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Exploring the safe and just space for urban and regional Australia

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Australia is a highly urbanised country, with over 85% of people living in city environments, so the lifestyles of city dwellers and the infrastructure of cities are critical to addressing sustainability issues. Australian cities have embraced the Doughnut Economics framework for sustainability; however, methodologies and data to comprehensively assess environmental and social sustainability are underdeveloped and locally focused, undermining the effectiveness of targets set. This research compares social outcomes of capital cities and regional areas within Australia with 12 environmental stressors and shows that consumption-based, environmental footprints are between 1.7 and 44 times higher than global averages. The most critical environmental issue is biodiversity loss within Australia while the most critical social issues are living standards in remote and regional communities, and inequality. The sustainability challenges for different actors, planetary boundaries, and economic sectors in Australia vary substantially, especially when viewed from a consumption rather than a production perspective.

Amidst growing recognition of the critical role of impact reduction by the wealthy^{1–3}, Australia has been singled out globally as an environmental laggard, with per-capita impacts being amongst the highest in the world⁴. Australia is a highly urbanised country, with over 85% of people living in city environments, so the lifestyles of city dwellers and the infrastructure of cities are critical to addressing sustainability issues. As one of the most urbanised and wealthy countries in the world, with 67% of people living in greater capital city areas (see Supplementary Information Section S3.1)⁵, Australian cities have both the means and the imperative to address the global sustainability challenge⁶.

Cities are seen as key actors in achieving sustainability, with a large and increasing share of the global population that is driving a disproportionately large impact on the environment both within and outside city limits⁷. Despite this challenge, cities are also areas of high innovation, with the potential to use city infrastructure to radically reshape resource use and pollution^{8,9}. Cities, however, generate most of their impacts remote from the city, and accordingly studying only local harms fails to understand the full consequences of urban consumption¹⁰. With limited time, political will and resources to address environmental issues, reliable data to understand the most worthwhile actions is critical.

Australian cities provide something of a paradox—an advanced economy but relying heavily on commodity exports; considered part of the “Global North” but situated in the physical South; a westernised, Commonwealth country but with major trading partners in the East Asia and the Pacific region; highly urbanised, but with vast sparsely populated rural and

arid areas; a colonial history but highly multicultural, with nearly half the population first- and second-generation migrants. These qualities mean that Australian city sustainability needs to be examined using local data, not assumed from other global cities.

Defining overarching sustainability goals has proven to be an elusive process, with innumerable possible actions and large numbers of potential schemes that serve to diffuse sustainability-focused efforts. Increasingly, the sustainability community is focusing on ‘just’ outcomes, looking at how to achieve optimal human and environmental outcomes^{11,12}. A popular iteration of this line of thinking, the “safe and just space” concept was defined in “Doughnut Economics” in 2012, as an economy in which basic human needs are met for all people while not exceeding the carrying capacity of the earth^{13–15}. It defines the “just space” as social foundations that are necessary for a minimum level of human functioning, including physical requirements, such as access to electricity and water, adequate nourishment and life expectancy; and social requirements, such as education and equality, taken from the Sustainable Development Goals. The “safe” space is taken from the “Planetary Boundaries” (PB) framework, which maps critical environmental thresholds and processes to retain the earth within a Holocene-like state of stability and includes considerations such as climate change, biodiversity, chemical pollution and water usage¹⁶.

The doughnut concept has captured the imagination of city stakeholders globally and within Australia, with locally adapted “Doughnut portraits” being created for major cities of Sydney, Melbourne and Brisbane. These portraits have been created by community-based regeneration

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movements, using multi-stakeholder discussions¹⁷ to develop indicators to address challenges and opportunities particular to an individual city that are related to the key social and environmental concerns identified in “Doughnut economics”.

The doughnut economics concept has been generally welcomed as a useful communication and coordination tool¹⁸. However, some concerns have been expressed about the possibility of oversimplification of complex social and environmental impacts and relationships, and the ability to implement at different governance scales^{19–21}.

To date, scholarship on the environmental sustainability of Australian cities has been highly focused on greenhouse gas emissions (see Supplementary Table 1). However, given that globally six of nine PBs have been exceeded²², understanding impacts more broadly is critical to ensuring that high risk activities are ameliorated.

Gaining a full understanding of city environmental sustainability is complicated by the very many activities and entities interacting in city spaces, with difficulties in defining physical city limits and sourcing data at this level²³. This level of complication means that bottom-up approaches to quantifying total impact flows are time consuming, while top-down approaches may not be able to source data at the appropriate level²⁴. PBs themselves have many complex drivers, only some of which are human-mediated, and in many cases consist of multiple more localised boundaries that may then cascade into global impacts²⁵.

Footprint calculations focus on the indirect impacts of consumption and are a particularly relevant locus of interest for city sustainability, as territorial studies omit the overwhelming level of impact from cities on their hinterlands²⁶. Footprint calculation aims to measure the indirect impact of consumption, considering the full supply chain of impacts (upstream) and ideally, further impacts arising from use and disposal (downstream).

Footprint calculations for urban areas have used four main approaches: ecological footprints, environmentally extended input-output (EEIO) analysis, lifecycle assessment (LCA) and hybrid EEIO-LCA assessment. Ecological footprints are a useful communication tool to demonstrate over-consumption, but do not have adequate detail to be useful in policy decisions²⁷. Life cycle assessment methodologies use data on the trade in products and multiply with coefficients of intensity to estimate a total footprint. However, they may suffer truncation errors, and lack data for services, which can be improved by using hybrid EEIO-LCA analysis²⁸. At a city level they are time consuming to consider the many thousands of potential products consumed and are rarely used in practice^{29–31}.

Environmentally extended input output analysis was first pioneered by Wassily Leontief and uses economic sales data to reallocate emissions from suppliers to purchasers using an iterative reallocation process to fully determine all supply chain levels. This approach has the advantages of completeness, in that all emissions in the global supply chain are included and are allocated somewhere, and in ensuring that emissions are allocated to a single end use, while enabling a relatively quick calculation method, and enables disaggregation^{27,29}. It does however rely on averaging processes that particularly impact small regions and sectors, and is a point in time estimation, compared with considering the entire life cycle of LCA methodology, that assumes that all impacts in a year can be attributed to all sales in a year. Downstream impacts from sales of items that pollute in the hands of customers, such as fossil fuel burning, are not included in input-output footprint calculations for the producer, but rather at the point of combustion/release, and accordingly may underestimate products such as petrol and gas that are burnt by households and governments.

Several different global input output tables and databases exist globally^{32,33}, with city-based data able to be “nested” into national tables to create a hybrid city/national table that can then be used to estimate global impacts from city consumption at a national scale³⁴. Multiregional input output analysis uses multiple global regions rather than a single “export” sector, which enables consideration of differing production intensities from different regions, and a more granulated understanding of supply chain impacts²⁷.

Several studies have calculated footprints of Australian cities, with 13 city carbon footprint studies, with often quite different spatial boundaries and methodologies and accordingly quite different outcomes (see Supplementary Fig. 18). Additionally, two water footprint studies and one ecological footprint have been completed at a city level. With a very limited timeframe remaining to address tipping-point risks, a comprehensive understanding of economic impacts on people and the environment to enable identification of high potential impact reduction efforts and actors is essential in efficiently targeting sustainability efforts^{35,36}.

Social sustainability and justice concepts have been subject to many different interpretations, from ensuring that environmental stressors do not significantly negatively affect humans¹¹, to ensuring procedures are fair³⁷, compensating for historic wrongdoings³⁸, enabling adequate resource access for all people¹⁵, and measuring social impacts from supply chains of product consumption, including inequality, corruption, employment, modern slavery and gender inequality^{39–43}.

“Doughnut Economics” uses indicators of human wellbeing that are largely unrelated to PBs themselves¹⁴, while the safe and just Earth system boundaries (ESB) concept, introduced in 2023, tightens the thresholds for PB stressors to additionally minimize significant harm caused to people¹¹, reflecting evolving understandings around the interdependencies between humans, other species and the environment, amidst ongoing debate about planetary justice⁴⁴.

In the Australian context, social sustainability as access to resources has often been subsumed within social studies concepts of poverty and deprivation^{45,46} or, at an urban planning level, using concepts such as liveability⁴⁷, with very limited consideration of social sustainability as a standalone concept⁴⁸. These social studies concepts define an acceptable minimum living standard, quantified either in terms of income, or access to material necessities and social inclusion, which then enable identification of groups suffering relative deprivation⁴⁹.

Australia is one of several countries that have recently adopted a “wellbeing framework”. This consists of reporting on 50 different indicators across themes of “healthy, secure, sustainable, cohesive and prosperous”, covering economic, social and environmental concerns at a national level^{50,51}.

While data mirroring the social indicators in “Doughnut Economics” has been collected for many years in Australia, including at a city level, notably by the Australian Bureau of Statistics, it has not been compiled and reported as a “social sustainability” assessment previously³², and typically thresholds for deprivation within Australia are significantly higher than benchmarks used in global studies^{34,35}. While this is appropriate within the context of typical Australian standard of living, examining Australia’s performance against international benchmarks in this study enables understanding of globally equivalent deprivation levels and provides an appropriate counterbalance to the base-level environmental outcomes implied by PBs.

Initial efforts to provide comprehensive environmental sustainability data at a global level show that consumption of products from two key mega-sectors – the food system and the built environment, drive most global impacts across all PBs⁵². Here we aim to then downscale this work to a city context, to assess the extent to which Australia is living within the safe and just space and provide a more granular understanding of which economic sectors and regions are driving environmental impacts in the Australian economy.

This research addresses the current knowledge gap by applying a nested environmentally extended, multi-region input-output (MRIO) database to investigate multi-indicator Australian city sustainability and comprehensively assess production and consumption-based drivers across all at-risk PBs, at a city and regional level, for the first time, and comparing this with the social outcomes achieved. Investigating this issue at a city, regional and national level provides a common knowledge base to inform decision makers at all levels of government of the key issues at play in the Australian sustainability context, providing critical systems knowledge for the sustainability transition⁵³.

Results

National environmental footprints

Globally nested footprints were calculated for 2019 for 12 environmental indicators representing human drivers of PBs, including greenhouse gases (GHG), plastics, pesticides, air pollution, ocean acidification, water consumption, nitrogen, excess phosphorus, land use, biodiversity loss and materials (see Table 1), and compared with global average per capita footprints. National footprints showed per capita Australian impacts between 2.0 and 14.2 times higher than global averages, apart from greenhouse gases from land use change, which are negative (i.e. reducing emissions) vs positive emissions globally.

PBs themselves are currently either within the safe boundary (green), between the safe boundary and the high-risk zone (orange) or above the high-risk zone (red). Where Australia exceeds the global average impacts and the global boundary is exceeded, it can be assumed that Australian impacts are not compatible with staying within PBs. Of all PBs, only three are currently within the safe zone (atmospheric aerosol loading, stratospheric ozone depletion, and ocean acidification) and, of these three, only ozone depletion (no footprint modelled) is comfortably within the safe zone and decreasing, while ocean acidification and aerosol loading are rapidly approaching overshoot of the safe zone²⁷. Thus, aerosol loading, where Australia has “only” double the average global per capita impact is the least concerning footprint calculated here. Note that aerosol loading has substantial natural drivers, including desert dust and soot from wildfires, which may also be substantially affected indirectly by exceedances of other PBs such as climate change and land use change.

Regional environmental footprints

All Australian urban and regional footprints with the exception of Greenhouse gases from Land use, Land Use Change and Forestry (LULUCF) are between 1.7 and 44 times higher than global average (see Figs. 1, 2, 3). The footprints that are closest to global averages are air pollution and pesticide use, while biodiversity and land use are at least seven times higher than the global average for all regions. Given that most PBs have already exceeded the safe zone this demonstrates the highly unsustainable nature of Australian consumption patterns across all PBs.

LULUCF are the only exception to this, with some forestry and agricultural regions showing a high uptake of carbon due to forestry regrowth. In these cases, particularly for Greater Hobart and the Rest of Tasmania, the per-capita drawdown from LULUCF exceeds the total per-capita emissions from other sources on a production basis, making this area a net negative GHG emitter on a production basis. However, the allocation of these emissions to the related product category of the landowner, in line with emission accounting protocols, means that consumption-based footprints in these regions are still high, e.g. forest regeneration activities are deemed to be sold to purchasers of timber products.

Netting out environmentally positive actions against environmentally negative actions (e.g. subtracting carbon drawdown from trees on farms from cow-based methane emissions) obscures the negative impacts of products, and thus the possibility of avoiding these impacts^{54–56}. An improvement in allocation methodology to attribute regeneration activities practiced by all industries to regeneration services, in both environmental and economic accounts, may offer a pathway to better assess the success of impact reduction initiatives, and include offset markets into analyses.

Household consumption expenditure is the greatest contributor to all footprints. However, fixed capital formation (including the building of residential and commercial buildings and infrastructure) is particularly high impact for ocean acidification, plastics and materials, where this demand type alone has a higher footprint than the entire global average.

A more detailed breakdown of underlying sectors (see Supplementary Figs. 1–16) shows that the three highest-impact product types purchased across all indicators are ‘animal-based food products’, ‘wholesale and retail trade’ and ‘plant-based food products’. The lowest impact consumption-based sectors were sectors that largely do not supply the household and government sectors – ‘coal mining’, ‘phosphate and fertiliser minerals’, and

‘glass and ceramic’ products – and thus reflect low expenditure. These results demonstrate that the food system is a key contributor to environmental impact in Australia, especially animal farming, which is not being addressed by the current 100% renewable energy focus. Australia has the capacity to improve environmental outcomes across multiple PBs by investing in improving land management and agricultural practice.

The greater capital city regions of Australia based on the eastern seaboard (Sydney, Melbourne, Brisbane, ACT and Adelaide) show a similar pattern of impacts, with regional impacts being imported into city regions for most impacts. Impacts driven by the food sector (see Fig. 3), including water use, excess phosphorus, nitrogen, pesticides, land use and biodiversity, are mostly imported from rest of state and rest of Australia, with these regional impacts are also partly exported overseas. Breaking this down further, purchases of products from the animal-based food manufacturing sector are the top contributors to land use, biodiversity, nitrogen, and excess phosphorus footprints, while horticultural products are a top contributor to pesticide and water footprints. Plant-based food manufacturing is a high contributor to water and excess phosphorus footprints.

As an importer of impacts, city regions can consider changing consumption habits to remove high-impact activities, such as switching some animal to plant-based food, reducing food waste and considering organic horticultural products to reduce pesticide and nitrogen footprints. Because most of these food-based impacts are generated within Australia there is also the possibility of working in partnership with regional areas to directly reduce impacts within agricultural production sector, with the objective of making technological changes, such as using regenerative agriculture, to reduce impacts. Production changes would also benefit exports of food products.

Energy and building dominated impacts are split between those where Australia is a net importer (including plastics and air pollution) and those where Australia is breakeven or an exporter (including greenhouse gases, materials, LULUCF and ocean acidification). Locally produced fossil fuel-based Electricity generation is the largest driver of greenhouse gases, air pollution, and ocean acidification, while materials used, air pollution and plastics are associated with products in the commercial buildings and heavy engineering sectors. Moving to ensure a 100% renewable electricity supply to Australian cities, as pioneered in the ACT, is critical in the sustainability transition and major Australian cities are already targeting this outcome. Reducing impacts from the built environment is more difficult, with ongoing pressure to increase housing supply in an overall tight market, and associated infrastructure requirements, and additionally infrastructure build for the renewable energy transition. Capital cities were a mix of importing and exporting materials footprints, and similarly LULUCF.

Greater Darwin and Perth were both neutral or exporting a number of impacts, particularly greenhouse gases, ocean acidification and materials, related to their role as a producer of fossil fuel products. On a consumption basis, Darwin also shows a high per capita level of impacts from infrastructure projects, while several Greater City regions showed a net export of LULUCF greenhouse gas reductions.

Regional rest of state areas exported all footprints, apart from plastics and air pollution, which were uniformly imported, while Rest of NT was unique in importing excess phosphorus and pesticide footprints, reflecting a food production sector that is low in agricultural inputs.

As regional areas are exporters of most emissions, they are a key area for changes in production techniques. Failure to recognise the innovation and adaptation required in regional areas may undermine the sustainability transition underway as ensuring that changes required are socially embedded and fair is critical to the success of this transition.

Urban areas need to adjust consumption levels to reduce the pressure on regions and enable this transition to occur. Continual increases in energy and materials requirements mean that production innovations, such as renewable electricity, may merely offset the increase in usage, rather than decrease the use of fossil fuels.

Table 1 | Planetary Boundaries, Indicators used and Australian and global average environmental footprints

Planetary Boundary	Boundary value ¹⁵	Current Value ^{a16}	Footprint Indicator Used	Australian Average Footprint (per capita)	Global Average Footprint (per capita)	Australian vs Global footprint
Climate Change	350 ppm CO2 Atmospheric CO2 concentration	417 ppm (R)	GHG - excluding Land use, land-use change and forestry (LULUCF) (t CO2-eq)	19.1	5.8	3.3x
			GHG - LULUCF (t CO2-eq)	-0.69	0.54	-1.3x
Introduction of novel entities	1 Wm ⁻² Radiative forcing	2.91 Wm ⁻² (E)	N/A	N/A	N/A	
			0% unreleased chemicals without adequate safety assessment and monitoring	Not quantified but exceeded (E)	60	3.3x
Stratospheric ozone depletion	Min 275.5 Global average stratospheric O ₃ concentration (DU)	284.6 (S)	N/A	N/A	N/A	
Atmospheric aerosol loading	0.1 mean annual interhemispheric difference in aerosol optical depth (AOD)	0.076 (S)	Air Pollution (DALY/1000)	28	14	2.0x
Ocean Acidification	>2.752 of global surface average carbonate ion concentration (Ω_{arag})	2.8 (S)	Carbon dioxide released (t CO2-eq OA)	14.4	4.0	3.6x
Modification of biogeochemical flows	62 Tg yr ⁻¹ Industrial and intentional biological fixation of Nitrogen	190 (E)	Nitrogen (Mg Nitrogen)	0.105	0.028	3.8x
	6.2 Tg yr ⁻¹ Regional P flow from fertilizers to erodible soils	17.5 (E)	Excess Phosphorus (kg Phosphorus)	6.8	1.8	3.8x
Freshwater	10.2% Bluewater - Global land area with human-induced deviations greater than during preindustrial	18.2% (R)	Water consumption (ML H2Oeq Blue water consumption)	490	149	3.3x
	11.1% Greenwater - Global land area with deviations from preindustrial water variability	15.8% (R)	N/A	N/A	N/A	
Land use	75% - Area of forested land as the percentage of original forest cover	60% (R)	Human land use (excluding for conservation) (ha/1000)	11 406	804	14.2x
Biodiversity Loss	<10 extinctions per million species-years	>100 (E)	N/A	N/A	N/A	
	10 GtC yr ⁻¹ Human appropriation of net primary production	30 (E)	Biodiversity loss (Potentially Disappeared Fraction)	8.3×10 ⁻⁸	9.0×10 ⁻⁹	9.2x
Materials	N/A	N/A	Material use (kg CUeq)	45 372	12 547	3.6x

^aCurrent values are either within the safe boundary (S), at risk, between the safe boundary and the high-risk zone (R) or exceeding the high-risk zone (E).

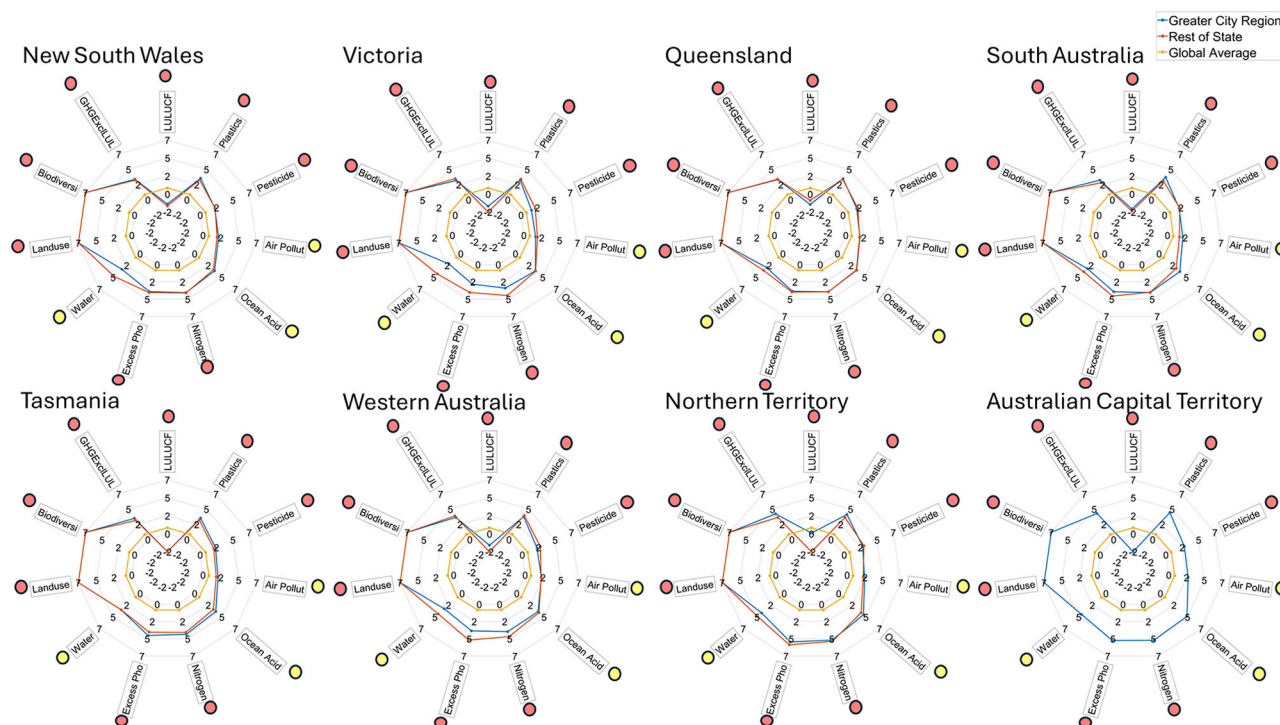


Fig. 1 | Planetary boundary footprints (excluding materials use) comparing capital city and regional areas vs global averages for Australia's major states. Values show per-capita footprint relative to global average per-capita footprint, e.g. 12 indicates 12 x higher impact than the global average person. Outer circles show

state of boundary exceedance – red is exceeded, yellow is in zone of risk. Global average is 1 in all cases. Where footprints are more than 7 times higher they are truncated to 7 for readability, and similarly when less than -2. See Figs. 3, 4 for a detailed breakdown.

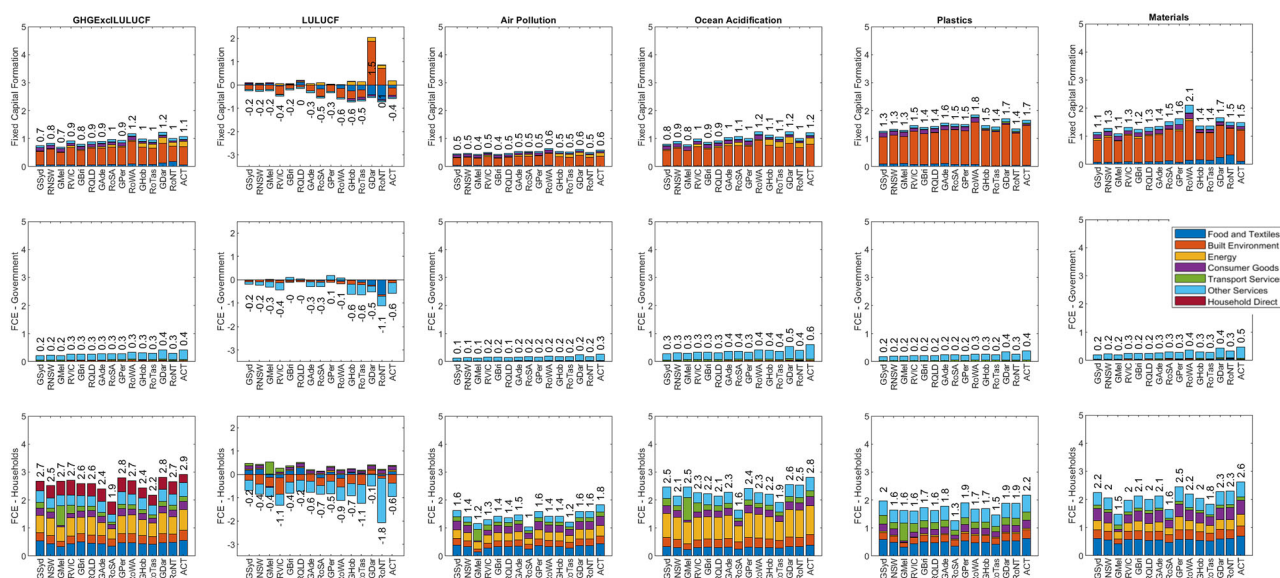


Fig. 2 | Regional footprints by final demand type showing consumption categories and final demand type for cities and regions within Australia—Indicators predominantly driven by energy use and built environment expenditure. Indicators are standardised to global average per capita impact. Note that the GHG Excl LULUCF is a summary indicator that can be further broken down into CO₂,

methane, nitrous oxides and Other GHG indicators (see Supplementary Fig. 17). FCE final consumption expenditure, excluding fixed capital items such as houses, factories and infrastructure. Indicators are standardised to global average per capita impact.

Production- vs consumption-based environmental impacts

A comparison of production and consumption-based impacts by sector for individual regions and Australia as a whole (Fig. 4), together with a carbon map analysis to identify the ultimate source region of impacts for each region (Fig. 5) enables analysis of the relative benefits of supply and demand

side policy responses. These results show that Australia is a net exporter of environmental impacts for most food and textile system PBs, including land-use, biodiversity, nitrogen, excess phosphorus, LULUCF and materials use. A high net level of imported impacts is shown for Air Pollution and Plastics (predominantly from rest of East Asia region). Water, greenhouse

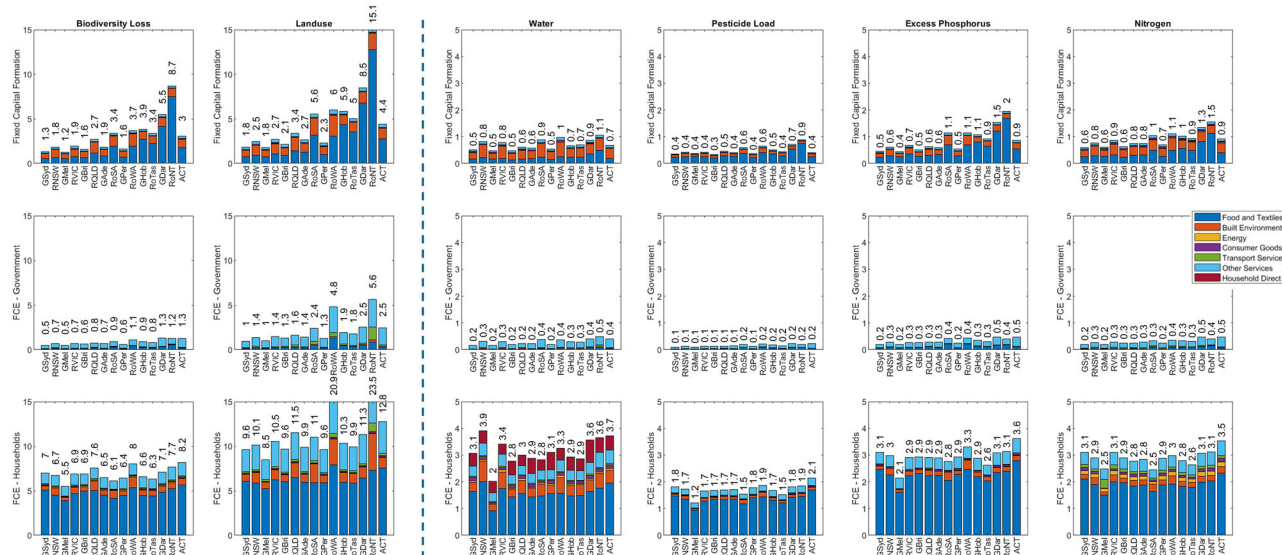


Fig. 3 | Regional footprints by final demand type showing consumption categories and final demand type for cities and regions within Australia - Indicators predominantly driven by food and textile product expenditure. Indicators are standardised to global average per capita impact. FCE final consumption expenditure.

gases (excluding land use change), pesticides and ocean acidification impacts are fairly evenly balanced between imports and exports (see Fig. 4). However, the ultimate source region analysis shows at least 30% of each footprint is external to Australia implying that there is both a substantial import and export of impacts, approximately balancing out in the year studied.

These data illustrate the extractive nature of the Australian economy, where high environmental damage underpins an export trade based on environmentally damaging mining and agricultural production.

Capital city vs regional footprints

Research suggests that achieving a high level of resource consumption is the reason for, not an unfortunate side-effect of city living, which acts to accelerate environmental crises^{57,58}. Previous research has found that urban residents generally have higher environmental footprints than residents of nearby rural areas, correlating with lower expenditure in such areas, although this outcome may be less pronounced as wealth increases^{59–63}. By contrast, these results show that for most states in Australia there is not a consistent variation in per-capita impact between capital city and regional areas.

Social indicators of earnings (see Fig. 6) show that Australian regional residents have a lower income on average, but this is not reflected in significantly lower environmental impacts – in fact in some categories regional areas have higher footprints.

Possible explanations may include the significant contribution of regional economies to Australian exports through mining and agriculture, with areas such as Regional Western Australia (WA) and Northern Territory (NT) having a higher gross domestic product (GDP) per capita than related Greater City Regions (GCR), the globally high cost of housing in Australian cities (reflecting land values) depressing other household consumption relative to regional areas; longer transport distances and associated impacts in regional areas; or possibly it suggests that the GCR used don't reflect the patterns of poverty and wealth in Australia – low-income households may settle in outer urban areas, while many regional areas attract tree and sea-change wealthy retirees.

Previous studies have shown significant variations in carbon footprints within Australian capital cities^{64,65}, and accordingly looking at smaller scale regions may provide a greater understanding of geographical variations in footprints.

Land use and biodiversity

Land use represents the highest relative per-capita footprint levels for Australia, driven by consumption of animal-based food manufacturing products. This reflects in part the low population in regional areas and extensive grazing in semi-natural ecosystems at low stocking levels through much of semi-arid and arid Australia⁶⁶. The approach taken here maps all human land use, though the land use PB control variable only considers some types of forest cover remaining, with no land use within Australia impacting this tipping point²⁵. Given this definition, and the fact that the vast majority of the land use footprint is sourced from Australia (see Fig. 5) the globally high land use within Australia does not currently represent a risk to tipping points. Should high-value agricultural land in tropical and boreal forest zones be returned to a wild state in line with PB requirements, however, it is likely that all remaining agricultural land would need to support more people, at which point Australia's per-capita land use footprint would need to fall.

Biodiversity is therefore the most critical PB impact from Australian consumption. Analysis of the ultimate source region of biodiversity loss shows that nearly all impacts are Australian driven (see Fig. 5), which represents an opportunity to address this issue both directly and through consumption changes.

Australia has globally high extinction rates, predicted to escalate, and ecosystems are collapsing, with even iconic Australian species such as the koala at risk of extinction⁶⁷. Pressures on biodiversity include loss and fragmentation of habitat, introduced species and the legal and illegal wildlife trade⁶⁸. These results show that reducing pressure on biodiversity from food production to enable release of land for habitat is essential, with the highest consumption-based impacts driven by animal-based food products. On a production basis, improvements in agricultural production systems and on the consumption side switching from animal- to plant-based protein, reducing food waste, and avoiding grain-fed meat would assist⁶⁹. Australian agriculture is projected to be highly impacted by climate change, and therefore the greater efficiency of plant-based diets may also be necessary if overall yields cannot be maintained in the face of drought, fire and flood, and projected global population growth. However, because of the many complex interactions, significant disturbance, climate change impacts, and ongoing requirement for human land use, reducing consumption of these products must be complemented by ecologically driven land-management to achieve improved biodiversity outcomes^{70–72} with urgent restoration of land and marine ecosystems required⁷³.

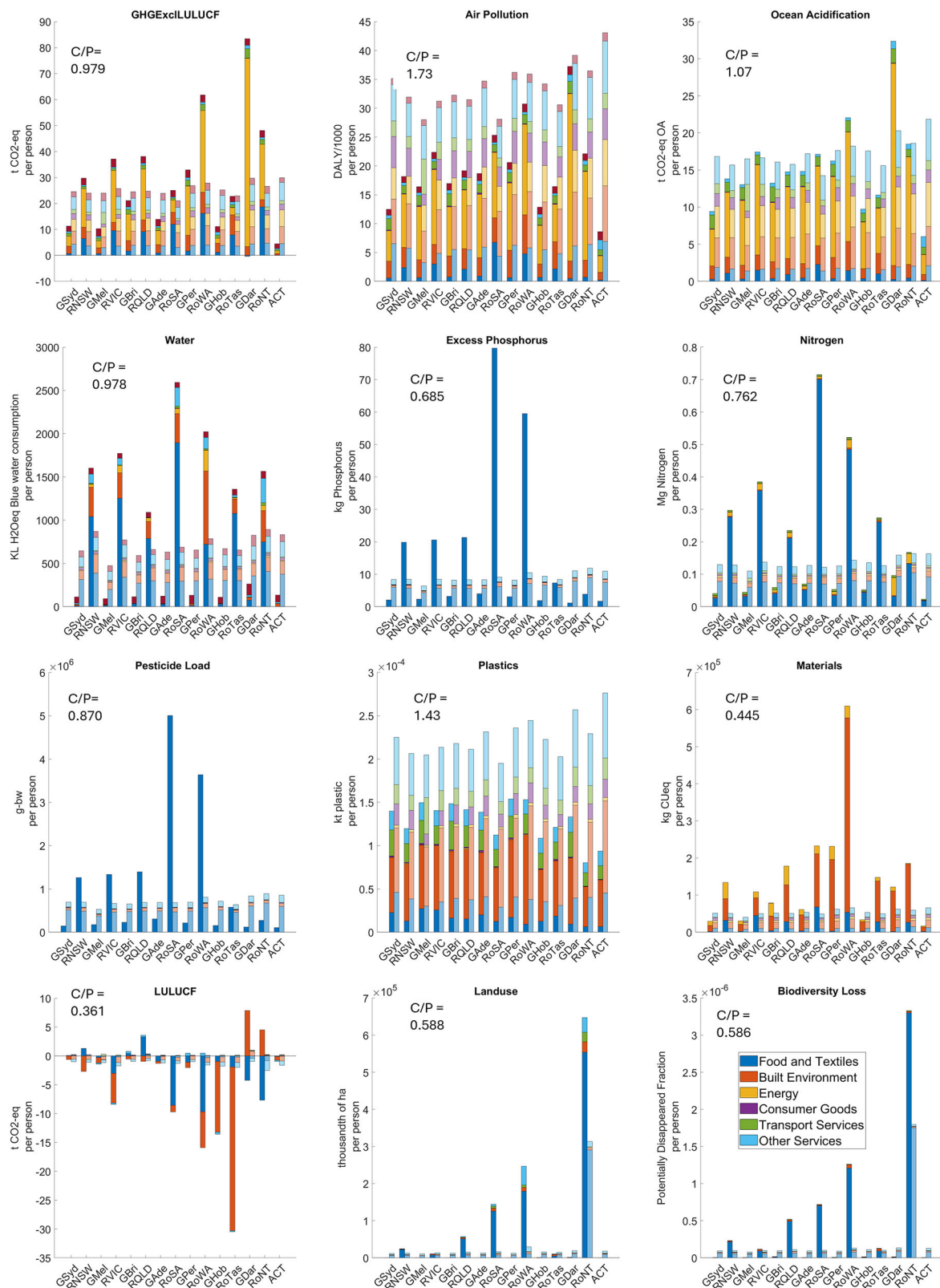


Fig. 4 | Per-capita locally produced impacts (“production-based”) vs footprints (“consumption-based”) by region, excluding household and government direct impacts. Production-based impacts are shown in full colour allocated to the sector that initially produces the impact. Footprints (consumption-based) are semi-transparent, allocated to the sector related to the final product purchased, and include impacts outside Australia. C/P shows the ratio of consumption emissions to

production emissions. Where the C/P ratio is less than 1 Australia is an overall net exporter of impacts, while greater than 1 indicates Australia is a net importer of impacts. This analysis includes impacts generated after the point of sale by households and end users for water, greenhouse gases (GHG) and Air Pollution (red bar segment at top).

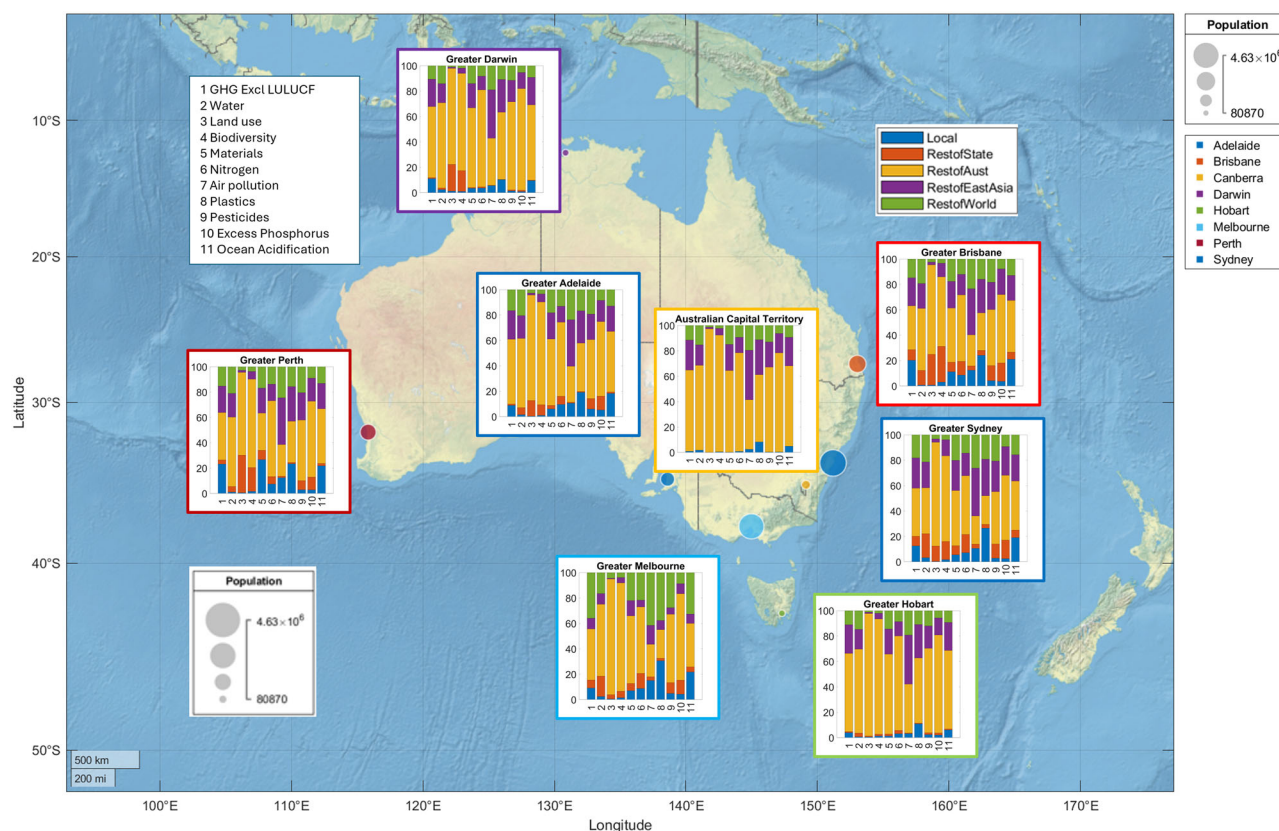


Fig. 5 | Ultimate source region of impacts as a percentage of total footprint for Greater City Regions (excluding LULUCF impacts).

Concepts of urban biodiversity frequently emphasise the services to humans provided by time in nature, carbon sequestration, tourism opportunities, purification of air and water, and temperature management^{74,75}. This human access to nature may add pressure to ecosystems through pollution impacts, road building and importation of feral and domesticated species both deliberately and accidentally^{76,77}, leading to international conservation efforts focused on large patch sizes and thus compact city approaches^{78–80}. By contrast, Australian cities harbour a disproportional number of endangered plant species, with significant cultural value attached, which need to be considered in planning approaches^{81,82}. The high level of urban sprawl in Australian cities is a further challenge to compact city approaches.

Novel entities

The novel entities control variable has been defined as “Percentage of synthetic chemicals released to the environment without adequate safety testing”. This boundary definition implies that we need a more rigorous system of approval for the development and release of new substances and technologies. However, it does not consider the issue of all the chemicals already in the environment, which still need to be safely detoxified or removed⁸³.

In the absence of relevant data two chemical types known for their environmental damage—pesticides and plastics—have been mapped here. Pesticide impacts are highly associated with Australian-sourced ‘horticulture and other agriculture’ products, while plastics are predominantly related to purchases for ‘commercial and residential building’, and to a lesser extent ‘wholesale and retail trade’ and ‘textile and footwear’ products.

Australian crops particularly associated with human and aquatic ecotoxicity from pesticides include cotton, citrus, winter legumes, sown pastures, grapes, winter cereals and rice⁸⁴. From a consumption-based perspective preferencing organically grown foods and cottons may reduce this impact and provide an incentive to develop alternative management strategies⁸⁵.

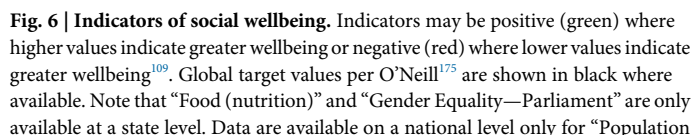
This study models the purchase of plastics by industries, rather than the more common focus on end-of-life waste^{86,87}. This aligns with the sales data used to allocate impacts to end-users in input-output analysis and the definition of the novel entities boundary in relation to the creation of untested chemical products, and suggests that all plastics sold have the potential to be pollutants. Increasingly the ubiquity and impact of microplastics and smaller fragments, and widespread addition of dangerous chemicals to plastic lead many to question the viability of consumption of plastics at all⁸⁸, with policy responses banning single-use plastics⁸⁹ and the negotiation of a Global Plastics Treaty⁹⁰; however, suitable substitutes may not be available for all applications⁹¹.

National social indicators

Overall, Australia performs well on most social indicators (see Table 2), reflecting the high level of income and quality of life for which it is renowned⁹², and is generally well above minimum suggested thresholds^{15,93}.

Social indicators are divided into two categories here—those that contribute to physical well-being, such as income, nutrition, and food, and those that contribute to social well-being, such as equality, education, and connection. It is in these social well-being indicators that the greatest area of social vulnerability for Australia is shown, with suboptimal gender and income inequality levels. This reflects the reality that many of Australia’s social issues relate to sharing, rather than inadequate resources—census statistics show many more empty houses than homeless people, and many more people with spare rooms than people living in overcrowded accommodation^{94,95}. A comparison of Gini indicators before and after social transfers (such as pensions etc) shows the equalising impact of Australia’s social welfare system, reducing from 0.479 for income excluding pensions and allowances, to 0.319 for disposable income. While a significant improvement this is still above the suggested global goal of 0.3.

Data for some indicators were only available on a national basis, including gender equality, political voice, and access to improved drinking water.



Gender equality data on the earnings gap between men and women shows a median gender pay gap of 19.0%, with every industry having a median gender pay gap in favour of men, with especially high gaps in male-dominated industries and for smaller employers, likely to

be more common in regional and rural areas^{96,97}. While no global target has been suggested, a result of 0% would imply equality has been reached. The Australian government targets a gender earnings gap of +/- 5%⁹⁸.

Table 2 | Social Foundation Indicators and Australian average values

Social foundation	Global measure used (Raworth, 2017)	Global measure used (O'Neill et al. ¹⁷⁵)	Global Goal per capita per year (O'Neill et al. ¹⁷⁵)	Indicator used	Australian average
Income and Work - Income	Population living on less than the international poverty line of \$3.10 a day	Population living on at least \$1.90 per day	95%	Equalized total household income (weekly) – Census \$1-\$499 per week	16%
Income and Work/ Jobs - Employment	Proportion of young people (aged 15-24) seeking but not able to find work	N/A		Youth Engagement in work/study	82%
Health	Population living in countries with under-five mortality rate exceeding 25 per 1,000 live births	1 – Unemployment rate	6%	Unemployment rate	5.1%
	Population living in countries with life expectancy at birth of less than 70 years	N/A		Under 1 year mortality per 1000 births	3.08
Food (Nutrition)	Population undernourished	Healthy life expectancy at birth (HALE)	65 years	Life expectancy at birth	83 years
	Population without access to improved drinking water	UN Food and Agriculture “food supply” indicator	2700 kcal per day	% food secure	66.8%
Water and Sanitation	Population without access to improved sanitation	Population living without improved sanitation facilities	95%	Population lacking access to SDG 6.1 def'n of basic level of drinking water quality	>99.5%
Energy	Population lacking access to electricity	N/A		N/A	
	Population lacking access to clean cooking facilities	Percentage of population with access to electricity	95%	Access to electricity	100% (assumed)
Housing	Proportion of global urban population living in slum housing in developing countries	N/A	N/A	N/A	
	Population stating that they are without someone to count on for help in times of trouble	% of population who have someone to count on whenever they need them	90%	Homeless persons per 10,000 persons (rate)	47.8
Networks (Social support)	Population without access to the Internet	Access to internet at home – occupied private dwellings		Dwellings with extra bedrooms needed (no.)	310476 dwellings
Political Voice (Democratic quality)	Population living in countries scoring 0.5 or less out of 1.0 in the Voice and Accountability Index	Average of “voice and accountability” and “political stability” from World Happiness Report	0.8	N/A	
Equality	Population living in countries with a Palma ratio of 2 or more (the ratio of the income share of the top 10% of people to that of the bottom 40%)	Maximum Gini coefficient (based on household disposable income)	0.3	Voice and accountability index	1.32
		Total income (excluding pensions and allowances) – Gini coefficient		Disposable income - Gini coefficient	0.479
					0.319

Table 2 (continued) | Social Foundation Indicators and Australian average values

Social foundation	Global measure used (Raworth, 2017)	Global measure used (O'Neill et al. ¹⁷⁵)	Global Goal per capita per year (O'Neill et al. ¹⁷⁵)	Indicator used	Australian average
Education	Adult population (aged 15 +) who are illiterate	Ratio of total high-school enrolment to high school age population	95%	Population over age of 15 - Did not go to school (%)	1.0%
	Children aged 12–15 out of school	N/A		Completed year 8 or below (%)	3.8%
Gender Equality –	Representation gap between women and men in national parliaments	N/A		Gender balance in state parliaments (% women)	42%
				Gender balance in national parliament (% women)	44%
	Worldwide earnings gap between women and men	N/A		Earnings gap	19%
Peace and Justice - Corruption	Population living in countries scoring 50 or less out of 100 in the Corruption Perceptions Index	N/A		Corruption perceptions index	77/100
Peace and Justice - Homicide	Population living in countries with a homicide rate of 10 or more per 10,000	N/A		Victimization rate per 100 000 people - Homicide and related offences	1.65

Political voice is measured globally using the voice and accountability index, with Australia ranking 15th in the world with a score of 1.32, against a suggested threshold of 0.5 or higher^{14,99}, showing considerable freedoms within Australia. This includes considerations such as participation in selecting government, freedom of expression, association, and media. An alternate measure of this aspect is the “freedom in the world” report¹⁰⁰, which scores Australia at 95/100. Some areas of concern documented in this report include disproportionate hardship experienced by subsections of the community, especially Aboriginal and Torres Strait Islander people, reflected in the other social indicators in this report.

Regional social sustainability—physical wellbeing

Comparing different GCR within Australia shows significant variances between regions, with regional and rural areas lagging in several areas, including income, unemployment and life expectancy, but cities generally are worse for homelessness, overcrowding and inequality. Even where data suggest full coverage, such as electricity connection, regional and remote areas, especially remote and Indigenous communities, suffer from disparities in regulatory protections for consumers, such as guaranteed service levels, that can lead to inadequate electricity access¹⁰¹. Similarly assumed universal coverage of water, sewerage and electricity in Australia may not apply for remote and regional Indigenous communities¹⁰².

Data were only available at a state level for infant mortality and food security. Infant mortality rates ranged between 1.8 (South Australia) and 8.3 (Northern Territory) deaths per 1000 births. This is well below suggested global targets of 25 per 1000 live births, however, does indicate that some regions could reasonably aspire to better outcomes.

Food security ranged between 65 and 71% for all regions, indicating that between 29 and 35% of households were either reducing the quality or quantity of food eaten for financial reasons in the past year. Particularly at-risk demographics, with over 50% moderately or severely food insecure included 18–24-year-olds, the unemployed, disability pensioners and carers, single parents with children, and those in social/mobile housing or homeless¹⁰³. These results did not significantly vary by state or regional vs metro residents.

A striking aspect of the social sustainability results is the especially poor outcomes in “Rest of NT”, which are consistent with high levels of disadvantage being experienced by Aboriginal and Torres Strait Islander peoples living in remote parts of Australia¹⁰⁴ given the high proportion of Indigenous families living in that region (see Fig. 6). This is one of the few areas in which Australia does not meet global social sustainability targets. Concerningly, this region also has very high per-capita production and consumption-based emissions, demonstrating an economy that is destructive to both people and planet.

The poor social outcomes for Aboriginal and Torres Strait Islander peoples in Australia are well acknowledged and have been specifically targeted for improvement with government initiatives such as Closing the Gap and the Northern Territory Intervention, but with limited improvement^{105,106}. The recent failure of the 2023 “Voice” referendum to include recognition of Aboriginal and Torres Strait Islanders in the Australian Constitution demonstrates that Australia is still grappling with the relationship between Indigenous and non-Indigenous citizens^{107,108}.

While the results of this study show a clear issue with physical wellbeing factors including housing, homelessness and education, other targets suggested as equally relevant to remote communities include adequate nutrition, access to transport and access to appropriate healthcare^{109,110}. Further measures of social wellbeing, such as “having someone to count on in times of need”, would help to recognise the demonstrated link between social support, involvement in culture and positive outcomes for Indigenous communities, and that act as buffers for other areas of deprivation^{110–113}.

Regional social sustainability—social well-being

Internet access is unsurprisingly shown as better in cities than related regional areas, while inequality is worse, and education levels vary; gender equality in parliament and homicide rate are only available on a state basis;

and all other social well-being indicators are available at a national level only (see Section "National Social Indicators" for discussion).

Gender equality in parliament is particularly low in Queensland, and high in the ACT and Victoria, reflecting a more conservative voting populism in QLD, and typically more progressive voters in the more urbanised ACT and Victoria. While homicide rates are low by global standards (avg. 1.65 per 100,000 vs a global target of below 10) there is a notably higher rate in Northern Territory (4.5) than the rest of Australia (between 1.3 and 2).

Education rates do not vary consistently between city and rest of state areas. Note that the statistics chosen show adults who have been either never educated or stopped schooling before Year 9, not current teenagers as suggested in "Doughnut Economics" due to unavailability of statistics. Interestingly the rate of "never educated" adults is higher in large capital cities such as Sydney and Melbourne, and it is speculated that this might reflect immigrants from regions without a comprehensive formal education system, given that schooling is compulsory until the age of 16 for all children in Australia, and these cities have a higher migrant community overall. Regional areas have a uniformly higher rate of limited schooling (< grade 8) than the related greater capital city areas. Adult education for affected persons would improve opportunities for those individuals.

Income equality (Gini index) is uniformly high, with a value of between 0.411 (Greater Darwin) and 0.504 (Greater Sydney), although note that these statistics are only available at a regional level for disposable income before transfers, while social security transfers significantly reduce inequality nationally (see discussion in Section "National Social Indicators"). Inequality has been linked to negative outcomes including undermining democracy, eroding social cohesion, and causing stress and illness¹¹⁴. While inequality disproportionately disadvantages the less well off, the association with sociopolitical instability, inability to respond to crisis, higher crime, worse institutions, and greater corruption also negatively impact the wealthy^{115,116}. Inequality bequeaths advantages to wealthy individuals that enable them to capture regulatory processes to their own advantage, which coupled with a greater belief in their own relative competence, tends to further increase inequality over time¹¹⁷.

Increasing city size has been positively correlated with rising inequality^{118,119}, which is generally reflected in Australian data, except for the Greater Perth region where inequality is disproportionately high for the population level. Inequality levels impact the adequacy of supply of physical goods such as water, where 100% access statistics do not reflect quite different levels and types of usage^{120,121}.

Discussion

Australian Government operates at a three-tier level, with Greater City Regions, as studied here, often administered by multiple local governments (e.g. 35 within Greater Sydney Region), with State oversight and Federal involvement, leading to a fragmented governance regime which complicates the ability to coordinate sustainability action.

Nationally, Australia has committed to Net Zero by 2050 and 43% below 2005 levels by 2030 translating to 11.8 t CO₂-eq per-capita (of production-based emissions) by 2030, approximately halving the 2019 emissions on a per-capita basis. Australia has also signed the Global Methane Pledge¹²² and Kunming Montreal Global Biodiversity Framework¹²³, with a national target to protect and conserve 30% of Australia's landmass and 30% of Australia's marine areas by 2030, and additionally a goal of no new extinctions. These data shows that the "no new extinctions" goal may well be the most difficult to achieve, with additional impacts from climate change exacerbating already high human impacts and potentially undermining entire ecosystems in the next decade, especially in the absence of effective climate action¹²⁴.

Policies need to address the most critical environmental issues of biodiversity loss, greenhouse gas emissions and novel entities; the most critical social issues of conditions in remote and Indigenous communities, and inequality; and focus on the highest footprint economic sectors – food system (especially animal-based food products), the built environment (especially commercial buildings and infrastructure), the energy system

(especially fossil fuel-based energy) and overall expenditure (via wholesale and retail trade).

The best policy approaches address multiple environmental, social, resilience, adaptation, and risk goals simultaneously. Policies should consider timing issues, including future demographics and climate, capital investment cycles, growing and shrinking industries, stages of technological adoption, following the sun for energy usage, and end of life impacts^{125–127}. Addressing the full economic and environmental system, considering both consumption and territorial impacts, potential rebound effects, needs of different sectors, highest impact processes, and all incentives at play will also improve policy making.

Transformation studies focused on the Sustainable Development Goals in Australia suggest policies such as increased expenditure on health, education, climate adaptation, agricultural training, water efficiency, renewable energy, electrification of buildings and transport, increase in timber buildings, regeneration and ecosystem protection and income redistribution to low-income earners are the most critical policies for Australia to achieve sustainability¹²⁸.

Policy options include price-based (such as taxes and subsidies), rights based (including tradeable permits), regulatory and legal, information and finance¹²⁹, with policy mixes more effective than single policy instruments^{130,131}. Pricing carbon has been shown to be an effective approach to reducing carbon emissions¹³⁰, including Australia's 2011 Carbon Tax¹³².

Market mechanisms to address environmental challenges including carbon and biodiversity markets and offsetting have been attempted in Australia to encourage private land conservation, however significant issues have been associated with these approaches, which ultimately function to support economic activity, not nature repair^{133,134}.

Concerns with market approaches include the level of ongoing market organisation required^{135,136}, lack of theoretical underpinning^{137–139}, and effectiveness and efficiency of using market-based approaches to address the market failure that environmental impacts represent^{133,138,140}.

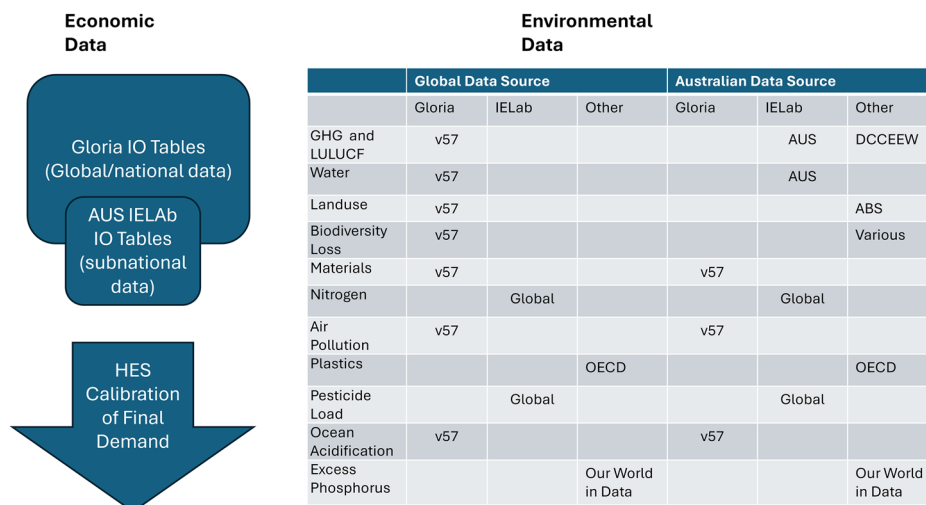
Safe and Just Space initiatives in Australian cities to date are largely focused on local and regional environmental and social issues^{141,142}, overlooking the broader issues from supply chains for city consumption shown here, and more challenging social conditions in many regional areas. Local and downstream impacts of Australia's exports also cause a significant environmental impact. Diversifying to sustainability-aligned export markets will be necessary to maintain Australian prosperity in a sustainability-focused world. Including consideration of upstream and downstream impacts in policy decisions, although complex and difficult, may contribute to a systemic improvement in environmental and social outcomes in Australia.

While mitigation of environmental impacts is of critical importance, a significant challenge for cities and regions going forward is likely to be the need for climate adaptation measures in the face of accelerating climate change impacts with indications that climate pathways are likely to exceed 1.5 degrees^{143–145}. Significant impacts from sea level rise, excessive rainfall and related flooding are predicted to occur by the mid-21st century^{146–149}. Given the major contribution of the construction sector to PB exceedance shown here, planning approaches that use climate adaptation forecasts to minimise the loss of built environment resources (and inter alia human suffering) will reduce long-term environmental impacts associated with the replacement of those resources¹⁵⁰. Durability and maintenance requirements of proposed city infrastructure should be carefully considered in light of worst-case scenarios of climate impacts and poly-crisis scholarship, which suggest the possibility of widespread supply chain disruptions within the design-life of built-environment assets^{151–153}.

Given the intertwined and unprecedented nature of these issues^{154,155}, cities are exploring experimental concepts of degrowth¹⁵⁶, circular economy^{157,158} and regeneration^{159,160}. Establishing pilot sustainability projects that generate scalable insights enables the exploration of desirable futures and facilitates fast responses to political opportunities¹⁶¹.

Beyond physical interventions, fundamental shifts in values that emphasise connection to and diversity of both people and nature are hoped

Fig. 7 | Sources of economic and environmental data for this study. The global environmentally-extended multi-region input-output database (GLORIA) is the primary source of data^{168,176}, and Industrial Ecology Lab (IELAB) – both the Australian IELab (AUS)¹⁶⁴ and Global IELab (Global)^{177,178}. Details of other data sources and references are included in Supplementary Table 5. IO tables input output tables, HES household expenditure survey, DCCEE Australian Government Department of Climate Change, Energy, the Environment and Water, ABS Australian Bureau of Statistics, OECD Organisation for Economic Cooperation and Development.



to underpin a movement from an extractive economy to environmental stewardship^{162,163}, and offer resilience benefits in an uncertain future.

Methods

Calculation of consumption-based impacts

This study used a nested environmentally extended input-output analysis to estimate the environmental footprints of Australian cities and regions.

The model used included 15 Australian Greater City regions and their respective Rest of State areas (where applicable), thus providing coverage of the whole of Australia. Sectoral breakdowns consisted of 51 economic sectors, which were chosen based on their relevance to key environmental issues (e.g. 'phosphate mining' and 'plastics and polymers') and to retain association with established sector groupings to maximise the alignment with underlying data sources. Sectors were also chosen to preserve as much information as possible by retaining economic relationships where possible (e.g. separating plant and animal-based products at both primary and secondary economic level). Where results are shown grouped into broad categories this grouping has occurred subsequently to calculating footprints.

Data on the supply and use of products in the Australian economy and financial inter-relationships between Australian producers and consumers were taken from the Australian IELab¹⁶⁴. The Australian IELab data are sourced from the Australian System of National Accounts, published by the Australian Bureau of Statistics^{165,166}. The Australian Industrial Ecology Lab (IELab) consists of 2214 regions and 1284 sectors and runs an algorithmic process to create customised input-output tables based on user-chosen combinations of pre-existing economic and satellite data, optimisation protocols, and sector and regional combinations.

For international data economic and environmental impact data we used Release 057 of the Global Resource Input-Output Assessment (GLORIA) environmentally extended multi-region input-output (MRIO) database¹⁶⁷, constructed in the Global MRIO Lab¹⁶⁸. The GLORIA database is a summarised version of the Global MRIO Lab industry-product input-output table consisting of 120 sectors and 164 regions. GLORIA tables were aggregated to 51 sectors and 14 regions consisting of eight regions in East Asia and the Pacific (including Australia), representing Australia's largest trading partners, and six other World Bank regions (see Supplementary Table 2).

The Australian subnational input-output (IO) tables were then nested within the aggregated global IO table (replacing the original Australian region), using the technique established by³⁴.

Four categories of final demand were included, to enable assessment of the actors responsible for final purchases, including household final consumption expenditure, government final consumption expenditure, fixed

capital formation, and changes in inventories. Household final consumption expenditure (excluding ownership of dwellings) for each city and region was recalibrated to total expenditure based on Household expenditure data for SA4 regions¹⁶⁹ plus expenditure from non-profit institutes serving households to improve the estimates for urban and regional areas (see Supplementary Table 3). This calibration was only undertaken at a total level due to the degree of anonymisation of the data undertaken by the Australian Bureau of Statistics resulting in significant arithmetic inconsistency at a lower level, with the underlying proportional split between sectors being retained from the original AusIELab run.

Environmental indicators were chosen to represent human-mediated drivers of PB impacts, consisting of 11 indicators that relate to PB drivers, and an additional indicator of materials use as a possible "missing" PB indicator (Goodwin 2020). The ozone layer boundary was not mapped due to available information not matching well with the model structure. This boundary is within the safe zone and improving, and globally the majority of ozone-damaging chemicals have now been phased out¹⁷⁰.

Australian environmental satellite production-based data was taken from bottom-up Australian data sources where possible or downscaled from national data using economic production value otherwise (see Supplementary Information section S3.5). Global Satellite data were sourced from a combination of GLORIA data feeds, Global IELab data feeds, and other reputable sources of Global data (see Fig. 7 for a detailed breakdown). Further details of the data used can be found in the Supplementary Tables 5 and 6.

Production-based impacts were reallocated to consumption-based products using a standard Leontief input-output analysis^{171–173}.

To calculate the ultimate source of emissions for each region and footprint a carbon mapping approach was used based on¹⁷⁴. This approach takes the final footprint for each region and then reverses the Leontief calculation to determine the original sectors and regions for each footprint.

Social impacts

Social impact scores were chosen to best reflect suggested social impact indicators in Raworth 2017¹⁵, given available data sources (see Supplementary Table 4). While many city-based implementations of "Doughnut Economics" concepts use a consensus process to establish locally relevant goals, this work takes a base level social goal, mirroring the base level environmental outcomes also being targeted. Given the limited resources available for sustainability initiatives and the perceived trade-off between people and planet this mirroring is important in prioritising the most critical socio-environmental issues.

Suggested targets for social impacts are taken from O'Neill, 2018¹⁷⁵ where available.

Data availability

Data sources are provided within the Supplementary Information.

Code availability

The codes used in this study are available from the corresponding author upon reasonable request.

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Author contributions

K.G. and T.W. conceptualised the article. M.L. curated the Gloria and IElab data. K.G. wrote the main manuscript text, wrote the Australian Greenhouse

IELab data feed, undertook the data analysis, and prepared all figures. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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