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Research Paper

Spatio-temporal access to protected areas from Australian significant urban areas

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HIGHLIGHTS

- Many studies highlight the importance of people accessing natural environment for their wellbeing.
- We use a novel gravity-index to compare the quality of access to protected areas for significant urban areas.
- We analyse the changes in the quality of access between protected areas and significant urban areas over a 24-year period.
- We found that quality of access to protected areas has declined for many significant urban areas.
- We identify significant urban areas where protected areas need to be expanded.

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ABSTRACT

There are many positive effects of the natural environment on human health and wellbeing. These benefits are closely linked to people's accessibility to protected areas like National Parks. In this study, we quantified spatial and temporal relationships between the extent of protected areas in, and adjacent to, significant urban areas (SUAs) in Australia, the populations of SUAs, and the network service area of connecting SUAs with protected areas between 2001 and 2024. To evaluate the accessibility of SUAs to protected areas, we developed a gravity-based accessibility index using a network analysis approach. The Gravity Index is a relative measure of attractiveness of a protected area in terms of the distance that needs to be travelled to access it, and the level of possible "congestion" placed on it from the population of the surrounding network service area. SUAs with a high value for the Gravity Index reflect shorter distances to travel to protected areas, along with fewer people per unit of area visiting protected areas (low congestion). Our results reveal marked differences in the Gravity Index for SUAs across Australia. Some SUAs, such as Hobart and Canberra, were characterized by a comparatively high Gravity Index, indicating extensive protected areas within a short distance of those population centres. Others, such as Melbourne (Australia's fastest growing SUA), had a very low and declining Gravity Index, associated with high population growth (1.8 million in 24 years), small fragmented existing protected areas surrounding the city, and limited additional land added to the protected area network over the period of population growth. Our results identify priority SUAs (such as Melbourne) where there is a need to expand the protected area network through, for example, changing land tenures to National Parks.

1. Introduction

An extensive body of research has demonstrated the positive effects of the natural environment on human health and wellbeing (e.g. Barragan-Jason et al., 2023; Evans et al., 2023; Keniger et al., 2013). Access to natural environments can reduce stress and depression (Swinson et al., 2020; van den Bosch & Meyer-Lindenberg, 2019), and, in some cases, be as effective as conventional medical treatments (Kondo et al., 2020). Direct experiences with nature are also critical in fostering pro-nature attitudes and behaviours (Soga & Gaston, 2023), and in preventing negative emotions such as 'biophobia', which is the fear, disgust, or strong dislike of particular aspects of nature (Soga & Evans, 2024; Soga et al., 2023). Research in environmental psychology further shows that people tend to prefer natural landscapes that are perceived as

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attractive and spatially open (Franěk, 2023). The spatial distribution and accessibility of natural environments relative to major urban population centres are therefore important not only for public health, but also for sustaining broader societal engagement with nature.

An important way in which people can connect with nature is through access to biodiverse green spaces (Jabbar et al., 2022). The value of this connection was especially evident during the COVID-19 pandemic, when urban residents sought out accessible natural areas (e.g. in Tokyo, Soga et al., 2021). Legislated protected areas, such as National Parks, are formally designated for the conservation of biodiversity and other environmental values, while also providing opportunities for public visitation and recreation (Buckley, 2020; Majewski et al., 2024; Schamel & Job, 2017; Worboys & Trzyna, 2015). These areas enable people to spend time in biodiverse green spaces, often engaging in outdoor recreation such as hiking and cycling.

While legislated protected areas are established primarily to conserve natural ecosystems that cannot be replicated in intensively managed landscapes (Dinerstein et al., 2024; Rodrigues & Brooks, 2007; Worboys, 2015), their proximity to urban populations also provides measurable health and wellbeing benefits. For example, Loch et al. (2024) found an association around the Australian city of Adelaide between visits to biodiverse green spaces, including National Parks and reserves, and substantially reduced healthcare costs. Fuller et al. (2007) showed that the psychological benefits of greenspace increased with biodiversity richness. Houlden et al. (2021) highlighted associations between floral diversity and human health. Given that biodiversity values are often highest in legislated protected areas such as National Parks (Bolam et al., 2020; Sanderson et al., 2023; Taylor & Lindenmayer, 2026), these areas usually offer enhanced recreational ecosystem services relative to more intensively modified landscapes (see Venter et al., 2025; Watson et al., 2018).

Collectively, these findings highlight that both proximity and ecological integrity matter where legislated protected areas near metropolitan and regional urban centres serve a dual role; that is, safeguarding biodiversity while delivering essential human health and wellbeing services. This dual role is formally recognised by the International Union for Conservation of Nature (IUCN). For example, National Parks (Category II) are defined as large natural or near-natural areas set aside to protect ecological processes and species, while also providing a foundation for spiritual, cultural, scientific, educational, recreational, and visitor opportunities (Dudley, 2008, p.16). National Parks are also the most visited of all IUCN protected area categories worldwide (Worboys & Trzyna, 2015). Similar dual purposes are recognised under other IUCN categories, including natural monuments (Category III), habitat or species management areas (Category IV), protected landscapes (Category V), and areas with sustainable use of natural resources (Category VI).

The extent to which the benefits to humans from nature are realised depends on the accessibility of protected areas (Soga et al., 2021) and hence how well these places serve human communities (Bushell & Eagles, 2006). Yet, such “equity of access” is complex and can be understood in multiple ways. Crowding, exclusion, and inequitable access are recognised as major challenges for protected area management (Spenceley et al., 2015). Proximity to major population centres and the size of nearby legislated protected areas can influence equity of access. For example, Sharifi et al. (2021) used a gravity model to assess the relative opportunity for access to green spaces, demonstrating that congestion and greater travel distances diminished both accessibility and experience. Such analyses do not capture other important dimensions of the integrity of protected areas such as species richness and landscape intactness, nor do they encompass cultural or aesthetic values, and visitor infrastructure specific to protected areas such as National Parks. They nevertheless provide a regionally consistent way to compare access and congestion to legislated protected areas such as National Parks.

While the creation of many legislated protected areas is often driven primarily by ecological and cultural values (Worboys, 2015), many also provide opportunities for public access and recreation, thereby contributing to the wellbeing of people (Job et al., 2021; Majewski et al., 2024; Schamel & Job, 2017). On this basis, in this study, we assessed spatial equity of access from metropolitan and regional urban areas across Australia to legislated protected areas as listed under the Collaborative Australian Protected Area Database (CAPAD) (DCCEEW, 2025) and where public amenity is a core management strategy. These include National Parks and other protected areas on public land.

We selected Australia for several key reasons. First, the issue of access to legislated protected areas is an important one in Australia (Loch et al., 2024), as it is in many parts of the world (Majewski et al., 2024). Indeed, post the COVID-19 pandemic, there has been a strong increase in visits to National Parks and other protected natural areas (Geng et al., 2025; Parks Victoria, 2025; Wipf et al., 2023). At the same time in Australia, there have been debates about whether the creation of National Parks and other legislated protected areas might exclude people from accessing natural areas, giving rise to public resistance to the establishment of new protected areas in some parts of Australia (Lindenmayer et al., 2018). Conversely, polling has shown strong support for protected areas, with 72% of Australians surveyed backing new National Parks (Biodiversity Council, 2025).

Second, Australia is highly urbanized with rapid population growth in some places but declining in others (ABS, 2025b). In 2024, nearly 88% of Australia’s population lived in metropolitan and regional urban areas, defined by the Australian Bureau of Statistics (ABS) as significant urban areas (SUAs), which are regions with populations exceeding 10,000 people (ABS, 2025c, 2025d). These SUAs cover only 54,584 km^2 or 0.71% of Australia’s terrestrial area, concentrating population demand within relatively small spatial areas, including the nation’s capital cities as well as regional cities and towns. Therefore, equity of access from these SUAs to legislated protected areas is becoming an important issue, as it has become elsewhere in the world (e.g. Majewski et al., 2024).

Third, Australia is a highly car-dependent society, with 91% of households having at least one vehicle (ABS, 2022). Access to legislated protected areas in Australia is overwhelmingly car dependent; Tourism Research Australia (2019) reported that 81% of visitors to National Parks drove to their destinations, with the remaining 19% likely to have used private bus charter tours. The dominance of private vehicles in Australia therefore serves as an important indicator in analysing the accessibility of protected areas via road networks.

The analytical unit in this study was the Level 2 Statistical Area (SA2) (as defined by the ABS; ABS, 2021b), located within SUAs across Australia. We evaluated the relative accessibility of these local areas to legislated protected areas using a Gravity Index (Hansen, 1959), which is a spatial interaction metric widely applied in accessibility research (Kapatsila et al., 2023; Sevtsuk & Mekonnen, 2012; Sharifi et al., 2021). For this investigation, we used a Gravity Index by integrating information on three measures: (1) population size in defined SA2s across SUAs, (2) the area and location of protected areas within 60 km road network of each SA2, and (3) the structure of the road network linking SA2s and legislated protected areas. We assumed that values for the Gravity Index broadly reflected a congested adjusted measure of potential accessibility, reflecting the balance between protected area supply, distance required to travel along the road network, and competing potential population demand for each SA2 (hereafter termed “equity of access”). On this basis, we motivated this study by answering three inter-related questions:

(Question 1) *Is there spatial variation in patterns of equity of access across SA2s to legislated protected areas?* As our dataset contained SA2s that varied markedly in human population size across SUAs, we hypothesized that our analyses would be characterized by evidence of strong spatial variation in values for the Gravity Index. We predicted that equity of access would be lower in SA2s that were part of larger and more densely populated SUAs (and especially capital cities) and higher in smaller and more remote (typically regional) centres.

(Question 2) *Have patterns of equity of access for SA2s to protected areas changed over time?* Temporal changes in equity of access may occur in response to population change in SA2s and/or changes in the area dedicated to legislated protected areas, such as National Parks. At the outset of this study, we postulated that the most marked declines in the equity of access across SA2s to legislated protected areas would be those in SUAs with the high populations and the most rapid rates of population growth (particularly metropolitan SUAs). Conversely, equity of access would increase in SA2s characterized by no population growth but an increase in protected areas or a decline in population, such as those in regional SUAs.

Australia has added new legislated protected areas over the past 20 years, with almost one quarter of Australia's landmass being designated as legislated protected areas (23%), up from 11% in 2004 (ABS, 2025a). This has been in part to meet the nation’s commitments to the Global Biodiversity Framework, and conserve at least 30 per cent of the continent by 2030 (DCCEEW, 2026). However, many of these protected areas are in remote and/or sparsely populated regions of the country (Bureau of Infrastructure, 2017). While the inclusion of areas of high environmental and cultural significance across remote areas is essential, we argue that equitable access to legislated protected areas near major population centres should also be prioritised. Given this, our third question was:

(Question 3) *Has the addition of new legislated protected areas offset human population growth in SA2s in terms of equity of access*? At the outset of this investigation, we predicted that very rapid rates of population growth in many SA2s, particularly those within large SUAs such as Australian metropolitan SUAs, would have outstripped increases in legislated protected areas. Such spatio-temporal changes would, in turn, be reflected in lower values for the Gravity Index and eroding equity of access. Conversely, we predicted the opposite trends for SA2s with declining populations, such as in parts of regional and sparsely populated areas of Australia.

2. Methods

2.1. Study area and data acquisition

Our investigation focused on the Statistical Area Level 2 (SA2), as defined by the ABS (ABS, 2021b), as the unit of our analysis. We analysed SA2 units within larger units defined as significant urban areas (SUA). Our analysis was underpinned by three key input variables: legislated protected areas where public visitation is prioritised in

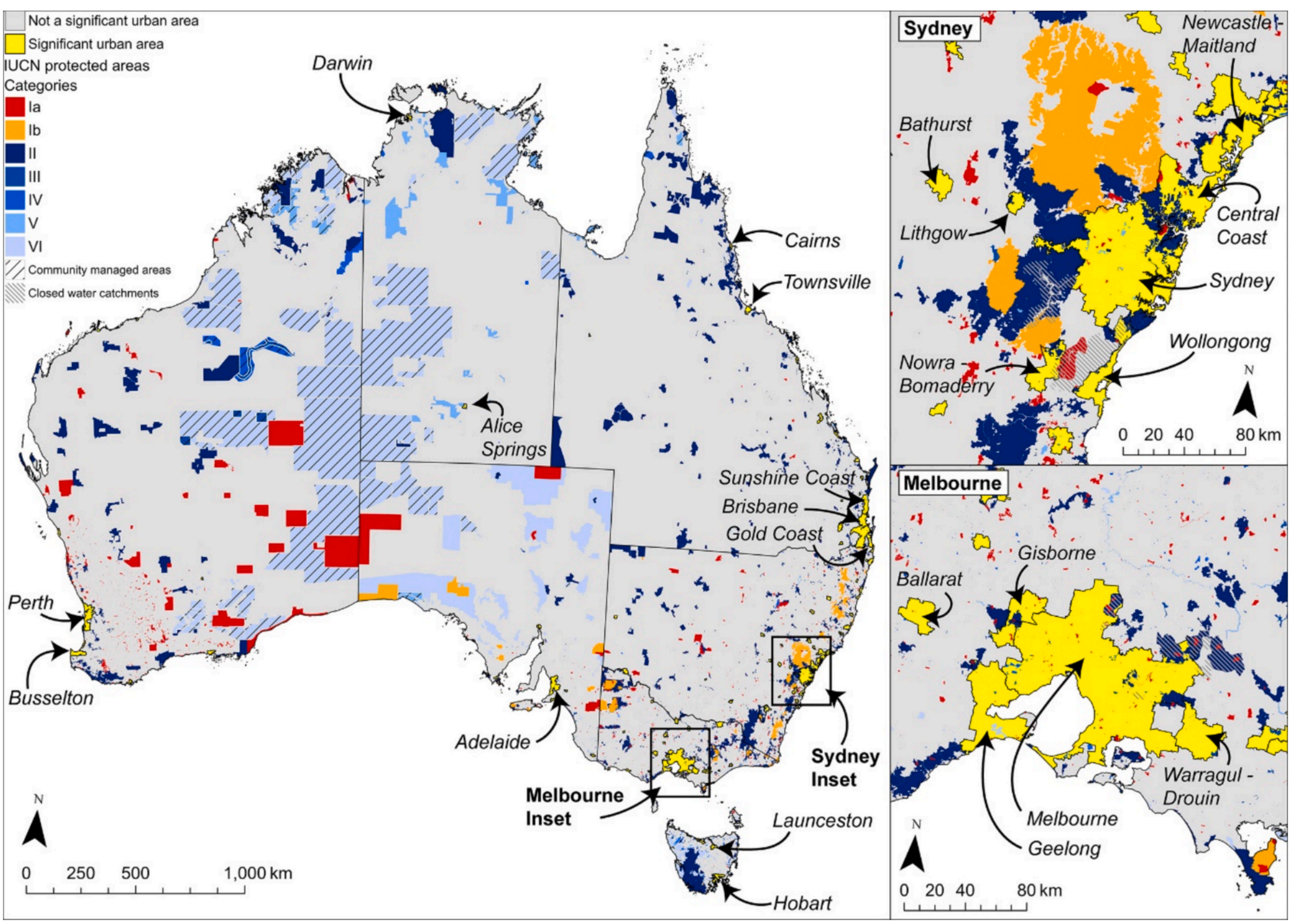

Fig. 1. Distribution of protected areas across Australia, classified by IUCN management categories (I–VI) and including community-managed areas and closed water catchments. SUAs are highlighted in yellow, with major centres labelled to illustrate their proximity to protected areas. Detailed insets of Sydney and Melbourne and surrounding SUAs are featured (SUA boundaries – ABS, 2025c; IUCN protected area categories – DCCEEW, 2025; Closed water catchments – Melbourne Water, 2020a; Water NSW and Office of Environment & Heritage, 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

protected area management, the cumulative estimated residential population (ERP) within the 60 km service area of the legislated protected areas where the SA2 is located, and the national road network linking protected areas with SA2s (Fig. 1).

We sourced data on Australia's legislated protected areas from the Collaborative Australian Protected Areas Database (CAPAD), which provides information on location, area (ha), and gazettal year (DCCEEW, 2025). These encompass National Parks and other protected areas. In Australia, legislated protected areas are designated IUCN protected area categories (Ia-VI) by the relevant managing authority within each jurisdiction and reported to CAPAD in accordance with IUCN and national reporting guidelines (DCCEEW, 2025). Legislated protected areas are managed by the Australian Government, State and Territory Governments, local councils, Indigenous and private landholders, and NGOs (NRMMC, 2009). While legislated protected areas are ecologically heterogeneous and conserve diverse habitats and biodiversity values, our analysis focused specifically on accessibility for public engagement with nature. Consistent with the IUCN category framework, we included Categories II-VI protected areas, which recognise the dual role of safeguarding ecosystems while also providing opportunities for education, recreation, and human wellbeing (see Dudley, 2008; Worboys & Trzyna, 2015). We excluded IUCN Category I (defined in the category as strict nature reserves and/or wilderness areas), restricted water catchments (Melbourne Water, 2020b; Viggers et al., 2013; Water NSW and Office of Environment & Heritage, 2015), and areas under private or restricted community management (e.g., Indigenous Protected Areas requiring authorisation for access). These exclusions ensured that our analysis centred on protected areas accessible to the public.

We sourced Estimated Residential Population (ERPs) data from 2001 to 2024 across Australia from the Australian Bureau of Statistics (ABS) GeoPackage dataset for each Statistical Area Level 2 (SA2) polygon (ABS, 2025b). SA2s are defined by the ABS as medium-sized statistical units designed to represent communities of approximately 3000 and 25,000 people with social and economic interaction (ABS, 2025d). ERP represents the official estimate of the Australian population and is assigned to the place of usual residence under the Australian Statistical Geography Standard (ABS, 2025b).

Each SA2 analysed was part of an SUA, which is an aggregation designed to represent significant urban concentrations. Under ABS criteria, an SUA must contain a combined population of at least 10,000 people. This threshold can be met through: (i) a single SA2 exceeding 10,000 people; (ii) multiple SUAs that collectively exceed 10,000 people; or (iii) smaller urban centres of >7000 people located within 5 km by sealed road of another urban centre where the combined population exceeds 10,000 (ABS, 2025c). As a result, SUA boundaries can include either contiguous SA2 polygons or nearby road connected clusters that function as a single urban area. In total, there are 102 SUAs across Australia. There are eight metropolitan SUAs that are the capital cities of their respective states, consisting of Adelaide, Brisbane, Canberra – Queanbeyan, Darwin, Hobart, Melbourne, Perth, and Sydney. We identified eight large regional SUAs based on their large population sizes, consisting of Alice Springs, Cairns, Geelong, Gold Coast – Tweed Heads, Launceston, Newcastle – Maitland, Sunshine Coast and Wollongong.

We used the National Roads dataset developed by Geoscape (2025) to calculate distances between publicly accessible protected areas (IUCN Categories II-VI) and SA2s located within SUAs. This dataset provides a digital representation of Australia's road network, including road geometry and classification attributes. For our analysis, we used roads that are accessible to standard two-wheel drive passenger vehicles, including freeways, highways, arterial roads, sub-arterial roads, and local roads, while excluding four-wheel drive tracks and other routes unsuitable for general passenger vehicles. The road network was treated as temporally constant over the study period (2001–2024), as the dataset did not include historical establishment dates or a nationally consistent time series of road network changes. We did not include public transport in our analysis, reflecting its limited role in accessing legislated protected areas, especially regarding National Parks. This was based on several factors. First, Australia is a highly car-dependent society (ABS, 2022). ABS data show a high rate of vehicle ownership in Australia, with 578 passenger vehicles per 1000 people in 2021 (ABS, 2021a). Second, Tourism Research Australia (2019) reported that 81% of visitors travelled to National Parks by private car. Data on the remaining alternative transport was not available. Third, while some protected areas are accessible by railway networks and public transport routes (Ogrizek, 2019; Parks Victoria, 2025; South Australia NPWS, 2019), many others are not. A consistent dataset of legislated protected areas accessible by public transport across all significant urban areas was not readily available. Finally, data on private bus charter tours to National Parks and other legislated protected areas are unavailable. However, we acknowledge that it is an important means for people without passenger vehicles to access protected areas. As a proxy, our focus was on road-based accessibility by passenger vehicles.

2.2. Gravity index and analysis

We assessed the public accessibility of protected areas (IUCN categories II–VI) to SA2s located within SUAs. Various methods exist for measuring accessibility. For example, Zhang and Chen (2024) compared four approaches for access to urban green space in London. These were (1) container measures (urban green spaces within administrative boundaries used for collecting and reporting population statistics), (2) distance-based methods (shortest distance from the origin to the destination urban green space), (3) gravity models (which incorporate both attractiveness of urban green spaces (e.g. urban green space area size) and distance decay), and (4) the Two-Step Floating Catchment Area (2SFCA) method, which is an enhanced approach of the gravity model evaluating disparities in potential accessibility. Enhanced variants of the 2SFCA method, including E2SFCA and Gaussian 2SFCA (Ga2SFCA), apply distance decay weights within a specified travel time or distance catchment to represent declining interaction with increasing travel distance (Luo & Qi, 2009; Mu et al., 2023). Accessibility is calculated in two steps: first is to calculate the supply-to-demand ratio of each urban green space based on the human population within a catchment, the area of urban green space, the distance required to travel to an urban green space and a Gaussian decay function; and second, to calculate the aggregate urban green space accessibility for each community within a specified search area (Zhang & Chen, 2024).

These approaches highlight important trade-offs: container and distance measures are straightforward to implement but do not account for congestion effects or cross-boundary flows. While 2SFCA and its variants are widely applied in intra-urban studies, they rely on a fixed catchment area within which accessibility is calculated and these calculations can be complex. Such calculations may be more difficult to apply at broader regional scales characterised by heterogeneous metropolitan and regional contexts. Because our analysis models access across multiple metropolitan and regional urban contexts as well as incorporating travel distances by private vehicle of up to 60 km, we adopted a gravity-based framework in which accessibility declines continuously with travel distance.

We used a modified Gravity model, guided by Sharifi et al. (2021), because it provided a continuous, nationally consistent, measure that integrated three key dimensions: (i) travel impedance, measured as road-network distance (rather than Euclidean measures); (ii) supply, represented by the size and number of protected areas; and (iii) demand, represented by the total population within a network service area, which captured potential congestion and equity of access. The model generated an index that therefore reflected the interaction between the distance that must be travelled, the number and size of protected areas and the potential competing human population, such that equity of access declines with increasing travel impedance but may be offset by larger sizes and number of protected areas or lower potential human population pressure. Higher Gravity Index values therefore correspond to combinations of shorter travel distances and/or less potential congestion and population pressure. The relative influence of these components is governed by a distance decay parameter, which determines the rate at which accessibility declines with increasing travel distance.

Our network service areas were defined as a maximum travel distance of 60 km from the centroid of each statistical area (SA2) within each SUA to the entry point of each protected area by passenger vehicle along accessible roads, as detailed in the National Roads dataset (Geoscape, 2025). We based the 60 km threshold on the analysis conducted by Loch et al. (2024), who found that 90% of day trips to National Parks for recreation around Adelaide (day trips) occurred within 60 km. Trips longer than 60 km were considered as tourist travel and we did not include these trips in our analysis. Data on recreational travel were unavailable for other states and territories, so we extrapolated this threshold for all SA2s across SUAs. We acknowledge that Adelaide is geographically smaller than metropolitan regions such as Melbourne or Sydney, where recreational travel distances may extend further. However, our objective was to model routine day-trip accessibility by private vehicle rather than longer distances required of overnight tourism travel. While some recreational trips may exceed 60 km, we considered this threshold to represent a reasonable upper bound for regular metropolitan access. In the absence of comparable mobility datasets for other SUAs, this threshold was applied consistently across the SUAs to maintain national consistency. We recognise that this may under-represent longer recreation trips in and around larger metropolitan SUAs.

We used SA2 centroids within SUAs as demand points. We snapped these centroids to the nearest road within 2 km to ensure connectivity between centroids and the road network. In ArcGIS, "snapping" is a function that adjusts the location of a point so that it lies directly on a line in the road network, allowing the software to calculate travel distances. We defined protected area access points as supply points. These were points where roads intersected with, or came within 500 m of, protected area boundaries. We snapped these supply points to the road network. We used both SA2 centroid demand points (defined as 'Incidents') and park access supply points (defined as 'facilities') as input for ArcGIS Pro's Network Analyst extension (Esri, 2024). To ensure computational efficiency, we limited the maximum number of protected area access point facilities searched per SA2 centroid to 500. This number was selected to ensure all protected area access points within the 60 km service area of each SA2 were selected. At the conclusion of our Network Analysis, the resulting maximum number of protected area facilities found for an SA2 was 220, which indicated that all protected area access facility supply points within the network service area of each SA2 were selected in our analysis.

The output network analysis consisted of a series of network routes between the centroid demand point of an SA2 (designated as Incident in the Closest Facility Network Analyst tool) and the supply access point of a legislated protected area (designated as a facility in the Closest Facility Network Analyst tool). The output route was measured in kilometres. The initial Closest Facility analysis generated 172,327 incident-facility routes within the 60 km network service area cut-off. Larger protected areas often contained multiple access points via the road network (for example, the Alpine National Park in Victoria which is approximately 650,000 ha in size has many road entry locations), resulting in multiple candidate routes between a given SA2 centroid demand point and the same protected area. To avoid double counting protected areas in the Gravity Index, we retained only the minimum network distance for each unique SA2-protected area pair (i.e. the shortest access route to that protected area). This minimum distance selection reduced the dataset to 97,689 unique SA2-protected area access pairs, representing a single travel route per SA2 to protected area combination. This step ensured that each protected area contributed only once to the Gravity Index relationship between an SA2 and a protected area. Following the generation of the route networks between each SA2 – protected area access point pair, we calculated the potential congestion population associated with each protected area. This is the sum of the estimated residential population (ERP) of all SA2s within the 60 km road network service area of protected area *f*, represented annually as:

$$P_f(y) = \sum_{s \in S_f} ERP_s(y)$$

where $P_f(y)$ is the total ERP in year *y* (2001–2024) for all SA2s within the set S_f, and S_f denotes the set of SA2s located within 60 km network distance of protected area *f*.

For each year *y* (2001–2024), we calculated a route specific Gravity Index for each pair of SA2 *i* and the access point for protected area *f* within a 60 km road network service distance. Following our modified gravity model (Sharifi et al., 2021), accessibility was defined as the protected area's size (in hectares) divided by an exponential distance decay function of the network distance in km *D* between the SA2 centroid *i* and the protected area access point *f*, and by the potential congestion population of the 60 km network service area of the protected area access point (as defined above). We assigned a distance decay parameter of $\beta = 0.01$ to produce a gradual, moderate exponential decay across the 0–60 km network service area, ensuring that nearby protected areas contribute more to equity of access than distant ones. We defined each route specific Gravity Index as:

$$GI_{if}(y) = \frac{A_f(y)}{e^{0.01D_{if}} P_f(y)}$$

where $A_f(y)$ is the area (ha) of protected area *f* in year *y*, D_{if} is the network distance (km) between SA2 *i* and protected area access point *f*, and $P_f(t)$ is the potential congestion population within 60 km network service area of protected area access point *f* in year *y*. For each SA2, the overall Gravity Index $G_i(y)$ was calculated annually as the sum of all route level values associated with that SA2:

$$G_i(y) = \sum_f GI_{if}(y)$$

The summed output Gravity Index represents a potential and comparative indicator of equity of access to protected areas for SA2s, rather than a measure of observed visitation to protected areas.

To answer Questions 1 and 2, we analysed the SA2 level Gravity Index values at the SUA level to which the SA2 belonged, enabling comparison between SUAs across Australia over time. To quantify relationships between the Gravity Index of each SUA over time and the differences between each SUA, we fitted a linear mixed model specifying the cube-rooted Gravity Index as our response. We cubed-rooted the Gravity Index response as it was heavily right skewed. We tested the linear effects of SUA and the linear and quadratic effects of year, as well as their interactions. This enabled us to test whether there was a significant difference in values between SUAs, whether there was an overall change over time, and whether the changes over time differed between SUAs. We included SA2 nested within SUAs as random intercept effects to account for the dependencies between repeated measures at each SUA. We scaled the year variable to have a mean of zero and standard deviation of one before model fitting using the scale() function in base R (R Core Team, 2023). Our linear mixed model is expressed as:

$$G_{ijt}^{(1/3)} = \beta_0 + \beta_1 Y_t + \beta_2 Y_t^2 + \beta_3 SUA_j + \beta_4 \left(Y_t SUA_j\right) + \beta_5 \left(Y_t^2 SUA_j\right) + b_{0j} + b_{0k(j)} + \varepsilon_{ijt}$$

where $G_{ijt}^{(1/3)}$ is the cube root of the Gravity Index for the SA2 *i*, in the SUA *j*, in year *t*, β_0 is the intercept, and β_1 to β_5 are the fixed effect coefficients for the linear and quadratic effects of year (Y_t), the linear effect of significant urban area (SUA_j), and their interactive effects. $b_{0j} + b_{0k(j)}$ represent the random intercept effects of SA2 nested in SUA, and ε_{ijt} is the residual error term. We fitted models using the 'glmmTMB' package

(Brooks et al., 2017) in R version 4.4.1 (R Core Team, 2023).

To answer Question 3, we constructed two counterfactual scenarios for each SA2. In the first scenario (population frozen at 2001), we maintained the estimated residential population of each SA2 fixed at its 2001 value while allowing protected area values to vary, thereby isolating the effect of protected area increase. In the second scenario (protected areas frozen at 2001), we maintained each protected area fixed at its 2001 value while allowing SA2 populations to vary as observed, isolating the effect of population growth. Constructing these two counterfactuals allowed us to decompose temporal changes in equity of access into the respective contributions of population growth and protected area expansion. This provided insight as to whether protected area additions were sufficient to offset the accessibility losses attributable to population growth.

3. Results

3.1. General findings

The total population of Australia's SUAs increased from 16.4 million people in 2001 to 23.8 million in 2024, an increase of 7.4 million people or 45% of the 2001 total. Larger metropolitan SUAs experienced the largest share of population growth. The SUA of Melbourne featured the largest population change, increasing from 3.4 million in 2001 to 5.2 million in 2024, an increase of 1.8 million people (53% increase) (Fig. 2). This was followed by Sydney, changing from a population of approximately 3.8 million people in 2001 to 5.1 million people in 2024, representing a 36.5% increase. Conversely, regional SUAs experienced lower population growth rates. Some regional SUAs even experienced a

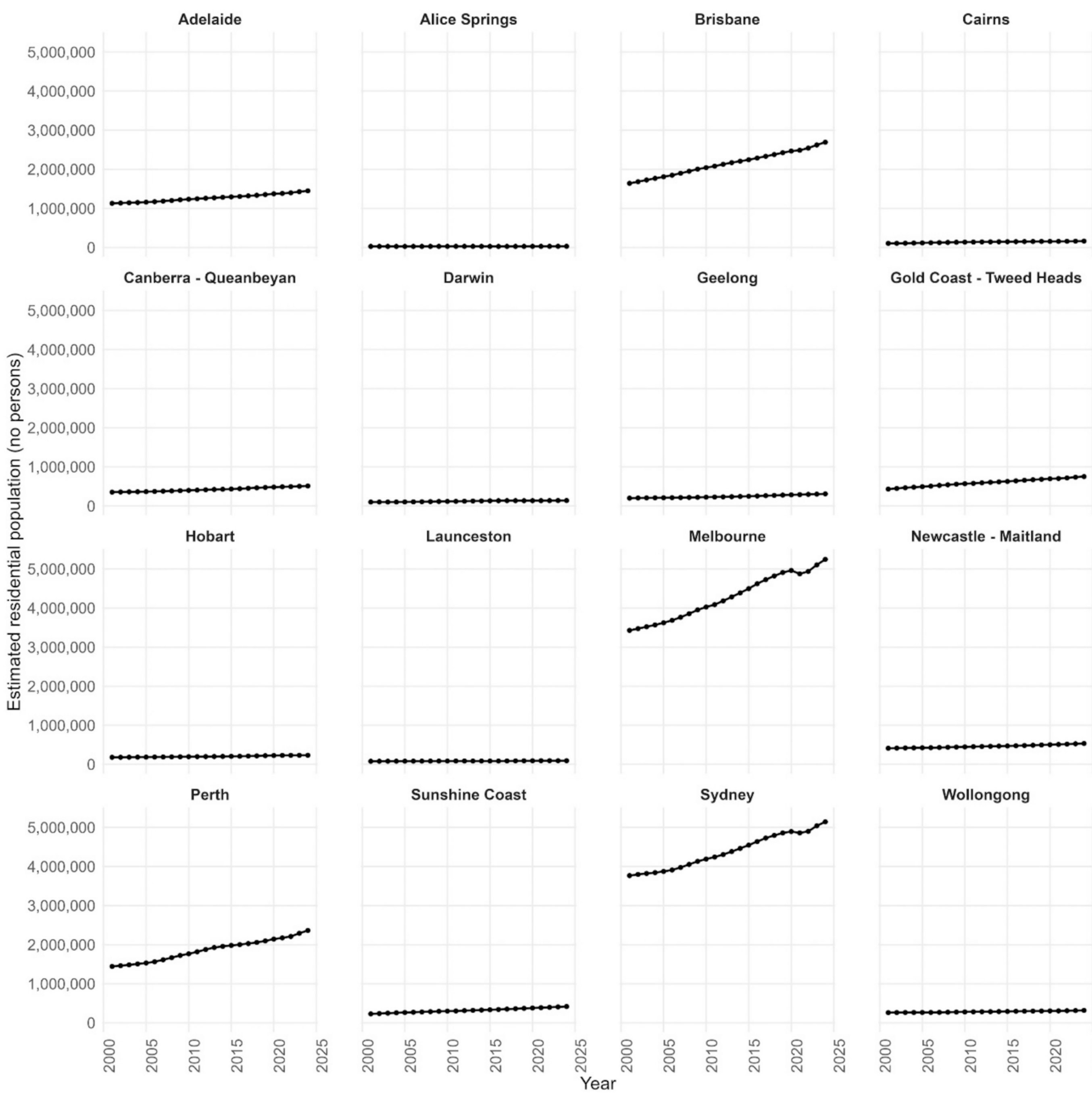

Fig. 2. Estimated residential population (ERP) changes across metropolitan and large regional SUAs in Australia.

population decrease. Notably, Broken Hill's population decreased from 20,929 people in 2001 to 17,541 people in 2024, a decline of 3,388 people (−16%).

We found that as of 2024, a total of 6.1 million ha of land, representing 11.4% of Australia's IUCN protected area under categories II-VI that are publicly accessible, occurred within the 60 km network service area around SUAs. This has increased from 5.1 million ha in 2001. Change was unevenly distributed. Of the metropolitan (capital city) SUAs, Melbourne increased its accessible legislated protected area from 103,846 ha in 2001 to 116,907 ha in 2024, an increase of 13,061 ha. Sydney increased its protected areas from 370,303 ha in 2001 to 428,571 ha in 2024, an increase of 58,268 ha, Adelaide increased from 68,729 ha in 2001 to 92,095 ha in 2024, a relatively large increase of 23,366 ha (Fig. 3). Canberra-Queanbeyan featured an increase of 7,566 ha between 2001 and 2024 to a total accessible area protected at 148,109 ha. Brisbane grew its accessible protected area from 204,382 ha in 2001 to 210,128 ha in 2024.

Hobart had by far the largest accessible protected area, with 706,609 ha in 2024, increasing from 695,717 ha in 2001. Other SUAs with large accessible protected areas by 2024 included Mildura-Buronga (479,688 ha), Sunshine Coast (361,006 ha), Gympie (343,722 ha), Horsham (324,179 ha), and Lithgow (289,458 ha). Darwin had the smallest accessible protected area of the metropolitan SUAs, at 28,317 ha by 2024. Among large populated regional SUAs, Cairns (373,819 ha) had extensive accessible protected areas within its respective network service area by 2024, while Alice Springs (131,401 ha), Geelong (152,818

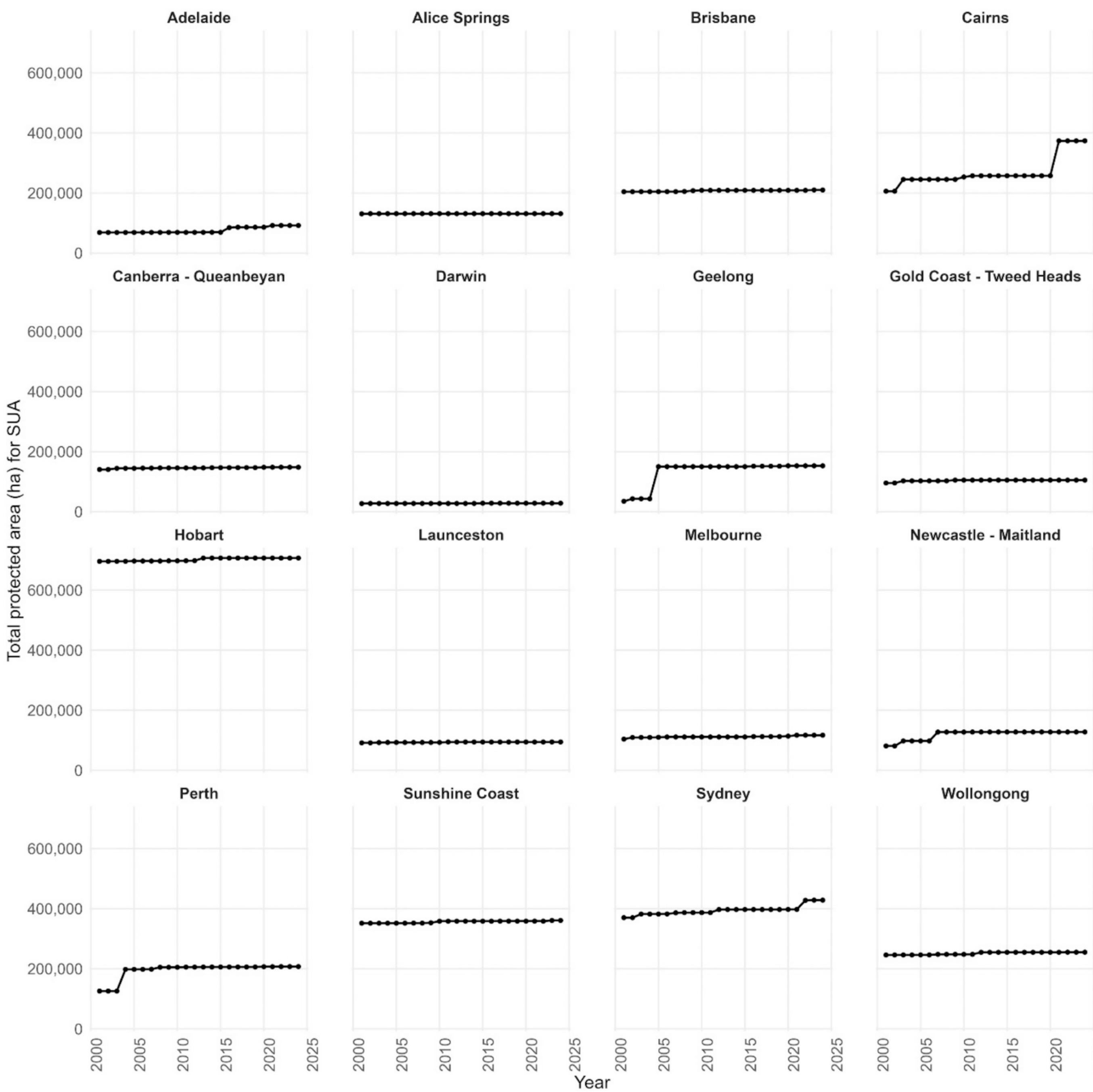

Fig. 3. Changes in legislated protected areas under IUCN Categories II to VI that are accessible to the public and within the 60 km network service area for metropolitan and large regional SUAs.

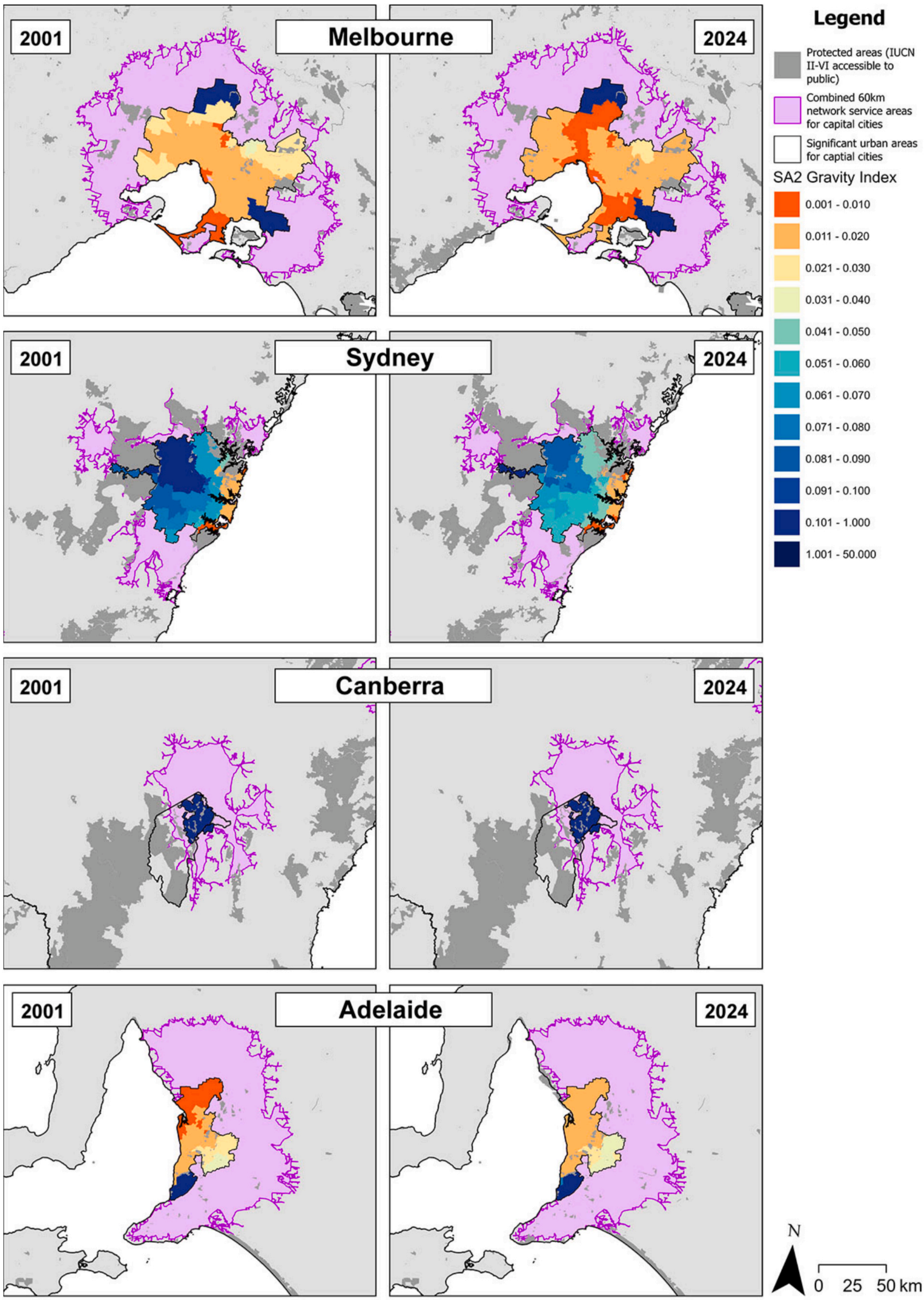

Fig. 4. Values for the Gravity Index for metropolitan (capital city) SUAs for the years 2001 and 2024 together with the combined 60 km network service areas.

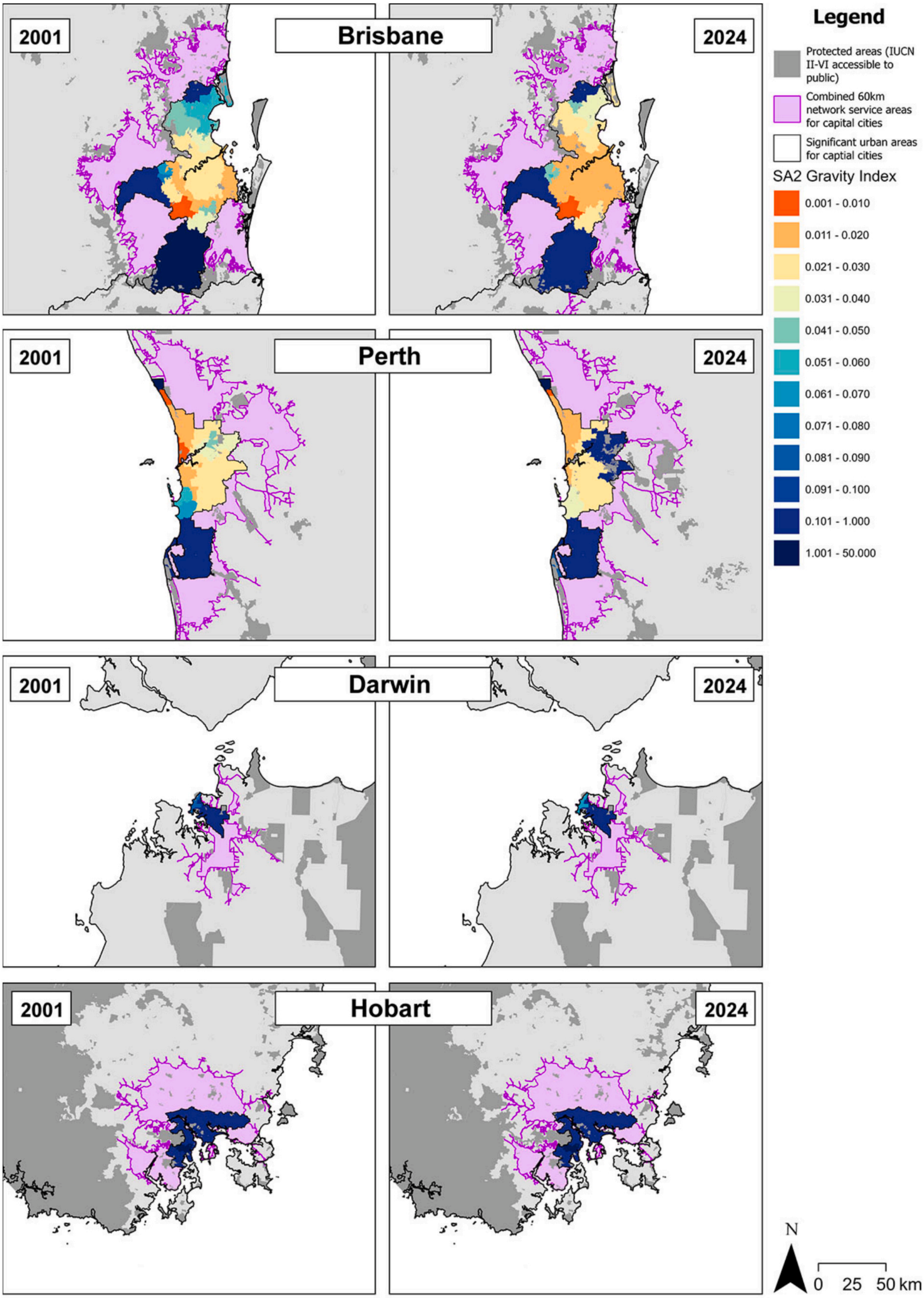

Fig. 4. (*continued*).

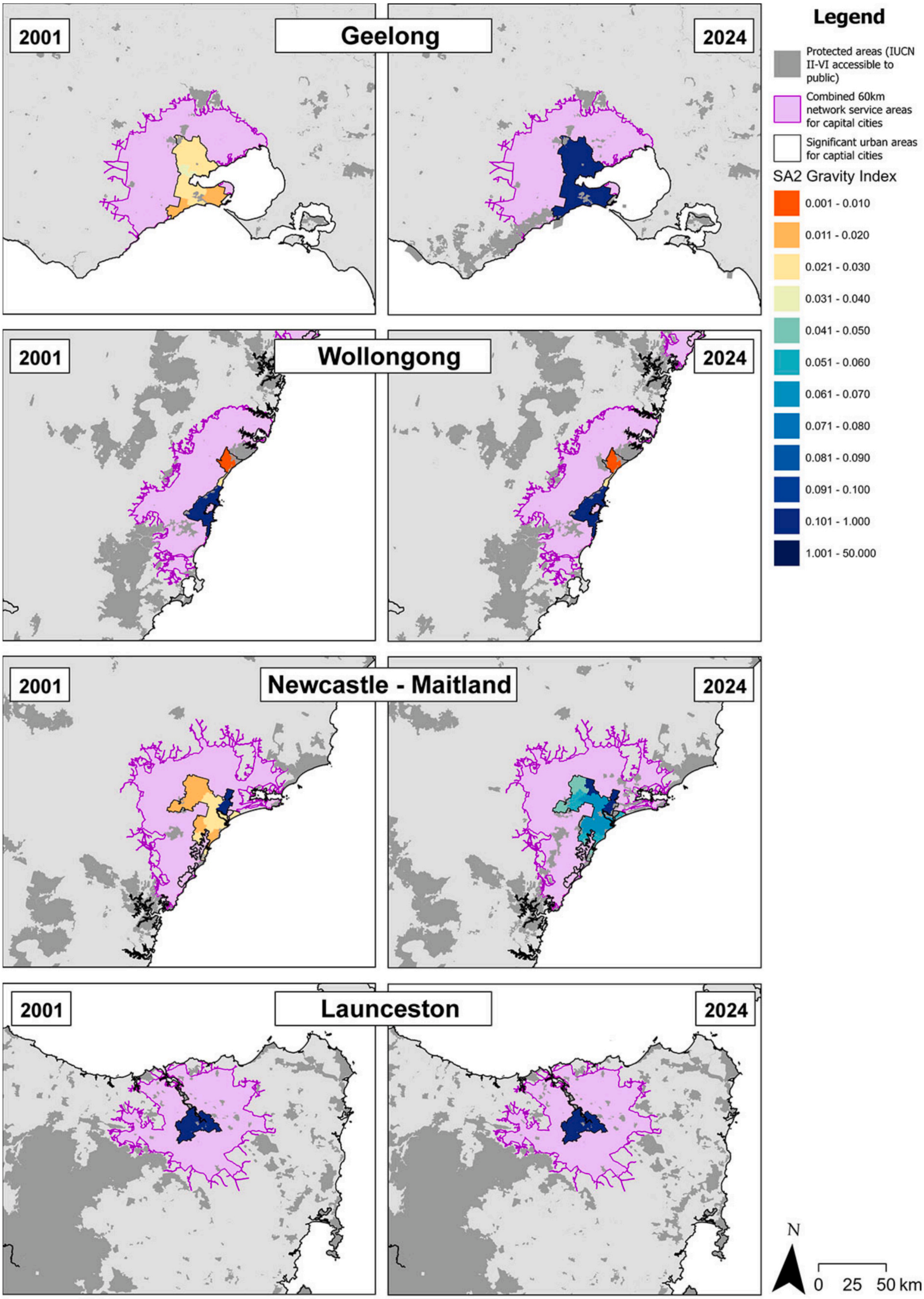

Fig. 5. Values for the Gravity Index in selected regional SUAs for the years 2001 and 2024 together with the combined 60 km network service areas.

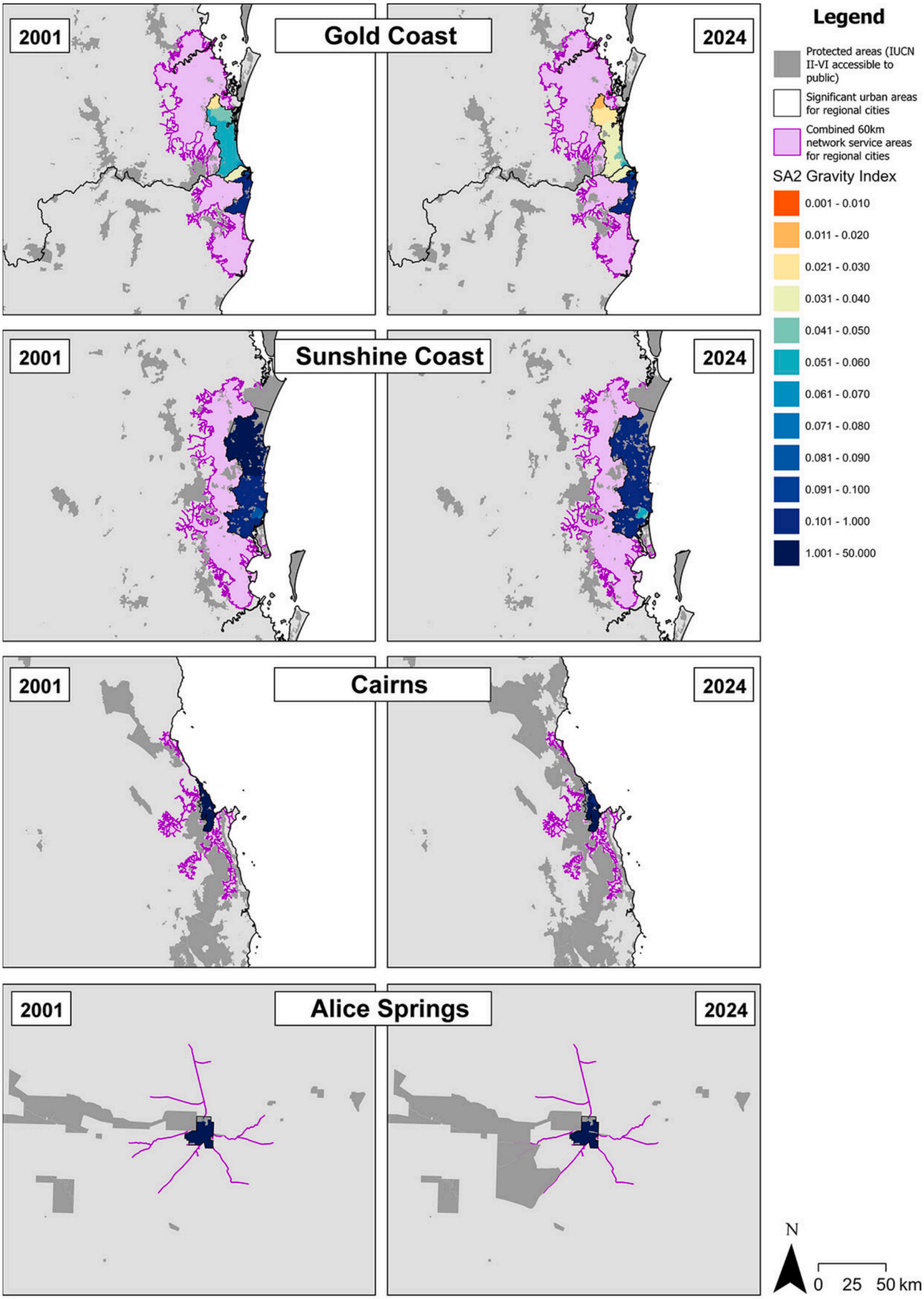

Fig. 5. (*continued*).

ha), Launceston (94,183 ha) and Gold Coast-Tweed Heads (105,203 ha) contained more modest amounts by 2024 (Fig. 3).

We found that median distances across network service areas between SUAs and publicly accessible protected areas (IUCN Categories II-VI) by 2024 ranged from 7.5 km in Emerald to 56.6 km in Mudgee. Among metropolitan SUAs, median distances were 43 km in Melbourne, 36.9 km in Sydney, 32.3 km in Perth, 33.5 km in Adelaide, 39 km in Brisbane, 17.7 km in Canberra – Queanbeyan, 34.1 km in Hobart and 32.3 km for Darwin. Among large population regional SUAs, median distances were 37.9 km in Geelong, 44.3 km in Launceston, 35.2 km in Gold Coast – Tweed Heads, 27.7 km in Cairns, 35.7 km in Newcastle – Maitland, 35 km in Sunshine Coast, 37.6 km in Wollongong and 13.5 km in Alice Springs.

(Question 1) *Is there spatial variation in patterns of equity of access from SUAs to protected areas*?

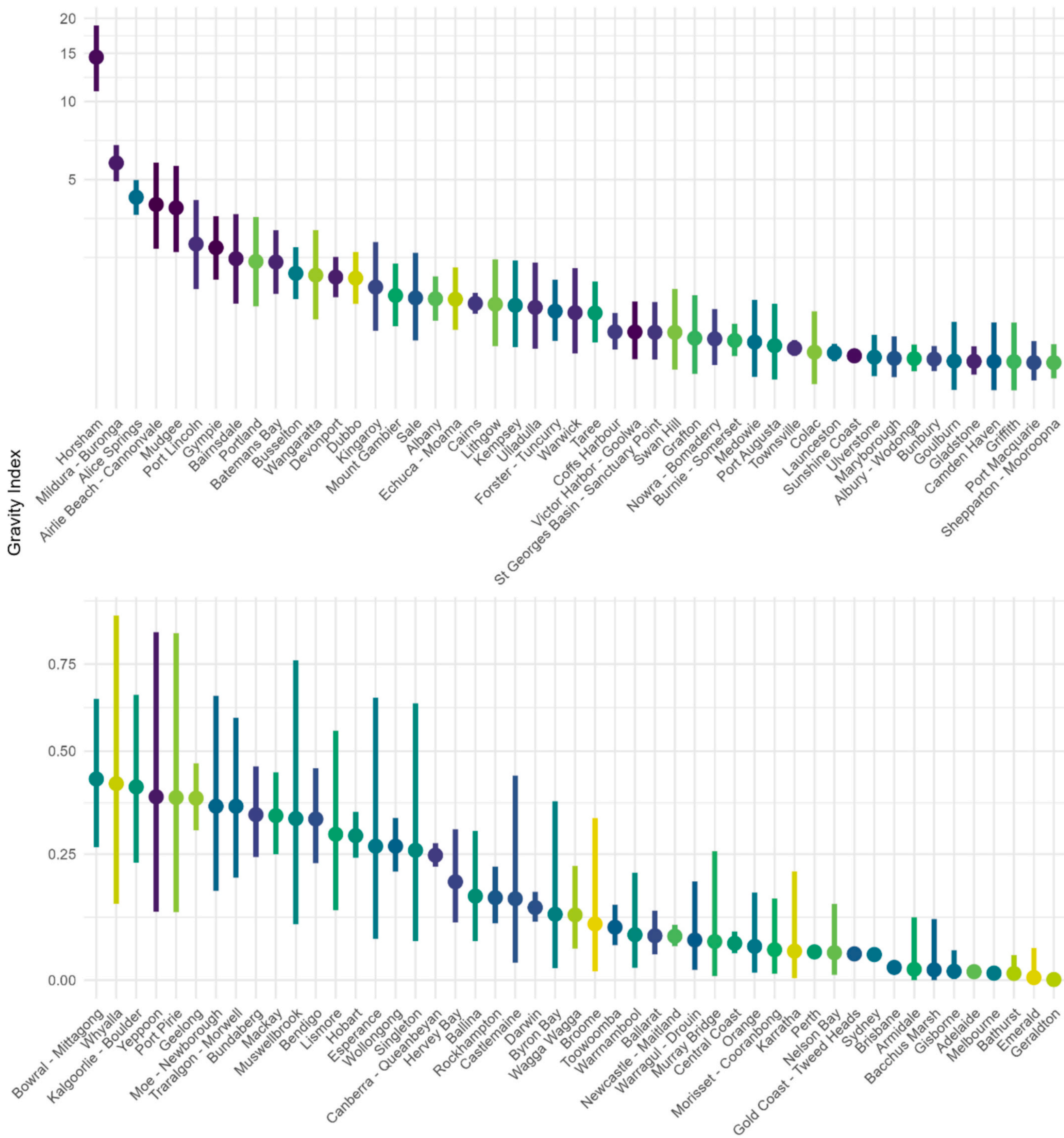

Fig. 6. Overall model-predicted means and 95% confidence intervals for the Gravity Index sum from 2001 to 2024 in SUAs. Note that the y axis is log(x + 1) scaled. Refer to Table S1 for the full model estimates and Fig. S1 for interaction effect sizes. Colours follow the viridis palette ordered by each city's estimated linear rate of change in Gravity Index over time, with dark purple indicating cities with the most negative (declining) trends and yellow indicating cities with the most positive (increasing) trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We found that values for the model-predicted mean Gravity Index exhibited substantial spatial variation among SUAs (Figs. 4 and 5). The larger and more populous SUAs, such as the metropolitan SUAs, were characterized by lower Gravity Index values, indicating more limited relative equity of access within their respective network service areas. In contrast, smaller regional SUAs displayed higher cubed mean Gravity Index values, reflecting comparatively greater accessibility. The highest-scoring SUA for all years was Horsham in Victoria, with a model-predicted mean Gravity Index of 14.53 (Fig. 6). This high score was driven by a relatively lower human population (16,956 in 2024) with access to large, protected areas (324,179 ha). The SUAs of Mount Isa, Port Hedland and Broken Hill returned a Gravity Index of 0, where no publicly accessible legislated protected areas under IUCN categories II-VI were detected within their respective 60 km network service areas. Melbourne performed the most poorly of the metropolitan SUAs, with a model-predicted mean Gravity Index of 0.01 (Fig. 6). Overall, it was ranked seventh lowest, followed by the small regional SUAs of Bathurst, Emerald, Geraldton, Mount Isa, Port Hedland and Broken Hill. Among the metropolitan SUAs, Hobart was the top performer with a Gravity Index score of 0.29, followed by Canberra–Queanbeyan (0.25), Darwin at 0.14, Perth and Sydney (both 0.05), Brisbane and Adelaide (both 0.02). Alice Springs had the highest mean Gravity Index of 4.22 of the large population regional SUAs, followed by Cairns (1.29), Launceston (0.56), Sunshine Coast (0.52), Geelong (0.38), Wollongong (0.27), Newcastle-Maitland (0.08), and Gold Coast-Tweed Heads (0.05).

(Question 2) *Have patterns of equity of access for SA2s to protected areas changed over time*?

We found that mean values for the Gravity Index exhibited substantial variation over time across SUAs. Between 2001 and 2024, the SUA of Echuca-Moama experienced the highest increase in mean Gravity Index, rising from 0.33 in 2001 to 1.51 in 2024. This was followed by Broome, which increased from 0 in 2001 to 0.99 in 2024. Among the metropolitan SUAs, Adelaide recorded the largest net gain, increasing from 0.015 in 2001 to 0.026 in 2024 (Fig. 5). The metropolitan SUAs of

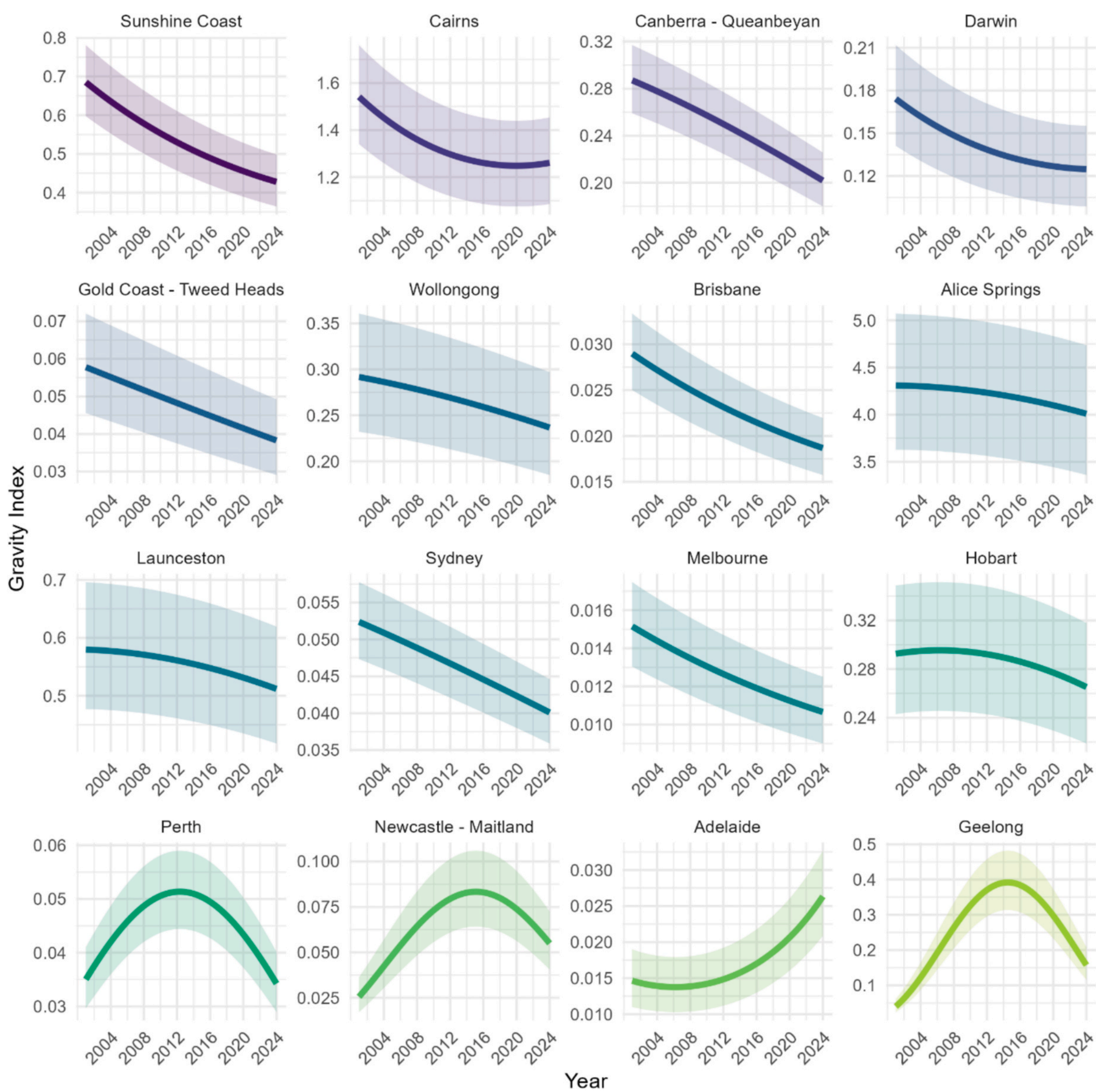

Fig. 7. Temporal model-predicted means and 95% confidence intervals for the Gravity Index sum from 2001 to 2024 in large population SUAs. Refer to Table S1 for the full model estimates and Fig. S2 for temporal trends for all SUAs. Colours follow the viridis palette ordered by each city's estimated linear rate of change in Gravity Index over time, with dark purple indicating cities with the most negative (declining) trends and yellow indicating cities with the most positive (increasing) trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

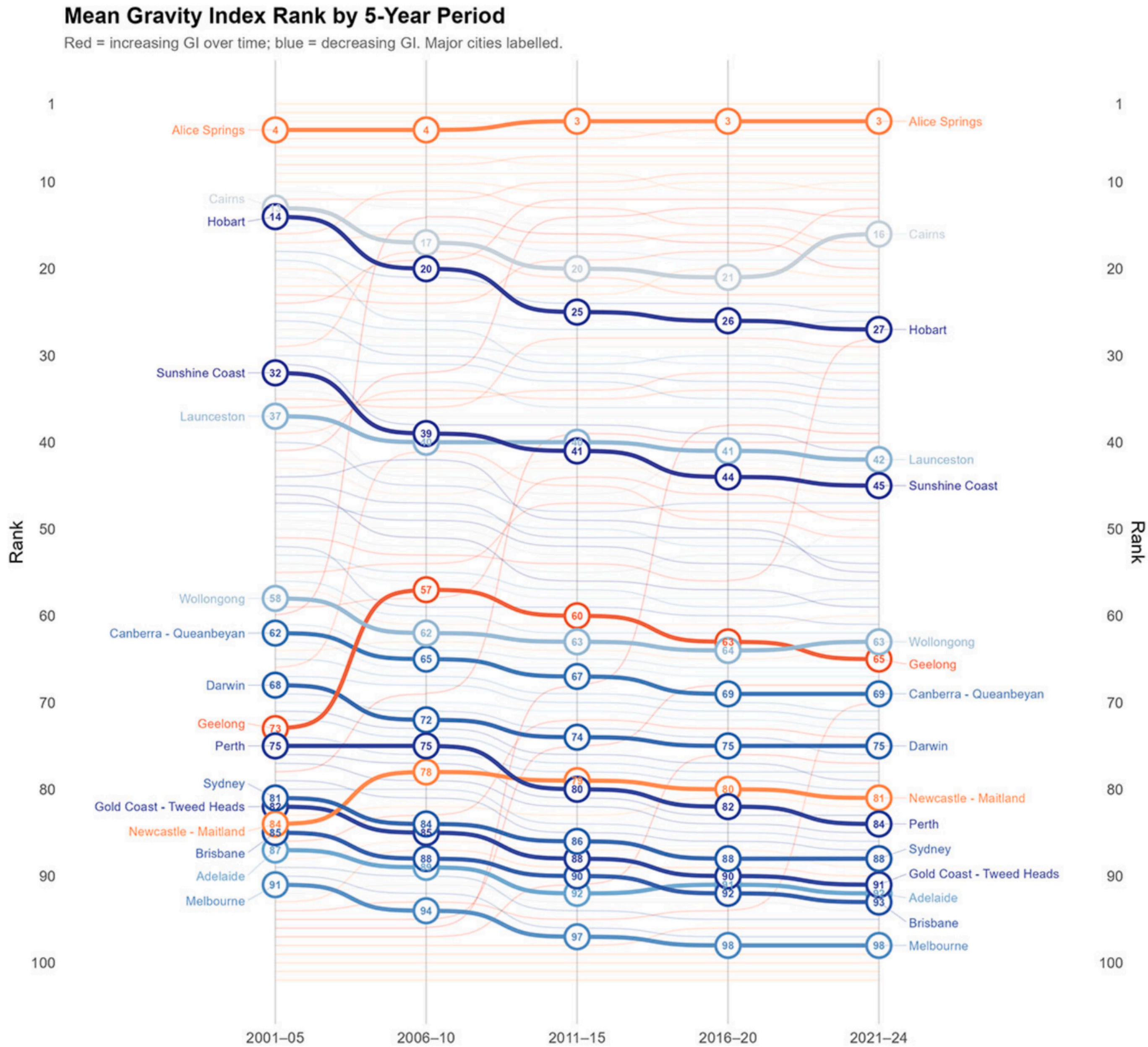

Fig. 8. Bump plot showing mean Gravity Index Ranks in 5-Year periods with metropolitan and large population regional SUAs highlighted. Colours represent whether SUAs have decreased (blue) or increased (red) in rank over the time of the study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Brisbane, Canberra – Queanbeyan, Sydney, and Melbourne all exhibited a decline over the analysis period (Fig. 7).

Over this time, Melbourne remained the lowest Gravity Index ranked of the metropolitan SUAs between 2001 and 2024 (Fig. 8). Overall, its ranking declined from 91st in 2001 to 98th in 2024 of all the SUAs analysed. The highest ranked metropolitan SUA was Hobart, ranking 14th in 2001 across all SUAs, but it too declined to 27th by 2024. Rankings changed amongst large population regional SUAs. Of these SUAs, Geelong had the highest rank change, moving from 73rd place in 2001 to 57th in 2006, but then declining to 65th ranking by 2024. Alice Springs maintained its highest Gravity Index ranking over the study period.

(Question 3) *Has the addition of new legislated protected areas offset human population growth in SUAs in terms of equity of access?*

Additions to the protected area network since 2001 compensated for the effects of population growth on equity of access (Fig. 9A). The median Gravity Index across all SUAs rose from 0.43 in 2001 to a peak of 0.48 in 2010, driven predominantly by substantial additions of protected areas during this period, and remained above the 2001 baseline throughout most of the study period. From 2010 onwards, the observed Gravity Index declined as population growth outpaced further park additions, although it remained above the 2001 baseline by 2024. If no new protected areas had been added since 2001, the median Gravity Index would have declined by 23% below the 2001 baseline by 2024. Conversely, if population remained at 2001 levels while protected areas expanded as observed, the median Gravity Index would have increased by 23% above the 2001 baseline by 2024, indicating that population growth substantially dampened the gains in equity of access attributable to protected area expansion. Among the 16 metropolitan and large regional SUAs examined (Fig. 9B), 13 recorded declines in the observed

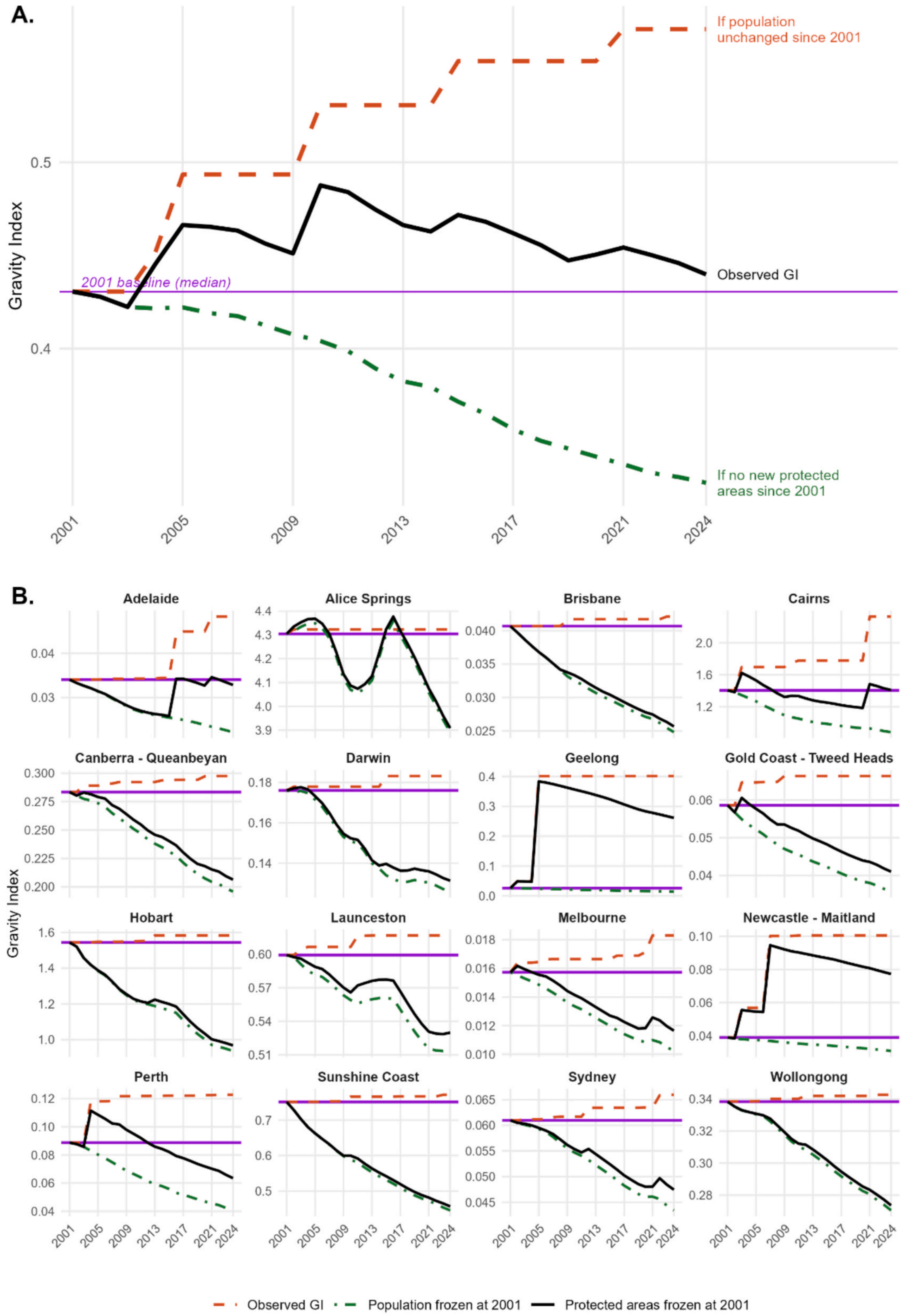

Fig. 9. Counterfactual decomposition of the Gravity Index across Australian SUAs, 2001–2024. Panel A shows the median Gravity Index across all SUAs for three scenarios: the observed Gravity Index (black solid line), a counterfactual in which SA2 populations are held constant at 2001 levels while protected areas expand as observed (orange dashed line), and a counterfactual in which protected area extents are held constant at 2001 levels while populations change as observed (green dot-dash line). The purple horizontal line denotes the 2001 median Gravity Index baseline. Panel B shows the same three scenarios for the 16 metropolitan and large regional SUAs examined in this study. Note that y-axes are scaled independently for each SUA to aid visual interpretation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Gravity Index between 2001 and 2024. In all cases, the protected-areas-frozen counterfactual declined more steeply than the observed trajectory, confirming that while protected area additions partially offset population-driven losses, they were insufficient to maintain equity of access at 2001 levels across most of these SUAs.

4. Discussion

We quantified spatial differences and temporal changes in the equity of access (corresponding to recreational day trips) between SA2s, their respective SUAs and publicly accessible legislated protected areas in Australia between 2001 and 2024. To do this, we applied a modified Gravity Model (*sensu* Sharifi et al., 2021) that integrated road-network distance, the size of protected areas and human population size within a network service area of a protected area. We calculated a Gravity Index for each individual route between an SA2 and a protected area entry point within a 60 km network service area of that SA2. We then summed the Gravity Indices for each SA2 and summarised them within their respective SUAs. We interpreted a higher summed Gravity Index as being beneficial because it indicates that people can access protected areas with shorter travel distances and less congestion. It also may reflect more dispersed visitation pressure across multiple sites, simultaneously improving human wellbeing and reducing ecological stress on individual protected areas. Our interpretation of low Gravity Index values often signalled a scarcity of accessible protected areas near significant urban area populations, leading to a potential concentrated demand on a comparatively small number of sites. This may exemplify a risk of further 'extinction of experience' (Soga & Gaston, 2016), which was first introduced as a term over 30 years ago to describe a decline in people interacting with nature (Pyle, 1993).

(Question 1) *Is there spatial variation in patterns of equity of access from SUAs to protected areas*?

Our analyses revealed marked spatial differences in values among SUAs for the Gravity Index and hence what we have termed equity of access (Fig. 4, Fig. 5). Such spatial variation was often characterized by, on the one hand, SUAs with high population pressure for some (but not all) metropolitan SUAs with lower Gravity Index values and, on the other, slower growing (and sometimes even declining) populations in SUAs in regional areas leading to comparatively higher Gravity Index values. However, patterns of spatial variation were nuanced. For example, whilst Australia's fastest growing metropolitan SUA (Melbourne) in terms of population had the worst (lowest) Gravity Index (Fig. 7, Fig. 8) among metropolitan SUAs, some regional SUAs also had similarly low values. We acknowledge that these outcomes highlight an inherent spatial dynamic; that bigger SUAs, by virtue of their respective larger populations, are likely to have a lower Gravity Index than smaller regional SUAs.

(Question 2) *Have patterns of equity of access for SA2s to protected areas changed over time*?
(Question 3) *Has the addition of new legislated protected areas offset human population growth in SUAs in terms of equity of access*?

At the outset of this investigation, we predicted that the very rapid rates of population growth in many SUAs, particularly in Australian metropolitan SUAs and most large populated regional SUAs, have outstripped increases in the area of protected areas in terms of equity of access (Fig. 9a and b). Such spatio-temporal changes are reflected in the declines of Gravity Indices between 2001 and 2024. For example, the SUA of Melbourne had the overall lowest mean Gravity Index of 0.01 of the metropolitan and larger population regional SUAs by 2024, which declined from 0.02 in 2001 (Fig. 7, Fig. 8). This was due to strong population growth of 1.8 million people over that time but only 13,061 ha of protected areas being added (a 13% increase) (Fig. 9b). Sydney was characterized by mean Gravity Index of 0.04 by 2024, which declined from 0.05 in 2001 (Fig. 7, Fig. 8) due to population increases. However, its accessible larger protected area network resulted in it maintaining a higher Gravity Index relative to Melbourne (Fig. 8).

Some SUAs experienced an increase in the Gravity Index over time. For example, Geelong, where population increases were broadly matched by increases in the extent of protected areas (Fig. 3, Fig. 7, Fig. 8), had an increase in its Gravity Index from 0.04 in 2001, peaking at 0.39 in 2014 following the addition of 118,076 ha of protected areas in 2005 (Fig. 9b) and declining to 0.16 in 2024 resulting from a population growth of 109,183 people (55% increase). Adelaide had a gain in its Gravity Index from 0.015 in 2001 to 0.026 in 2024, with its population growth of 318,849 people being offset by a larger expansion of its protected area estate by 23,366 ha (a 34% increase) (Fig. 9b).

4.1. Opportunities to reverse declines in the equity of access

We contend that protected areas around large SUAs with a low and declining Gravity Index are likely to be subject to increasing pressure. Focusing the creation of new protected areas, especially around SUAs with lower values for the Gravity Index, can help relieve such pressure, especially for metropolitan SUAs. This approach should be complemented by increased investment in the agencies responsible for protected area management. Current levels of urban development and patterns of land tenure will preclude an increase in the extent of protected areas adjacent to some SUAs. There are, however, important opportunities to expand protected areas and reverse trends in the Gravity Index in others. For example, there is approximately 327,690 ha of State Forest surrounding the Melbourne SUA that could be considered for potential expansion of the legislated protected area network. Previous studies have found that many of the unprotected State Forest areas east of Melbourne are characterized by high conservation values (Taylor & Lindenmayer, 2026). The Victorian Environment Assessment Council (VEAC) identified these values as commensurate with legislated protected area designation (VEAC, 2026).

While publicly accessible legislated protected areas under IUCN categories II-VI recognise the dual role of protecting biodiversity while providing opportunities for recreation, education, and wellbeing (Dudley, 2008), we also note that high visitation can place pressure on ecological values. It is therefore critical to ensure that efforts to increase human access to National Parks and other protected areas do not undermine their ecological condition and biodiversity values – which can occur through overuse (Buckley, 2020). For example, greater accessibility can require an expanded road network (especially when modes of transport are dominated by private motor vehicle use) with potentially increased environmental impacts such as greater levels of habitat fragmentation, elevated animal mortality, and increased spread of invasive plants (Ibisch et al., 2016; Wace, 1977). This highlights a need to balance demands for greater human access to National Parks and other legislated protected areas with the maintenance of other key values in such places, like the protection of biodiversity and ecosystem condition (Worboys & Trzyna, 2015). Improvements in visitor infrastructure, as well as adequate and consistent resourcing for the repair and maintenance, can be effective strategies for facilitating the visitor experience as well as protecting environmental values in popular protected areas (Dixon, 2017). In addition, better public transport to protected areas, especially National Parks, might mitigate impacts such as vehicle collisions associated with improved equity of access to protected areas.

5. Study limitations

We recognize there are several limitations to our work. First, the term "equity of access" can be interpreted in multiple ways, and we defined it specifically in terms of ease of reaching and using protected areas, through the distance travelled to a legislated protected area, and potential congestion (human population within the network service area of a protected area). While these variables allow for a consistent national comparison, they capture only part of the visitor experience. Important dimensions such as ecological richness (see Fuller et al., 2007; Gillerot et al., 2025), cultural values, landscape intactness, aesthetic values, and visitor infrastructure were not considered. This was because consistent national data were unavailable for them.

Second, protected areas are not homogenous green spaces and the heterogeneity of environments which characterize them can influence not only the biodiversity which depends on them but potentially also the quality of the human experience during visitation (Fuller et al., 2007; Gillerot et al., 2025; Houlden et al., 2021). We did not account for the biodiversity values of protected areas in our analyses. Rather, our approach using legislated IUCN protected area categories II-VI recognised the dual role of safeguarding ecosystems while also providing opportunities for education, recreation, and human wellbeing.

Third, our Gravity Index was a composite measure with three dimensions. The impact on human well-being of trade-offs between the different measures such as lower population growth versus greater expansion of protected areas is unknown. Therefore, an increase in population size (leading to more potential congestion) might have a different impact on well- being than an increase in the extent of the total protected area within a certain distance, even if changes in one versus the other results in a similar change in value for the Gravity Index value. For example, proportionately fewer people in densely populated SUAs may seek nature experiences (Soga & Gaston, 2016) or alternatively, more people may travel further to more remote parts of National Parks that are distant from popular locations (as seen in Canada post-COVID-19; Geng et al., 2025).

Finally, our distance input calculations to our Gravity Index between the SA2s and protected areas focused on roads accessible by passenger vehicles. We acknowledge this can be limiting as other forms of transport are excluded. Our focus on access by passenger vehicle is based on the lack of comprehensive visitation data across Australian protected areas. There are some broad generalisations, such as Tourism Research Australia reporting in 2019 that most visitors (81%) to National Parks across Australia travelled by private car. Passenger vehicle use in Australia is high compared with other countries. However, this does not equate to universal accessibility. Vehicle ownership is unevenly distributed, and a substantial minority of the population lacks direct access to a car. For example, nearly 24% of Australians are under the age of 20 and generally cannot drive themselves, relying instead on family members for transport. Similarly, elderly people, people living with disabilities inhibiting their ability to drive, and others without a driver's licence, face barriers in accessing protected areas. Equity in access is not fully captured by car ownership statistics. While our Gravity Index accounted for distance and congestion, it does not differentiate between drivers and non-drivers lacking the ability to access a vehicle. Data were not available for our analysis on alternative modes of transport to protected areas that would otherwise accommodate for the needs of people living with limited mobility.

6. Concluding comments

Protected areas provide crucial benefits by supporting human health, fostering pro-nature attitudes, and contributing to local economies. Facilitating access to protected areas for urban populations creates opportunities for recreation, human well-being, and biodiversity conservation. We employed a novel application of the Gravity Index to quantify spatial differences and temporal changes in the equity of access between SUAs and publicly accessible protected areas across Australia. Our results highlighted marked differences in equity of access between SUAs and often large temporal changes in values for the Gravity Index, often driven by rapid growth in human populations between 2001 and 2024. In other cases, increases in extent of protected areas offset temporal declines in the Gravity Index. Our results highlight those SUAs where protected area expansion could help facilitate greater access to protected areas and, in turn, partially offset declines in equity of access due to population increase.

CRediT authorship contribution statement

Chris Taylor: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maldwyn John Evans:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis. **Sarah Rees:** Writing – review & editing, Validation, Investigation. **David Lindenmayer:** Writing – review & editing, Validation, Supervision, Investigation, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2026.105696.

The Supplementary Materials contains Table S1 - model estimates table for the linear mixed model quantifying relationships between the gravity index of each significant urban area over time and the differences between each significant urban area; Figure S1 - linear and quadratic effect sizes (estimates) for the interaction terms of city and time in the linear mixed model; and Figure S2 - temporal model-predicted means for the Gravity Index sum from 2001 to 2024 in all SUAs

Data availability

Data will be made available on request.

References

ABS. (2021a). *Motor vehicle census* (Australian Bureau of Statistics. https://www.abs.gov.au/statistics/industry/tourism-and-transport/motor-vehicle-census-australia/latest-release.

ABS. (2021b). *Statistical Area Level 2 - Australian Statistical Geography Standard (ASGS) Edition 3*. https://www.abs.gov.au/statistics/standards/australian-statistical-geography-standard-asgs-edition-3/jul2021-jun2026/main-structure-and-greater-capital-city-statistical-areas/statistical-area-level-2.

ABS. (2022). *Transport: Census*. https://www.abs.gov.au/statistics/industry/tourism-and-transport/transport-census/latest-release.

ABS. (2025a). *Protected areas: Protect, repair and manage the environment*. : https://www.abs.gov.au/statistics/measuring-what-matters/measuring-what-matters-themes-and-indicators/sustainable/protected-areas.

ABS. (2025b). *Regional population methodology* (Australian Bureau of Statistics. https://www.abs.gov.au/methodologies/regional-population-methodology/2023-24.

ABS. (2025c). *Significant Urban Areas - Australian Statistical Geography Standard (ASGS) Edition 3*. https://www.abs.gov.au/statistics/standards/australian-statistical-geography-standard-asgs-edition-3/jul2021-jun2026/significant-urban-areas-urban-centres-and-localities-section-state/significant-urban-areas.

ABS. (2025d). *Statistical Area Level 2* (Australian Bureau of Statistics. https://www.abs.gov.au/statistics/standards/australian-statistical-geography-standard-asgs-edition-3/jul2021-jun2026/main-structure-and-greater-capital-city-statistical-areas/statistical-area-level-2.

Barragan-Jason, G., Loreau, M., de Mazancourt, C., Singer, M. C., & Parmesan, C. (2023). Psychological and physical connections with nature improve both human well-being and nature conservation: A systematic review of meta-analyses. *Biological Conservation, 277*, Article 109842. https://doi.org/10.1016/j.biocon.2022.109842

Biodiversity Council. (2025). *2024–2025 Biodiversity Concerns Report: A survey of community attitudes toward nature conservation*. https://www.biodiversitycouncil.org.au..

Bolam, F. C., Mair, L., Angelico, M., Brooks, T. M., Burgman, M., Hermes, C., Hoffmann, M., Martin, R. W., McGowan, P. J., Rodrigues, A. S., Rondinini, C., Westrip, J. R., Wheatley, H., Bedolla-Guzmán, Y., Calzada, J., Child, M. F., Cranswick, P. A., Dickman, C. R., Fessl, B.,…Butchart, S. H. (2020). How many bird and mammal extinctions has recent conservation action prevented? *Conservation Letters*, *14*, e12762. https://doi.org/https://doi.org/10.1111/conl.12762.

Brooks, M. E., Kristensen, K., van Benthem, K. J., Magnusson, A., Berg, C. W., Nielsen, A., Skaug, H. J., Machler, M., & Bolker, B. M. (2017). glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *The R journal, 9*, 378–400. https://doi.org/10.3929/ethz-b-000240890

Buckley, R. (2020). Nature tourism and mental health: Parks, happiness, and causation. *Journal of Sustainable Tourism, 28*, 1409–1424. https://doi.org/10.1080/09669582.2020.1742725

Bureau of Infrastructure, T. a. R. E. (2017). *Progress in Australian Regions – Yearbook*. https://www.bitre.gov.au/publications/2017/regional-yearbook-2017.

Bushell, R., & Eagles, P. F. (Eds.). (2006). *Tourism and protected areas: Benefits beyond boundaries*. CABI Publishing.

DCCEEW. (2025). *Collaborative Australian Protected Areas Database (CAPAD): protected area data* (Department of Climate Change, Energy, the Environment, and Water. https://www.dcceew.gov.au/environment/land/nrs/science/capad.

DCCEEW. (2026). *Achieving 30 by 30*. DCCEEW. Retrieved 3 March 2026 from https://www.dcceew.gov.au/environment/land/achieving-30-by-30.

Dinerstein, E., Joshi, A. R., Hahn, N. R., Lee, A. T. L., Vynne, C., Burkart, K., Asner, G. P., Beckham, C., Ceballos, G., Cuthbert, R., Dirzo, R., Fankem, O., Hertel, S., Li, B. V., Mellin, H., Pharand-Deschênes, F., Olson, D., Pandav, B., Peres, C. A.,…Zolli, A. (2024). Conservation Imperatives: securing the last unprotected terrestrial sites harboring irreplaceable biodiversity [Frontiers in Science Lead Article]. *Frontiers in Science, Volume 2 - 2024*. https://doi.org/10.3389/fsci.2024.1349350.

Dixon, G. (2017). A longitudinal study of backcountry track and campsite conditions on the Overland Track, Tasmania, Australia. *Journal of Outdoor Recreation and Tourism, 19*, 25–36. https://doi.org/10.1016/j.jort.2017.05.002

Dudley, N. (2008). *Guidelines for Applying Protected Area Management Categories*. https://portals.iucn.org/library/sites/library/files/documents/pag-021.pdf.

Esri. (2024). ArcGIS Pro (Version 3.3). In https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.

Evans, M. J., Gaston, K. J., Cox, D. T. C., & Soga, M. (2023). The research landscape of direct, sensory human–nature interactions. *People and Nature, 5*, 1893–1907. https://doi.org/10.1002/pan3.10556

Franěk, M. (2023). Landscape preference: the role of attractiveness and spatial openness of the environment. *Behavioral Sciences. Behavioral Sciences, 13*(8), 666. https://doi.org/10.3390/bs13080666

Fuller, R. A., Irvine, K. N., Devine-Wright, P., Warren, P. H., & Gaston, K. J. (2007). Psychological benefits of greenspace increase with biodiversity. *Biology Letters, 3*, 390–394. https://doi.org/10.1098/rsbl.2007.0149

Geng, D. H., Chen, M., Seely, H., H.W., H., Gaston, C., Wu, W., & Wang, G. (2025). Adapting to change: Visitor patterns in national parks across the pandemic timeline. *Trees, Forests and People 20*, 100874. https://doi.org/https://doi.org/10.1016/j.tfp.2025.100874.

Geoscape. (2025). *National Roads* (Digital Atlas of Australia. https://ecat.ga.gov.au/geonetwork/srv/api/records/36f8e03f-d982-42c1-ad52-a3f2452faffc.

Gillerot, L., Landuyt, D., Bourdin, A., Rozario, K., Shaw, T., Steinparzer, M., Stojek, K., Vanroy, T., Cuentas Romero, A. G., Müller, S., Oh, R. R. Y., Proß, T., Bonal, D., Bonn, A., Bruelheide, H., Godbold, D., Haluza, D., Jactel, H., Jaroszewicz, B.,…Verheyen, K. (2025). Forest biodiversity and structure modulate human health benefits and risks. *Nature Sustainability*, *8*(5), 485-497. https://doi.org/https://doi.org/10.1038/s41893-025-01547-3.

Hansen, W. G. (1959). How Accessibility Shapes Land Use. *Journal of the American Institute of Planners, 25*, 73–76. https://doi.org/10.1080/01944365908978307

Houlden, V., Jani, A., & Hong, A. (2021). Is biodiversity of greenspace important for human health and wellbeing? a bibliometric analysis and systematic literature review. *Urban Forestry and Urban Greening, 66*, Article 127385. https://doi.org/10.1016/j.ufug.2021.127385

Ibisch, P. L., Hoffmann, M. T., Stefan Kreft, S., Pe'er, G., Kati, V., Biber-Freudenberger, L., DellaSala, D. A., Vale, M. M., Hobson, P. R., & Selva, N. (2016). A global map of roadless areas and their conservation status. *Science*, *354*, 1423-1427. https://doi.org/https://doi.org/10.1126/science.aaf7166.

Jabbar, M., Yusoff, M. M., & Shafie, A. (2022). Assessing the role of urban green spaces for human well-being: A systematic review. *GeoJournal, 87*, 4405–4423. https://doi.org/10.1007/s10708-021-10474-7

Job, H., Majewski, L., Engelbauer, M., Bittlingmaier, S., & Woltering, M. (2021). Establishing a standard for park visitation analyses: Insights from Germany. *Journal of Outdoor Recreation and Tourism, 35*, 1–19. https://doi.org/10.1016/j.jort.2021.100404

Kapatsila, B., Palacios, M. S., Grisé, E., & El-Geneidy, A. (2023). Resolving the accessibility dilemma: Comparing cumulative and gravity-based measures of accessibility in eight Canadian cities. *Journal of Transport Geography, 107*, Article 103530. https://doi.org/10.1016/j.jtrangeo.2023.103530

Keniger, L. E., Gaston, K. J., Irvine, K. N., & Fuller, R. A. (2013). What are the benefits of interacting with nature? *International Journal of Environmental Research and Public Health, 10*(3), 913–935. https://doi.org/10.3390/ijerph10030913

Kondo, M. C., Oyekanmi, K. O., Gibson, A., South, E. C., Bocarro, J., & Hipp, J. A. (2020). Nature prescriptions for health: A review of evidence and research opportunities. *International Journal of Environmental Research and Public Health, 17*, 4213. https://doi.org/10.3390/ijerph17124213

Lindenmayer, D. B., Thorn, S., & Noss, R. (2018). Countering resistance to protected area extension. *Conservation Biology, 32*, 315–321. https://doi.org/10.1111/cobi.12990

Loch, A., Sexton, S., Maclean, J., O'Connor, P., Adamson, D., & Scholz, G. (2024). Increased monetary equity and health wellbeing benefits for marginal urban socioeconomic groups from access to green space. *Urban Forestry & Urban Greening, 102*, Article 128576. https://doi.org/10.1016/j.ufug.2024.128576

Luo, W., & Qi, Y. (2009). An enhanced two-step floating catchment area (E2SFCA) method for measuring spatial accessibility to primary care physicians. *Health & Place, 15*, 1100–1107. https://doi.org/10.1016/j.healthplace.2009.06.002

Majewski, L., Frieser, A., Lang-Novikov, K., & Woltering, M. (2024). Mapping the Distance: An Analysis of Visitor Travel Distance to German National Parks and Biosphere Reserves. *Raumforschung und Raumordnung, 82*, 384–404. https://doi.org/10.14512/rur.2571

Melbourne Water. (2020a). *Water Supply Catchments for Melbourne Water* (Melbourne Water. https://data-melbournewater.opendata.arcgis.com/datasets/melbournewater::water-supply-catchments-for-melbourne-water/about.

Melbourne Water. (2020b). *Water Supply Catchments for Melbourne Water*. https://data-melbournewater.opendata.arcgis.com/datasets/melbournewater::water-supply-catchments-for-melbourne-water/about.

Mu, L., Xing, L., Jing, Y., & Hu, Q. (2023). Spatial optimization of park green spaces by an improved two-step optimization model from the perspective of maximizing accessibility equity. *Land, 12*(5), 948. https://doi.org/10.3390/land12050948

NRMMC. (2009). *Australia's Strategy for the National Reserve System 2009–2030* (Australia's Strategy for the National Reserve System 2009 – 2030, Issue. https://www.dcceew.gov.au/environment/land/nrs/publications/strategy-national-reserve-system.

Ogrizek, M. (2019). *Australia's National Parks by Public Transport*. Bright, VIC.

Parks Victoria. (2025). *5 top walks near Melbourne accessible via public transport*. Victoria State Government. Retrieved 03/10/2025 from https://www.parks.vic.gov.au/things-to-do/hiking-and-bushwalking/walks-near-melbourne-public-transport.

Pyle, R. M. (1993). *The thunder tree: Lessons from an urban wildland*. Houghton Mifflin.

R Core Team. (2023). *R: A language and environment for statistical computing*. In R Foundation for Statistical Computing. https://www.R-project.org/.

Rodrigues, A. S. L., & Brooks, T. M. (2007). Shortcuts for Biodiversity Conservation Planning: The Effectiveness of Surrogates. *Annual Review of Ecology, Evolution, and Systematics*, *38*(Volume 38, 2007), 713-737. https://doi.org/https://doi.org/10.1146/annurev.ecolsys.38.091206.095737.

Sanderson, F. J., Wilson, J. D., Franks, S. E., & Buchanan, G. M. (2023). Benefits of protected area networks for breeding bird populations and communities. *Animal Conservation, 26*, 279–289. https://doi.org/10.1111/acv.12832

Schamel, J., & Job, H. (2017). National parks and demographic change - modelling the effects of ageing hikers on mountain landscape intra-area accessibility. *Landscape and Urban Planning, 163*, 32–43. https://doi.org/10.1016/j.landurbplan.2017.03.001

Sevtsuk, A., & Mekonnen, M. (2012). Urban network analysis: a new toolbox for measuring city form in ArcGIS. Proceedings of the 2012 symposium on simulation for architecture and urban design San Diego, California.

Sharifi, F., Nygaard, A., Stone, W. M., & Levin, I. (2021). Accessing green space in Melbourne: Measuring inequity and household mobility. *Landscape and Urban Planning, 207*, Article 104004. https://doi.org/10.1016/j.landurbplan.2020.104004

Soga, M., & Evans, M. J. (2024). Biophobia: What it is, how it works and why it matters. *People and Nature, 6*, 922–931. https://doi.org/10.1002/pan3.10647

Soga, M., Evans, M. J., Tsuchiya, K., & Fukano, Y. (2021). A room with a green view: The importance of nearby nature for mental health during the COVID-19 pandemic. *Ecological Applications, 31*(2), Article e2248. https://doi.org/10.1002/eap.2248

Soga, M., & Gaston, K. J. (2016). Extinction of experience: The loss of human–nature interactions. *Frontiers in Ecology and the Environment, 14*, 94–101. https://doi.org/10.1002/fee.1225

Soga, M., & Gaston, K. J. (2023). Nature benefit hypothesis: Direct experiences of nature predict self-reported pro-biodiversity behaviors. *Conservation Letters, 16*, Article e12945. https://doi.org/10.1111/conl.12945

Soga, M., Gaston, K. J., Fukano, Y., & Evans, M. J. (2023). The vicious cycle of biophobia. *Trends in Ecology & Evolution, 38*, 512–520. https://doi.org/10.1016/j.tree.2022.12.012

South Australia NPWS. (2019). *7 national parks you can get to on public transport*. South Australia National Parks and Wildlife Service. Retrieved 03/10/2025 from https://www.environment.sa.gov.au/goodliving/posts/2017/10/public-transport-to-parks.

Spenceley, A., Kohl, J., McArthur, S., Myles, P., Notarianni, M., Paleczny, D., Pickering, C., & Worboys, G. L. (2015). Visitor management. In G. L. Worboys, M. Lockwood, A. Kothari, S. Feary, & I. Pulsford (Eds.), *Protected Area Governance and Management* (pp. 715-750).

Swinson, T., Wenborn, J., & Sugarhood, P. (2020). Green walking groups: A mixed-methods review of the mental health outcomes for adults with mental health problems. *British Journal of Occupational Therapy, 83*(3), 162–171. https://doi.org/10.1177/0308022619888880

Taylor, C., & Lindenmayer, D. B. (2026). Where are the important hotspots for forest biodiversity? A detailed spatial analysis for the Australian state of Victoria. *Austral Ecology, 51*, Article e70182. https://doi.org/10.1111/aec.70182

Tourism Research Australia. (2019). *National Parks and Bushwalking*. https://www.tra.gov.au/content/dam/austrade-assets/global/wip/tra/documents/tra-domestic-visitor-profiles-national-parks.pdf.

van den Bosch, M., & Meyer-Lindenberg, A. (2019). Environmental Exposures and Depression: Biological Mechanisms and Epidemiological evidence. *Annual Reviews in*

Public Health, 40, 239–259. https://doi.org/10.1146/annurev-publhealth-040218-044106

VEAC. (2026). *Assessment of the values of state forests in the Central Highlands - Final report*. https://www.veac.vic.gov.au/investigations-assessments/current-assessments/investigation/assessment-of-the-values-of-the-immediate-protection-areas-in-the-central-highlands-and-east-gippsland.

Venter, Z. S., Barton, D. N., & Gundersen, V. (2025). Impacts of forest clear-cutting on recreational activity: Evidence from crowdsourced mobility data. *Landscape and Urban Planning, 258*, Article 105332. https://doi.org/10.1016/j.landurbplan.2025.105332

Viggers, J. I., Weaver, H., & Lindenmayer, D. B. (2013). Melbourne's Water Catchments: Perspectives on a World-Class Water Supply. *CSIRO Publishing*.

Wace, N. (1977). Assessment of dispersal of plant species - the car borne flora of Canberra. Exotic Species in Australia - Their Establishment and Success, Proceedings of the Ecological Society of Australia 10.

Water NSW and Office of Environment & Heritage. (2015). *Special Areas Strategic Plan of Management 2015*. https://www.waternsw.com.au/documents/publications/general-publications/strategies,-plans-and-policies/Special-Areas-Strategic-Plan-of-Management-2015.pdf.

Watson, J. E., Evans, T., Venter, O., Williams, B., Tulloch, A., Stewart, C., Thompson, I., Ray, J. C., Murray, K., Salazar, A., McAlpine, C., Potapov, P., Walston, J., Robinson, J. G., Painter, M., Wilkie, D., Filardi, C., Laurance, W. F., Houghton, R. A.,… Lindenmayer, D. B. (2018). The exceptional value of intact forest ecosystems. *Nature Ecology and Evolution*, *2*, 599-610. https://doi.org/https://doi.org/10.1038/s41559-018-0490-x.

Wipf, S., Michel, A. H., Walder, D., Poelsma, F., Anderwald, P., Cruickshank, S. S., Jaroszynska, F., Rossi, C., & Backhaus, N. (2023). Boost in visitor numbers post COVID-19 shutdown: Consequences for an Alpine national park. *Mountain Research and Development, 43*, R12–R21. https://doi.org/10.1659/mrd.2022.00025

Worboys, G. L. (2015). Concept, purpose and challenges. In G. L. Worboys, M. Lockwood, A. Kothari, S. Feary, & I. Pulsford (Eds.), *Protected Area Governance and Management* (pp. 9–42). ANU Press.

Worboys, G. L., & Trzyna, T. (2015). Managing protected areas. In G. L. Worboys, M. Lockwood, A. Kothari, S. Feary, & I. Pulsford (Eds.), *Protected Area Governance and Management* (pp. 207-250). ANU Press.

Zhang, K., & Chen, M. (2024). Multi-method analysis of urban green space accessibility: Influences of land use, greenery types, and individual characteristics factors. *Urban Forestry & Urban Greening, 96*, Article 128366. https://doi.org/10.1016/j.ufug.2024.128366