due to the proximity to the bushfires (Figure 2). The findings of Otmani *et al.* (2020) are similar to the significant difference found in the current study for particulate matter between the normal time and the COVID-19 outbreak (Otmani et al. 2020). Otmani et al (2020) found that government restrictions resulted in a 75% decrease in PM_{10}. Likewise, Cadotte (2020) found that PM_{10} significantly decreased during the government restrictions imposed due to COVID-19 across China, Japan, and Korea (Cadotte 2020).

The comparison between the two types of events, a natural disaster and a global anthropocentric pandemic, in this study, highlighted the unexpected differences in air quality and the need for more diverse and multifaceted approaches to handling air pollution and its associated impact on human health (Figure 7). Though ambient NO_2 was within guidelines for Sydney during this study, the unexpected NO_2 concentrations during COVID-19 compared to the normal time period indicate a need for continual monitoring and investigation, particularly with the potential associated human health and ecosystem health impacts (Barnett Adrian et al. 2006, Kamarehie et al. 2017, Lu et al. 2018). NO2 in particular is of concern. Barnett *et al.* (2006) found a significant positive association between exposure to common urban air pollutants, such as NO_2 and PM, and hospital admissions for five types of cardiovascular disease in cities across Australia despite the levels being well below national health guidelines (Barnett Adrian et al. 2006).

In reference to bushfire emissions, previous work has found that daily respiratory hospital admission rates increased as ambient PM_{10} increased and that this correlation was stronger during bushfire periods (Chen et al. 2006). More specifically, in Sydney, a 5% increase in mortality was associated with bushfire smoke and a 6% increase in same-day hospital admissions for respiratory diseases during bushfires, with 13% and 12% increases for COPD and asthma, respectively (Dean &Green 2018, Johnston et al. 2011, Martin et al. 2013). Studies have also found respiratory morbidity from PM_{10} generated from bushfires was equivalent to that of urban sourced PM_{10} (Dennekamp &Abramson 2011), highlighting the importance of multidimensional approaches. Additionally, those suffering from comorbidities, such as cardiovascular and respiratory illnesses, are at higher risk of adverse health effects from the PM_{10} released as ash and suspended debris created by combustion during bushfires (MacIntyre et al. 2021, Vardoulakis et al. 2020a).

With the impacts of climate change intensifying and the severity and frequency of extremes events increasing (Borchers Arriagada et al. 2020), the need for countries subjected to similar climatic conditions as Australia to implement innovative and effective approaches to mitigate air pollution impacts resulting from catastrophic events, such as bushfires and pandemics, is critical to ensure the health and safety of the public (Borchers Arriagada et al. 2020, Nolan et al. 2020). The impact of government restrictions during the COVID-19 lockdown on air quality were clearly detectable as the reduced human activity resulted in significantly less PM_{10} emissions. The impact of this societal change on air pollution could be used as a metaphorical starting block that could pave the way for new workplace and governmental policies that would positively benefit air quality. These findings indicate that employers could play a role in decreasing emissions by allowing employees to work from home. Additionally, employers who encourage their staff to adopt green practices and behaviours have been shown to increase these behaviours (Wen et al. 2010). Governmental policies that lessen commercial demand, reduce transportation requirements, and alter human activity could effectively reduce urban air pollution (Cadotte 2020). Hence, government and workplace policies could facilitate improvements in urban air quality. Further, the implementation of early detection methods for forest fires could be used, which have the potential to predict and thus manage the associated risk with these environmental problems (Varotsos et al. 2020). The outcomes of this study highlight the importance of ensuring we understand the effects of different catastrophic events on air quality to ensure the most appropriate policies are implemented.

The environmental and procedural complexities surrounding bushfire management is challenging as there is no simple approach to address these natural phenomena. A commonly implemented strategy in Australia is reducing fuel load prior to the bushfire season through prescribed burns. While these burns reduce bushfire intensity, duration, spread, smoke plume height, and pollution dispersion, they have environmental and human health trade-offs, particularly to air quality (Cowie et al. 2021, Dawkins 2021, Dunne 2020, McCormick 2002, Vardoulakis et al. 2020b, Williamson et al. 2016, Williamson et al. 2013, Zhang et al. 2021). Additionally, the risk of bushfires in many countries has increased over time, as fire seasons are prolonged and extreme fire weather conditions become more severe as a result of climate change (Cowie et al. 2021, Dunne 2020, Vardoulakis et al. 2020b). Thus, the complexities associated with bushfires emphasise the need for strong governmental support and leadership to recognise and develop transdisciplinary policies and to employ ambitious climate change mitigation targets to manage the upstream impacts of climate change on bushfire risk.

These findings also indicate a need to develop spatially relevant and adaptive policies. The traditional approaches to monitoring air pollutant concentrations, evaluating air pollution mitigation methods, and nationally sweeping guidelines must be updated as they are currently insufficient. Research has shown that local conditions should be considered when developing air pollution guidelines, along with the localised characteristics of social and economic development (Goodkind et al. 2014, Moglia et al. 2021, Song et al. 2020), Figure 3, Figure 4). Furthermore, the importance of source-specific policies continues to grow, as broad and cost-effective general policies do not account for spatial differences in impacts incurred by source and distance from pollutant source (Goodkind et al. 2014, Song et al. 2020). This study elucidated the impact of source, distance from source, and spatial influences and how they vary across a cityscape (Figure 2, Figure 3, Figure 4). Thus, they should be considered, and effectively incorporated into regionally and locally relevant policies (Goodkind et al. 2014, Moglia et al. 2021, Song et al. 2020).

Thus centralised governments, organisations and departments should continue to lead and update the standards, policies, and guidelines while simultaneously strengthening the local governments' responsibilities for atmospheric environmental protection and encouraging inter-regional strategic interaction of air pollution regulations (Goodkind et al. 2014, Moglia et al. 2021, Song et al. 2020). Different regions also need to recognise and discern effective assessments and incentive efforts when applying nationally assessed guidelines, allowing for regional and cross-sectoral cooperation (Elliott et al. 2020, Sharifi &Khavarian-Garmsir 2020). Multifaceted approaches and management strategies are crucial when responding to the impacts of natural disasters and climate change or anthropocentric pandemics. They have the potential to address early warning signs, trade-offs between perceived economic risks and the greater public good, and support the potential to build partnerships between governments, private organisations and interested stakeholders, with a common focus (Chung et al. 2020, Cole 2020, Moglia et al. 2021). As a result of the COVID-19 pandemic, research has been dedicated to developing methods of predicting the spread of disease by examining various scenarios depending on the range of people movements and interactions (Varotsos &Krapivin 2020). This has led to designated decision-making systems designed to assess epidemic parameters and predict the epidemic consequences. Some of these consequences in the name of society safety include air pollutant generating activities like; restrictions of international and domestic flights, prohibition of population concentration in groups, and a transition to remote working regime (Varotsos et al. 2021b). Similarly, the level of potential risk from a possible change in the environment can be made through these decision-making systems, which can be used to understand and predict future regional dynamics of both pandemic features and upcoming natural events. Using the data from the current study, future predictive models could better indicate the impacts of such events.

Studies on specific aspects of urban air pollution must take potentially confounding variables into account. The covariables included in this analysis have been previously shown to impact pollutant concentrations. Kwak *et al.* (2017) observed that PM_{10} concentrations decrease during rainfall, with the effect of rain washout being so significant that it outweighed the increased traffic pollution from slower traffic during rain. Kwak *et al.* (2017) also found that the inverse of this washout relationship is true for NO_2, as the increase in traffic emissions resulting from reduced speed outweighed the washout effects of rain (Kwak et al. 2017). Thus, rain was included as a covariable to correct for either of these confounds that rain may have produced in air pollutant concentrations.

The spatial GIS method utilised in this study accounted for geographical variations in temperature across the study area, and thus corrected for any impacts of temperature on air pollution. Kalisa *et al.* (2018) detected a positive linear relationship between both PM_{10} and NO_2 and temperature, particularly during heatwaves, where the air becomes stagnant and traps pollutants in the atmosphere (Kalisa et al. 2018). Interestingly, another study that investigated the effects of forest fires on air quality in Sumatra and Borneo found a relationship between low precipitation, high temperature and air pollution (Yin et al. 2020). Ulpiani *et al.* (2020) monitored Sydney's microclimate from December 2019 to January 2020, and confirmed that drought, heatwaves, and high pollution levels occurred alongside the bushfires (Ulpiani et al. 2020). This relationship between low rainfall, high temperatures and air pollution was also seen during the bushfires investigated in this current study, and these conditions would have contributed to the prolonged duration and high intensity of the fires, supporting the inclusion of these meteorological covariables in this study.

This study, however, did not consider industrial sources of pollutants, nor wind speed and direction. It would be of value if future studies could incorporate these effects as covariables due to their potential influence on ambient pollutant concentrations (Kalisa et al. 2018). Additionally, the investigation of other pollutants and the incorporation of health impacts would improve the understanding of these events on human health. Also, the addition of paired spatial tools or GIS techniques to integrate additional covariables and geographical factors (Roteta et al. 2021) might reveal additional trends. Ultimately, the current study provides valuable information to assist enterprises and government organisations in developing new regulations and standards for addressing green behaviours, air pollution, and associated health impacts (Jalaludin et al. 2020). The development of multifaceted approaches would also add to the resilience of the impacted sectors and assist with the recovery of these industries in a more sustainable way.

5. Conclusion

This study is one of few to spatially analyse the relationship between air pollutants during the regionally-relevant natural bushfire disaster event in comparison with the global pandemic. Meteorological factors and traffic were included as covariables to ensure the effects of these events on air pollution were investigated. This study showed significantly higher concentrations of PM_{10} during the bushfire period than during normal times, and significantly lower PM_{10} during COVID-19 restrictions. The reverse was found for NO_2, as there was significantly less ambient NO_2 during the bushfires and more during the COVID-19 period. The surprising findings have highlighted the need for multifaceted policies and approaches when mitigating air pollution and ameliorating air quality during extreme events, particularly as these types of events will increase in more frequency and severity in the future. The need for spatially interwoven and mutually supportive standards and guidelines will be vital if air pollution mitigation strategies are to be successful as urban development increases. Future studies should examine the response of other pollutants during these extreme episodes, while more spatially relevant variables should be investigated to understand the impact they have on air pollution during these events. Furthermore, this study has highlighted the strong and unique impacts of regional and global events on air quality and the need to re-evaluate single faceted approaches if we wish to manage air pollution during these extreme and challenging crises.

6. References

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