# South Australian Human Industrial Footprint and Intactness Assessment

## DEW Technical Report 2023/82

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Department for Environment and Water

## Technical Report – Preamble

The Wilderness Inventory was first prepared in the early 1990s as a series of maps identifying wilderness quality through two key attributes: remoteness and naturalness. While the dataset had not been updated for many years, it remained a valuable baseline tool in South Australia for implementing the *Wilderness Protection Act 1992* (WP Act), which requires that all land in the state is assessed for its wilderness quality.

In late 2022, the Department of Environment and Water (DEW), working with the Parks and Wilderness Council and The Wilderness Society, commissioned the University of Queensland to develop an updated Wilderness Inventory. This study used two refined attributes for identifying wilderness quality: modern industrial levels and habitat area, quality and fragmentation. The data generated in this assessment has been made publicly available via Data SA.

By updating the Wilderness Inventory, accurate and modern information will be available to assess wilderness quality and inform conservation efforts. It also provides DEW and the general public with a dataset and analysis method that can be consistently and repeatedly used to apply wilderness quality assessment over any terrestrial area of the state.

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## Introduction

The scope of the proposed work is to provide the Department for Environment and Water (DEW) with datasets and an analytical framework to apply wilderness quality assessment over any terrestrial area of the State. To allow DEW staff to repeat the analysis consistently, a clear workflow summarising the datasets and methods used is provided.

The work followed a phased approach. First, a workshop was conducted in December 2022 to generate an agreed methodology. At that workshop, two broad approaches were agreed upon to support mapping the State's wilderness: (i) utilising the human footprint methodological framework of Venter et al. (2016) to generate what we call here a South Australian Human Industrial Footprint Index and (ii) utilising an intactness metric that is sensitive to changes in habitat area, quality, and fragmentation of habitat (Beyer et al., 2020). Both methodologies are summarised in detail below.

The second phase was to produce the first draft maps, and these were presented at an April 2023 online workshop. Different datasets that could be used to identify different land uses for the State were discussed during the workshop.

The final phase was to finalise the maps and provide the report and methodological workflow. The intention of this report is to summarise these final products.

We note that some terms used in mapping wilderness efforts are perceived as inconsiderate and harmful owing to their apparent erasure of historical and contemporary interactions between human societies and their traditional lands and waters. Throughout this review we still refer to terms like wilderness (given the nature of this work brief and the fact it is about informing The Wilderness Act) but recognise this could be offensive to some. Like with all the wilderness mapping products we have undertaken, our definition is not exclusionary of Indigenous Peoples and the mapping recognises indigenous and local peoples have managed and maintained these ecosystems for millennia.

## Methodological approach

### Generating a Human Industrial Footprint (HII) Index for South Australia

To produce a map that can be used to assess wilderness quality in South Australia the human industrial footprint index (HII) approach was used, adopting the methods originally developed by Sanderson et al. (2002) and later refined by Venter et al.(2016) and Watson et al. (2016). The methodology (originally called the human footprint index; see Figure 1 for an example of how a human footprint is generated), maps modern industrial level pressures at fine resolution (e.g., agriculture, mining, urban environments). We have adopted the name of human industrial footprint index for the output generated here, as the index does not capture historic pressures and modifications caused on the environment from traditional indigenous practices and only captures recent contemporary pressure.

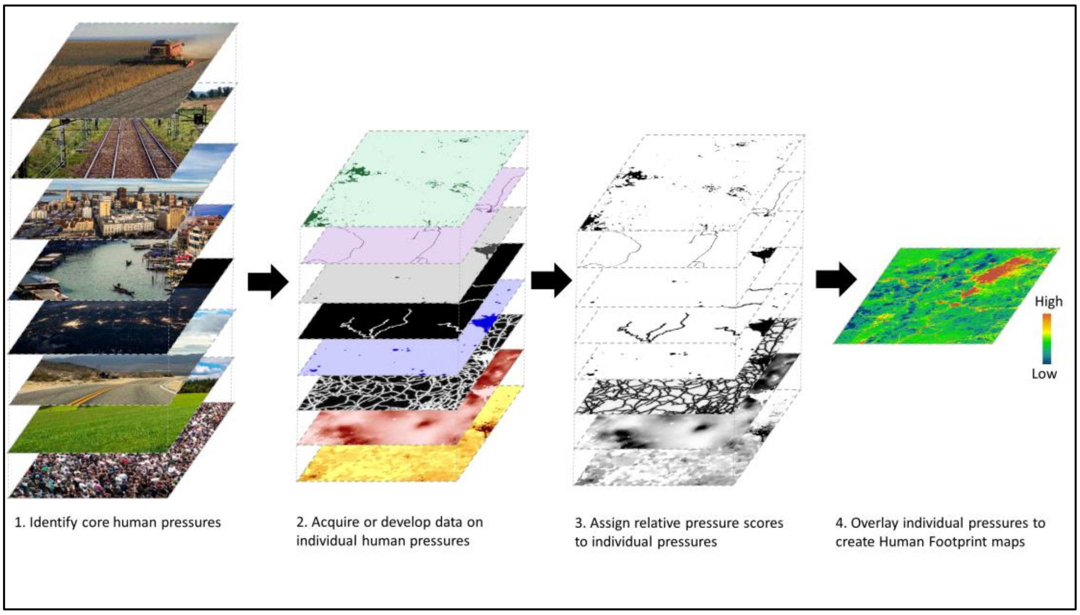


**Figure 1.** The broad methodological framework used to create a map of cumulative human pressure.

The human footprint method has been used to quantify the loss and fragmentation of natural ecosystems, its subsequent effects on species distributions, abundance and extinction risk, and the invasion of landscapes by non-native species (see summary in Watson and Venter, 2019). It is considered best practice to map wilderness at different scales, from global (Watson et al., 2016) to regional and national scales (Woolmer et al., 2008; Hirsh-Pearson et al., 2022). These human influence mapping efforts that identify wilderness have been used in a myriad of planning efforts around the world. For example, wilderness maps produced in 2016 became the foundations of the "Three Conditions" framework for conservation planning inside the Convention on Biological Diversity (Locke et al., 2019), and were captured in global assessments such as the Convention on Biological Diversity's Global Biodiversity Outlook and Biodiversity Indicator's Partnership.

Notably, the human industrial footprint index we generated can be used as proxy to represent the continuum of human modification of the natural environment. This continuum of modification underpinned the Australian National Wilderness Inventory (NWI) (Lesslie and Taylor, 1985), which has provided substantial support for the protection of high quality areas in South Australia, and set the bases for assessments such as the HII. It is important to clarify that the HII and the Intactness Index maps generated here are not an update of the NWI, which was completed for South Australia in 1983 (Lesslie and Taylor, 1983). Importantly, due to differences in the methodologies and data used to create the maps, these are not directly comparable. See Annex 1 for a short note on why these maps are not directly comparable, and for a simple visual comparison of the NWI and the maps generated as part of this report that show important similarities.

The pressures considered for the South Australia human industrial footprint index analysis (and wilderness assessment) are: (i) the extent of built environments, (ii) crop land, (iii) pastureland, (iv) human population density, (v) night-time lights, (vi) railways, (vii) roads, (viii) navigable waterways, dams and reservoirs, (ix) mining activity, (x) oil and gas, and (xi) forestry (Table 1). These were agreed to at the December 2022 workshop.

Scoring methods follow pre-existing peer-reviewed articles (Woolmer et al., 2008; Venter et al., 2016; Hirsh-Pearson et al., 2022). Each anthropogenic pressure was placed on a 0–10 scale to allow for comparison across pressures but also to identify the lowest scores per pressure to generate a wilderness map.

To produce the final product of the terrestrial human industrial index map, all the weighted layers were summed together. While some pressures may overlap spatially, some pressures are mutually exclusive. The final map was created at a resolution of 300 m as per the Canadian human footprint analysis by Hirsh-Pearson et al. (2022), and as suggested during the December workshop.

The HII captures a wide range of anthropogenic impacts on ecological systems, including effects related to proximity to disturbance sources and transportation networks that facilitate access. For example, an HII value of zero represents areas that are free of significant human impact. We will use an exponential transformation to scale HFI (i.e., range [0, 50]) to assess 'quality' (i.e. range [0, 1]) such that quality is 1 when HFI is 0, and quality is 20% when HFI is ~ 4. We also evaluate alternative transformations (quality is 10% or 30% when HFI is 4) to evaluate the sensitivity of the analysis to these assumptions.

### *Pressure layers*

This section describes the pressures used in the HII mapping for South Australia (Table 1), the data and the scoring system applied to these data to quantify each of the pressures (Table 2). The pressures data from different types of land use, were largely based on the South Australian Land Use data (DEW 2017) created for the Australian Collaborative Land Use and Management Program (ACLUMP). However, these data were updated where possible (as explained for each land use class below) with complimentary datasets. The scoring system is based on pre-existing peer-reviewed articles (Woolmer et al., 2008; Hirsh-Pearson et al., 2022).

#### Built-up environments

Built environments include buildings, paved surfaces, and general urban settings (e.g., urban parks, sewerage systems). Built-up areas are arguably one of the most extreme land cover changes that can take place in the natural environment, as the constructed infrastructure does not provide a viable habitat for most biodiversity of conservation concern (Tratalos et al., 2007). In fact, urban development is one of the main drivers threatening biodiversity (Maxwell et al., 2016).

Therefore, for the HII analysis, built environments were assigned a pressure score of 10 (Venter et al., 2016; Hirsh-Pearson et al., 2022).

To create the pressure layer from built-up environments, we used the ACLUMP polygon dataset. Built-up environments included classes 13, 14 and 15 (excluding roads and railways) from the 18-class classification System in ACLUMP, embedded in the primary classification as intensive uses. These classes include several land use types that indicate human settlement (besides urban and rural residences) such as recreation and culture, poultry farms, glasshouses, landfill, and industrial complexes.

**Table 1. Pressures included in the human industrial footprint index elaboration, and details of source data.**

| Data layer | Year | Resolution | Data Source |
|---|---|---|---|
| **Built environments** | 2008-2017 | 1:20,000<br>1:100,000<br>1:250,000 | Land use -ACLUM-<br>https://data.sa.gov.au/data/dataset/land-use-aclump |
| **Crop lands** | 2008-2017 | 1:20,000<br>1:100,000<br>1:250,000 | Land use -ACLUM-<br>https://data.sa.gov.au/data/dataset/land-use-aclump |
| **Pasture land** | 2008-2017 | 1:20,000<br>1:100,000<br>1:250,000 | Land use -ACLUM-<br>https://data.sa.gov.au/data/dataset/land-use-aclump |
| **Human population density** | 2016 | 1 $km^2$ | Australian population grid<br>(Australian Bureau of Statistics 2023).<br>https://www.abs.gov.au/statistics/people/population/regional-population/2021-22/32180_ERP_SA2_2021_gpkg.zip |
| **Night-time lights** | 2016 | ~589 m | VIIRS Annual Night Lights version 2.1 (Elvidge et al., 2017) |
| **Roads** | Last updated 2022 | Accuracy ± 5m,<br>± 25m, ± 125m | State-wide Road Network (DEW 2022)<br>https://data.sa.gov.au/data/dataset/roads<br>Complemented with data from Open Street Maps (roads = Tracks). |
| **Railways** | Last updated 2022 | Accuracy ± 20m | State-wide Rail Network (DEW 2022)<br>https://data.sa.gov.au/data/dataset/statewide-rail-network |
| **Navigable waterways** | 2016 | 300 m | Generated for this study following methods in Venter et al (2016) |
| **Dams and reservoirs** | 2014<br>Last updated 2022 | 1:50,000<br>Between 12-100 m of its true position | Waterbodies in SA<br>https://data.sa.gov.au/data/dataset/waterbodies-in-south-australia |
| **Forestry** | 2008-2017 | 1:20,000<br>1:100,000<br>1:250,000 | Land use -ACLUM-<br>https://data.sa.gov.au/data/dataset/land-use-aclump |
| **Mining** | 2008-2017 | 25m<br>Years 1987-2015 | Land use -ACLUM-<br>https://data.sa.gov.au/data/dataset/land-use-aclump |
| **Oil and gas** | Last updated 2023 | | Petroleum production licenses (link)<br>Petroleum Pipeline Facilities and Licenses (Link)<br>Both datasets from the department for Energy and Mining |

Crop Lands

While intensive agricultural practices have increased to feed Earth's growing human population, it is has become the main driver of biodiversity decline and the degradation of natural landscapes (Green et al., 2005; Maxwell et al., 2016). Crop lands can receive high inputs of pesticides and fertilisers or can suffer from slash-and-burn practices furthering environmental degradation.

Following Venter et al. (2016), we assigned crops a pressure score of 7, as some native species can still use crop lands (Grass et al., 2019), unlike most built environments.

To create the pressure layer from built-up environments, we used the ACLUMP polygon dataset. Built-up environments included classes 8, 9, 11, and 12 from the 18-class classification System in ACLUMP.

Pasture lands

With over 40% of the State's land in pastoral leases, livestock grazing is a pervasive pressure on South Australia's environment. Grazing can be associated with fences, soil compaction, intensive browsing, invasive species, and altered fire regimes (Kauffman and Krueger 1984). Domestic herbivores have multi-trophic effects on plant and animal biodiversity, which inevitably cost biodiversity (Filazzola et al., 2020).

We adapted (Venter et al., 2016) method to score the pressure from pasturelands, to assign different scores to areas with grazing from native vegetation and areas with grazing from modified or irrigated pastures. Thus, modified pasture lands were assigned a score of 4, while native vegetation pasturelands were assigned a score of 2.

The above scoring scheme was facilitated using the ACLUMP land use dataset from the Department of the Environment and Water (2020), which maps pasturelands in the categories outlined above.

Human population density

The intensity of degradation of the natural environment in a particular location can often be associated with the proximity to human populations. This degradation results from activities such as recreation, hunting, logging, and introducing non-native species.

We used the Australian Population Grid created by the Australian Bureau of Statistics (ABS), modelled from census data estimated at the SA1 level and modelled down to a 1 $km^2$ grid for Australia. The data represents the population density (number of people per square kilometre) in the cell.

The population density layer was transformed into a pressure layer following Venter et al. (2016). For all locations with more than 1,000 people per $km^2$, we assigned a pressure score of 10, under the assumption that population density becomes saturated at that level. For areas with a density under 1000 people/$km^2$, we logarithmically scaled the pressure score as follows:

$$\text{Pressure Score} = 3.333 * \log(\text{population density} + 1)$$

**Table 2. Pressure scheme for assigning weights to the individual pressures in the Human Industrial Footprint map.**

| Pressure | Scoring scheme | Issues/Comments |
|---|---|---|
| Built environments | 0, 10 | All built areas are given a score of 10<br>(Venter et al 2016) |
| Night-time lights | 0 - 10 Continuous | Pressure Score = 3.106 x log (night-time lights +1)<br>(Gassert et al 2023) |
| Croplands | 0, 7 | All cropland areas are given a score of 7<br>(Venter et al 2016) |
| Pasturelands | 0, 2, 4 | Irrigated and modified pastures are given a score of 4<br>Native vegetation pasturelands (mostly in the Arid zone<br>are given a score of 2 |
| Population density | 0 - 10 Continuous | Pressure score = 3.333 x log (pop density + 1) |
| Roads | 0,8 Direct impacts<br>0,4 Indirect | 600 m either side of roads are given a score of 8<br>Starting at 600 m out from road, pressure score of 4 exponentially decaying out to 15km<br>(Venter et al 2016) |
| Railways | 0,8 600 m buffer from railways | 600 m either side of railways are given a score of 8<br>(Venter et al 2016) |
| Navigable Waterways | 0, 4 Continuous | Pressure score of 4, exponentially decaying to 15 km<br>(Venter et al 2016) |
| Dams/Reservoirs | 0,10 Reservoirs.<br>0,5 Farm Dams | All mapped reservoirs are given a score of 10<br>All mapped small dams (mostly farm dams) are given a score of 5 |
| Mining activity | 0,8 Direct impacts 8. | All mapped mining areas are given a score of 8.<br>Oil and gas extraction areas are considered as mining activity (Adapted from Woolmer et al 2008) |
| Oil and Gas Pipelines | 0,1 | All mapped pipeline areas are given a score of 1.<br>(Adapted from Woolmer et al 2008) |
| Forestry | 0,7 | All mapped forestry areas are given a score of 7<br>(Assuming a similar pressure to cropping) |

Night-time lights

Night-time lights are associated with electric infrastructure in urban centres, rural and suburban areas. However, they are also representative of other important human infrastructures such as industrial installations, for example, in working landscapes, all of which have associated pressures on natural environments (Small et al., 2011).

We used the VIIRS Annual Night Lights version 2.1 (VNL v2.1) to map pressures from electric infrastructure. VNL provides estimates of average annual radiance at approximately 500 m resolution. Following Gassert et al. (in review), we will assign a maximum score of 10 to a radiance of 25 $\mu W/cm_2/sr$, a threshold of brightness usually exceeded in moderately sized cities in developed countries. The pressure score for values below 25 are logarithmically scaled as follows:

Pressure Score = 3.106 * (log night-time lights +1)

Roads

There are at least seven general effects of roads on terrestrial and aquatic ecosystems which include mortality from construction, road kill, animal behaviour change, alteration from the physical and chemical environment, spread of exotics, and increase use of areas by humans (Trombulak and Frissell, 2000).

This linear infrastructure has direct and indirect pressures on the environment, which is accounted for in the pressure scoring. We followed Venter et al. (2016) to assign these direct and indirect pressure scores. A score of 8 was assigned to a 0.6 km buffer from the road, and indirect pressures arising from the access that these infrastructures provide for other human activities, are assigned a score of 4 at 0.6 km and decaying exponentially until 15km on either side of the road.

We used DEW's Road layer, which represents navigable roads, including public and private access roads and tracks. The accuracy of the data varies between ± 5m of their true position in urban areas, ± 25m in rural areas, and ± 125 m in pastoral regions. We removed from the dataset those features with a status of proposed or non-existent. This road layer was complemented with data from Open Street Maps, which allowed to capture tracks mainly in the Arid lands that were visible through high resolution satellite imagery but not mapped in the State's Road layer.

Railways

Railways are linear infrastructures that directly convert habitat, resulting in fragmentation which can produce edge effects. However, railways are less conducive to providing access to natural environments than roads, given that passengers would usually only disembark at rail stations. The direct pressure of railways was assigned a pressure score of 8 for 0.5 km on either side of the railway.

The data to be used is the “State Rail Network” from the SA Department of Infrastructure and Planning, with a positional accuracy of ± 20 m of the line. The dataset includes opened, closed, and other tracks. We removed from the datasets those features with a status of dismantled, proposed, or disused.

Navigable Waterways

Navigable waterways - in the form of navigable rivers, lakes, and marine coastlines - facilitate human accessibility to the natural environment, in a way analogous to that of roads. We consider waterways navigable for 80km in all directions from human settlements, an approximation of how far a motorised vessel might travel within daylight hours. As we do not include non-motorised vessels in this assumption, we do not include the shorelines of several large reservoirs in South Australia that restrict boat access to non-motorised vessels. Human settlements were determined as those areas with a mapped nighttime lights signal greater than 0.5 (VIIRS).

Maps of navigable rivers were generated based on rivers’ distance to human settlement, stream depth, and other derived hydrological data. Rivers were considered navigable if we find indications of human settlement within 4km of their banks - settlements determined using a nighttime lights value greater than 0.5 - and if river depth was greater than 2 metres, based on Hydrosheds (REF) data and the following formulae:

Stream width = 8.1 discharge [m3/s]0.58

and

Velocity  = 4.0 discharge [m3/s]0.6/ width [m]

and

Cross-Sectional Area = discharge/velocity

and

Depth =  1.5 cross-sectional area / width

Assuming channel shape follows a second order parabola.

In South Australia there is only one mapped navigable river - the Murray-Darling River. We do not include any mapped lakes, such as Lakes Alexandrina and Albert.

After merging both derived navigable coastline and river layers together into a single navigable waterways layer, we applied a  pressure score based on Venter et al (2016), which assigns a score of 4 adjacent to the  water body, and exponentially decaying to15 km from the waterway.

Dams and reservoirs

Dams in South Australia's agricultural landscape are widespread. They are used to catch and store water for livestock, irrigation, crop spraying, firefighting, and domestic purposes. However, dams can significantly impact sensitive water-dependent ecosystems by changing the hydrology of areas (Woolmer et al., 2008; Liddicoat et al., 2022). Moreover, they directly modify the environment, accumulate pollution from run-off, and can produce greenhouse gases. Similarly, larger reservoirs will also change the hydrology of a particular area and modify the environment while providing access to nature areas (Woolmer et al., 2008). All mapped reservoirs  were assigned a pressure score of 10 (Hirsh-Pearson et al., 2022), and all mapped farm dams were assigned a score of 5.

Forestry

According to the Department of Agriculture, Fisheries and Forestry of South Australia, the State has approximately 188,110 hectares of plantation forest, both softwood (radiata pine) and hardwood (Tasmanian blue gum). These plantations remove habitat for species, including tree cavities, and alter paths of travel. Given that these plantations are monocultures, we assigned a pressure score of 7, akin to crop lands.

Data on forestry plantations was obtained from the ACLUMP land use map.

Mining

As a type of land conversion, mining modifies terrain, waterways, and removes topsoil. Furthermore, mining can be a point source for air and water pollution (Woolmer et al., 2008). From exploration to the post-closure phase, mining can have detrimental effects on biodiversity, ecosystems, and ecosystem services (Sonter et al., 2018; Boldy et al., 2021).

We adapted the scoring method from Woolmer et al (2008) to assign a score of 8 to the direct pressures from mining, i.e., areas mapped as mining are assigned this score. We did not score indirect pressures as in Woolmer et al (2008) and Hirsh-Pearson et al (2020), as the mining data used in this analysis was not in a point format as in the mentioned studies, but as a polygon, which often span several mining footprints over a mining tenement.

We created the mining pressure layer by updating the mining land use class from ACLUMP land use map with the Mineral Production Tenements datasets (Department of Energy and Mining). These last datasets were downloaded from the SARIG catalogue. Given that some petroleum mining areas are incorporated in the ACLUMP dataset in the mining land use class, we have included the active petroleum licenses (see below) in the mining pressure layer.

<u>Oil and gas</u>

Environmental pressures from oil and gas exploration and extraction include wildlife mortality, habitat loss and fragmentation, noise and light pollution, introduction of invasive species, and sedimentation of waterways.

We used a petroleum production licenses polygon shapefile (DEM 2023) obtained from the SARIG catalogue to map pressures from areas where petroleum is being extracted. These sites were treated as mines and given a score of 8 accounting for direct impacts but noting that the footprint includes the lease block and not only the area of actual extraction (however, but it is also important to note that these blocks include many miscellaneous structures such as roads and buildings). Petroleum exploration licenses are restricted to the North-Western area of the Arid Lands NRM region.

We also mapped pressures from petroleum pipelines licenses (DEM 2023) obtained from the SARIG catalogue to map pressures from areas where petroleum is being extracted. Pipelines are a form of pressure, as these linear infrastructures need to areas to be kept open and could potentially fragment habitat. Moreover, they can be associated to risks due to failures that can result in important environmental consequences. For the present analysis we decided to be conservative and assigned a score of 1 to the areas where this infrastructure is recorded.

**Generating an intactness metric for South Australia**

An intactness metric that is sensitive to changes in habitat area, quality, and fragmentation of habitat will be also used, utilising the methodology of Beyer et al. (2020) (see Figure 2) with the formula outlined in the published paper. It will be based on a continuous, grid-based (raster) representation of variable habitat quality, thereby obviating the need for a binary representation of habitat, and can be calculated at large spatial scales (e.g., ecosystem types, ecoregions, bioregions etc). The metric is designed and parameterized to meet the following design criteria: (a) to be proportional to habitat area when there is no habitat fragmentation; (b) to decline mono- tonically as fragmentation increases and to be sensitive to both the number of patches and the separation between patches; and (c) to be proportional to habitat quality for a given total area of habitat and degree of fragmentation.

Application of this metric requires only a relative measure of habitat quality among cells. We will use the South Australian's human industrial footprint index generated as a proxy for habitat quality.

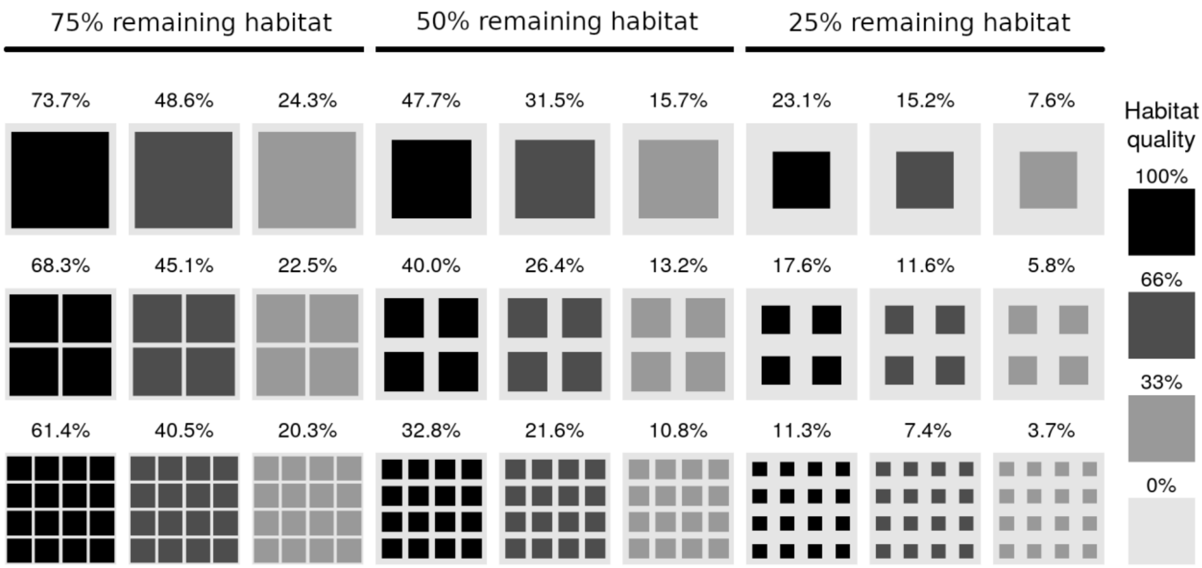


FIGURE 2. Hypothetical 100x100 km landscapes to illustrate the sensitivity of the intactness metric (Q is the number above each landscape) to changes in habitat area, quality, and fragmentation. A landscape filled completely with maximum quality habitat has an intactness score of 100%. (Taken from Beyer et al 2020)

## Results and interpretation section

### Human Industrial Footprint Index map for South Australia

The Human Industrial Footprint Index map for South Australia (Fig 3) ranges between the values of 0 and 53, with a mean value of 4 ± 4.9 for the State. The use of thresholds in pressure maps such as the HII helps characterise different pressure levels and provides a proxy for categorising an area as wilderness (Leslie et al., 1998; Sanderson et al., 2002; Sawyer, 2015; Watson et al., 2016). For example, Figure 4 shows the same preliminary human industrial footprint map for South Australia categorised into 3 categories that have been used before to provide a proxy for wilderness areas (values <1), intact lands (values < 4), and highly modified lands (≥ 4) (Allan et al., 2017; Williams et al., 2020). An HII value below 1 represents areas that are free of significant industrial impact (Watson et al., 2016), values between 1 and 4 are associated with areas of low industrial pressure that are dominated predominantly by pasture, being 4 a reasonable threshold of areas facing habitat conversion (Jones et al., 2018); i.e. areas with an HII value below 4 could be considered relatively intact areas.

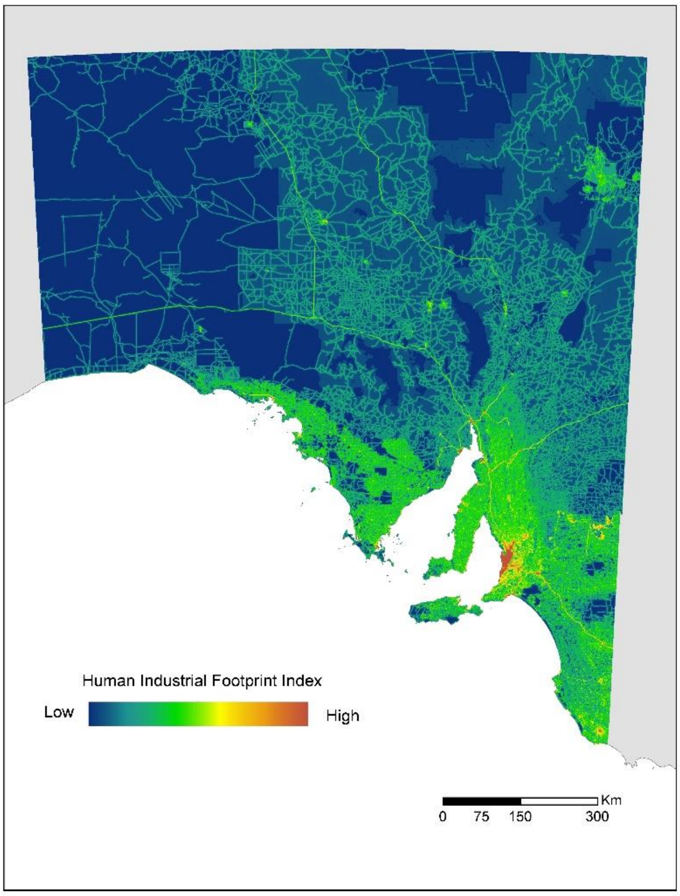


Figure 3. Human Industrial Footprint index for South Australia, using 12 pressures outlined in Table 1.

Using the threshold values outlined above, South Australia has 65.2% of its land under HII values considered as not heavily degraded (HII < 4). It must be noted that most areas with values between 1 and 4 (33% of the State) correspond to areas of grazing in native vegetation in the South Australian Arid Lands, which score was set to be 2, or areas potentially affected due to their distance from roads.

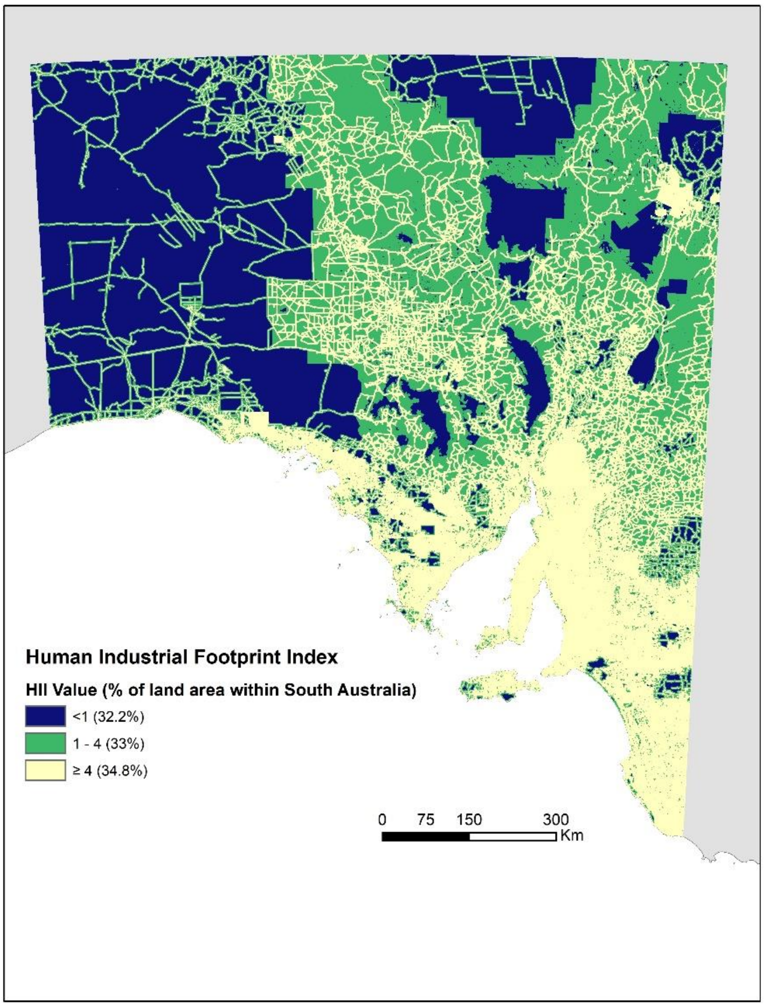


Figure 4. Human Industrial Footprint for South Australia is categorised into three classes associated in the literature (Sanderson et al., 2002; Jones et al., 2018) with wilderness (HII values <1), intact lands (HII values < 4), and degraded lands (HII Values ≥ 7). In parenthesis, the percentage of the total land area in South Australia under each of the three classes.

**Wilderness in South Australia**

As mentioned, maps of cumulative pressures like the HII are often categorised into different pressure categories to use as a proxy of habitat intactness or degradation, and to map wilderness and intact areas. For example, Sanderson et al. (2002) and Watson et al. (2016) mapped wilderness areas at the global scale using human footprint maps, using an HFI value of < 1 (no observable pressures) and areas greater than 10,000 $km^2$ as wilderness areas. Here, we illustrate how wilderness would look in South Australia when applying an arbitrary value threshold of <1 to define them (but as outlined above, a threshold of 4 could be considered areas with low pressure). We also apply varying area thresholds, noting that the *Wilderness Protection Act 1992* does not assign an area threshold to define wilderness in South Australia.

Applying an HII value threshold of 1 to define wilderness areas would identify 32.2% of South Australia as wilderness, most of which is west of the State (Figure 5). Only 3.5% of these area does not reach the 8000 Ha area threshold (as set in JANIS for forested wilderness). Using global areal thresholds of significant wilderness areas (those ≥ 10,000 $Km^2$- (Sanderson et al., 2002; Watson et al., 2016), the area of South Australia categorised as wilderness is reduced by 42% (blue areas in Figure 5).

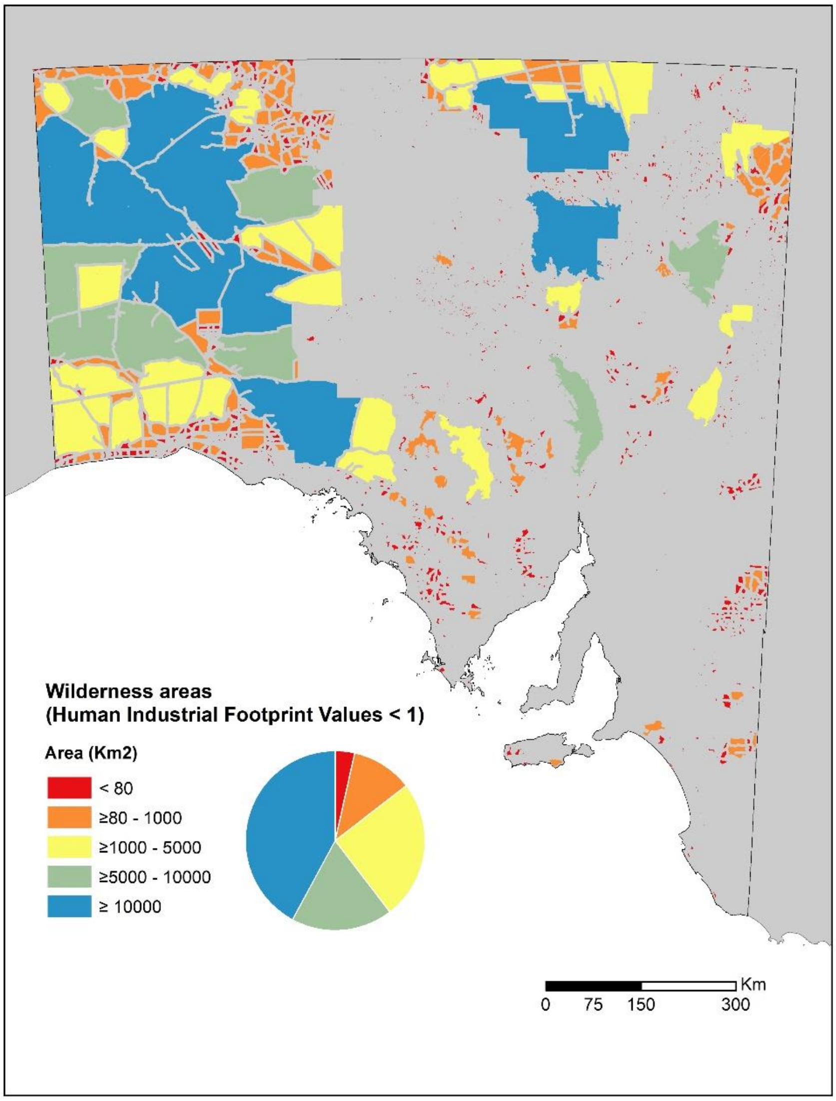


Figure 5. Wilderness areas in South Australia obtained by applying a threshold of 1 to the Human Industrial Footprint and categorised by the area (in $km^2$)of each wilderness patch.

Finally, wilderness maps overlayed with other information can provide a clear idea of how threatened different environments and biodiversity can be. For example, the area of wilderness within each bioregion can be assessed, showing that nine of the 17 bioregions in the State have less than 10% of their area free of the mapped industrial pressures (Fig 6), and that most remaining Wilderness spans the Great Victoria Desert, Simpson Strzelecki Dunefields, and Nullarbor bioregions (Fig 7).

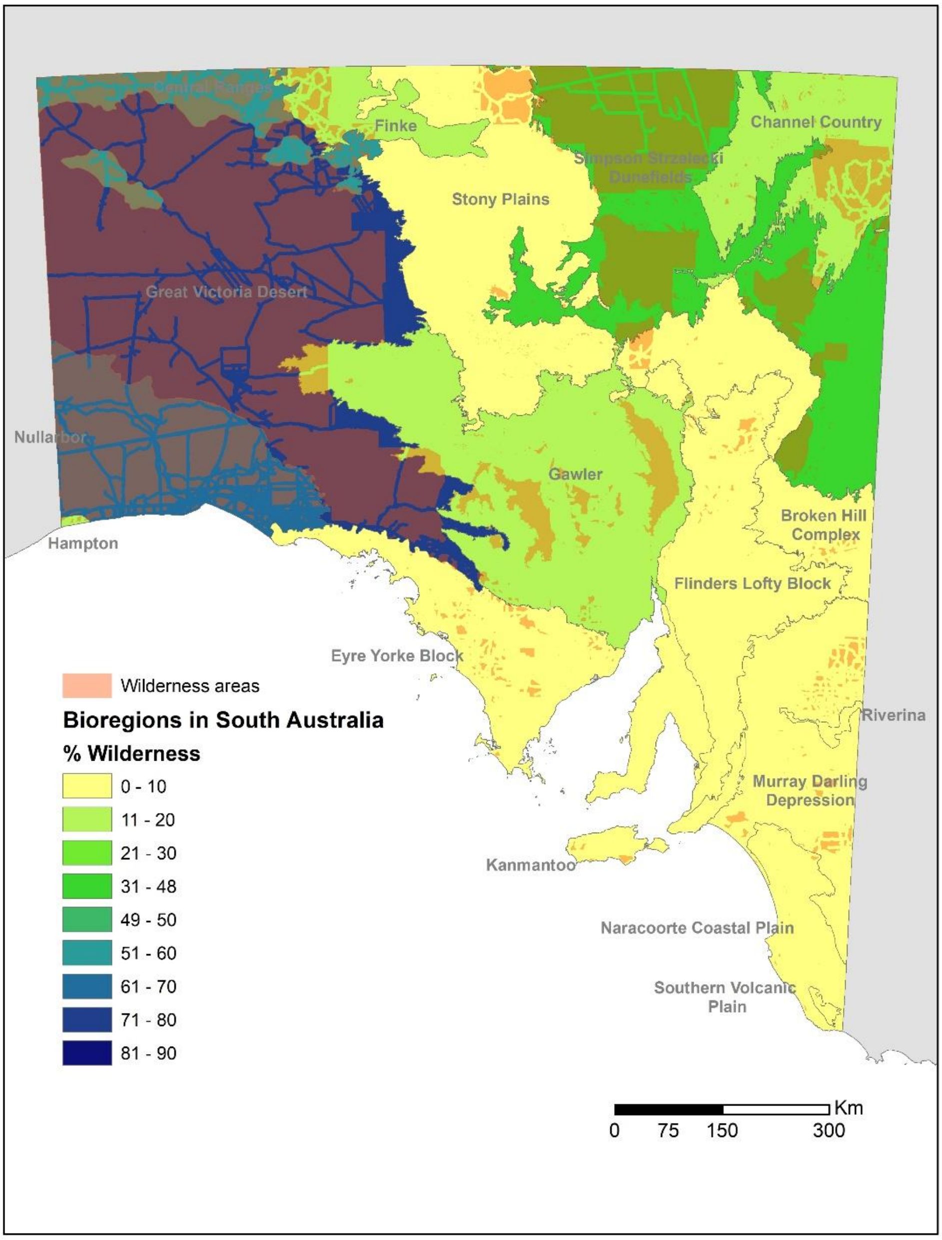


Figure 6. Bioregions in South Australia, and the area (%) that remains wilderness for each of these, based on the Human Industrial Footprint Index (HII). Shaded areas represent wilderness areas based on a threshold value of 1 for the HII.

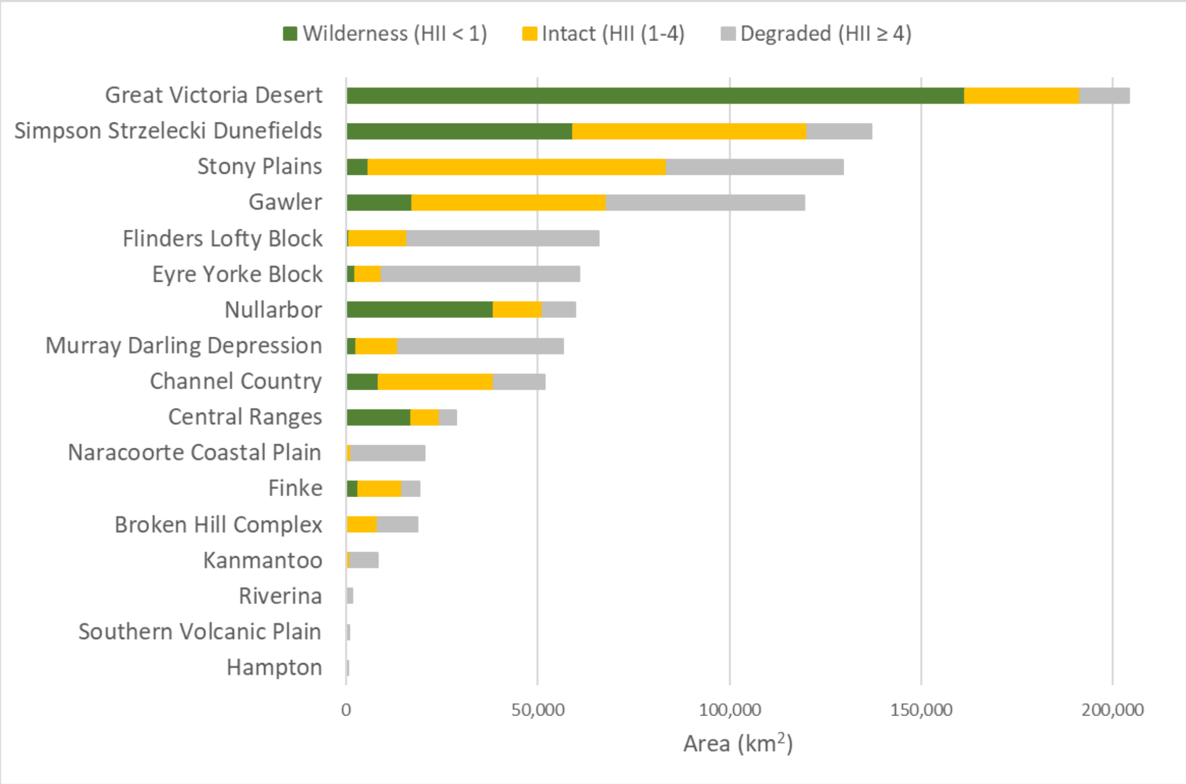


Figure 7. Historic (Intact and Degraded) and current extent of wilderness areas per bioregion in South Australia based on arbitrary Human Industrial Index thresholds.

## Intactness in South Australia

The ecological intactness index utilising the Beyer et al. (2020) methodology was successfully generated for South Australia (Fig 8a), with the input layer being the Human Industrial Footprint Index. The resulting map shows that South Australia has an average intactness of 0.42 ± 0.36. As expected, the 30% threshold we set with the highest intactness values across the State fall within wilderness areas as mapped in the previous section (HII ≤ 1) (Fig 8b), excluding the edges of these patches and smaller patches.

It is valuable to highlight that not all wilderness areas have the same levels of intactness, which might be important to formulating policies around the wilderness concept, as priorities could be set on this variability (Fig 8c).

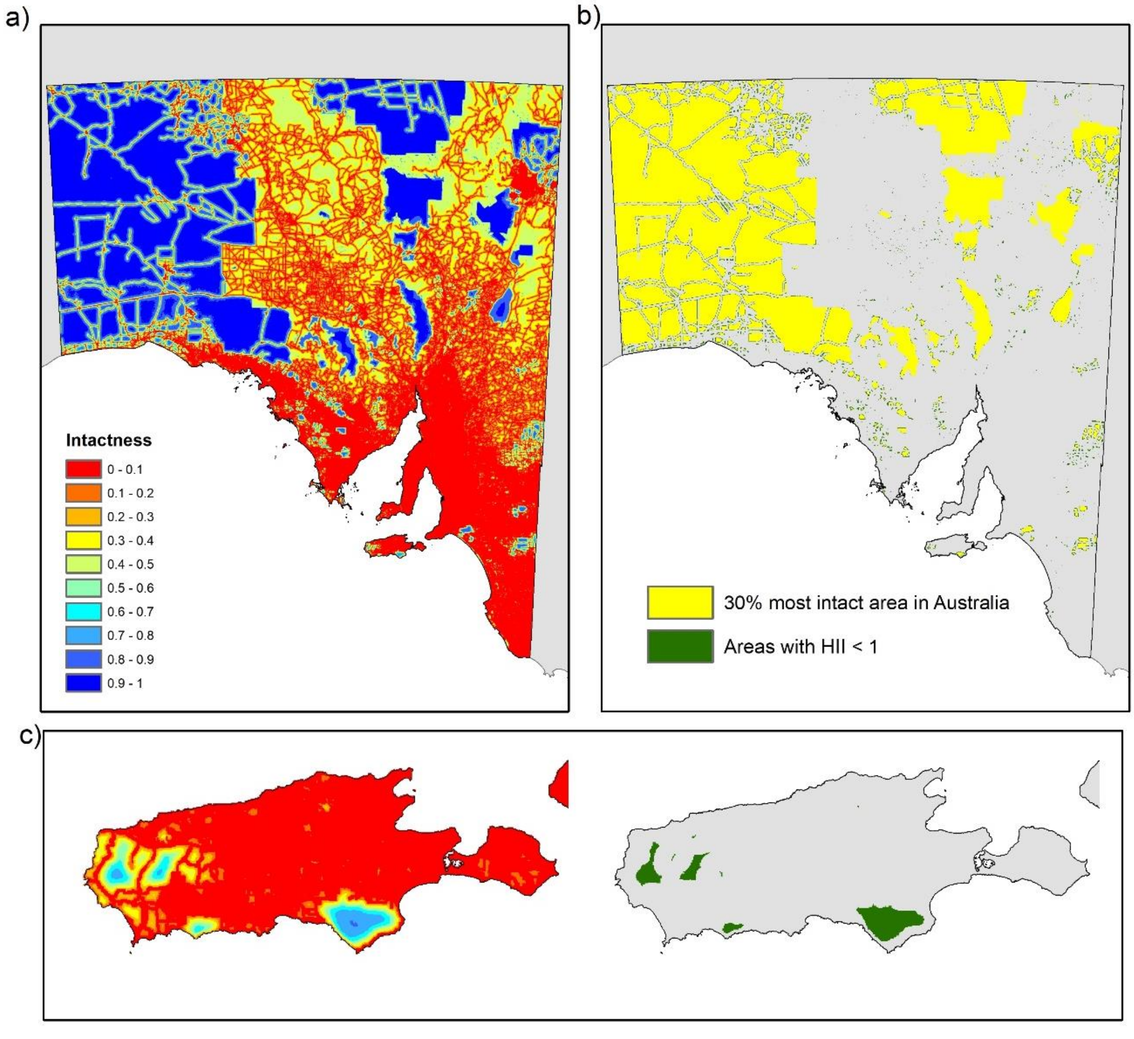


Figure 8. a) Intactness index for South Australia created through the Beyer method (Beyer et al 2020). b) The 30% most intact land in South Australia overlaid on top of those areas with a Human Industrial Footprint Index below 1 (a proxy for wilderness areas), c) A close-up to identified wilderness areas in Kangaroo Island (map on the left) and their intactness (map on the right).

When defining wilderness, it is potentially helpful to consider the concepts “last of the best” and “best of the last” (Fig 9). In this case, the last of the best takes the highest proportions of intactness per bioregion using a threshold of 30% (Fig 9a). It is, therefore, relative to the unit being mapped (in this case, bioregions). The 30% threshold is arbitrary and can be set at any level.

The best of the last is a strict threshold of the best 30% and thus not relative (Fig 9b).

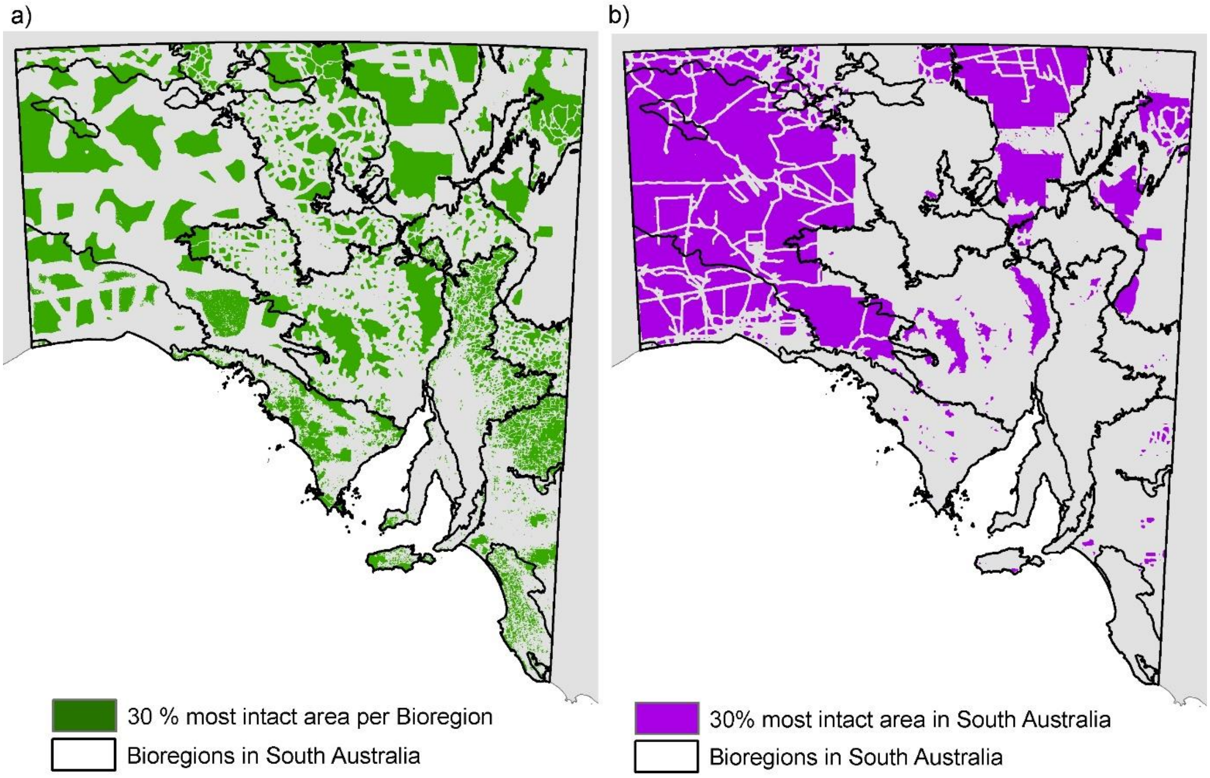


Figure 9. Wilderness identification through the intactness layer can be done through two different concepts. One in which the concept of representativity is considered to identify the most intact areas in different ecological regions (Fig 9a) (IBRA Bioregions shown in this case), and one in which the most intact areas in the State are considered wilderness (Fig 9b).

## Note

The pastureland data used in this analysis does not co-occur with protected areas. Thus, any grazing pressure on protected areas is not captured with this dataset. However, this is known to be an activity accruing in the Protected Areas in the State (Prowse et al., 2019)

## References

Allan, J. R., Venter, O., and Watson, J. E. M. (2017). Temporally inter-comparable maps of terrestrial wilderness and the Last of the Wild. *Sci Data* 4, 170187. doi:10.1038/sdata.2017.187.

Beyer, H. L., Venter, O., Grantham, H. S., and Watson, J. E. M. (2020). Substantial losses in ecoregion intactness highlight urgency of globally coordinated action. *Conserv Lett* 13, e12692. doi:10.1111/CONL.12692.

Boldy, R., Santini, T., Annandale, M., Erskine, P. D., and Sonter, L. J. (2021). Understanding the impacts of mining on ecosystem services through a systematic review. *Extr Ind Soc* 8, 457–466. doi:10.1016/J.EXIS.2020.12.005.

Elvidge, C. D., Baugh, K., Zhizhin, M., Hsu, F. C., and Ghosh, T. (2017). VIIRS night-time lights. *Int J Remote Sens* 38, 5860–5879. doi:10.1080/01431161.2017.1342050.

Filazzola, A., Brown, C., Dettlaff, M. A., Batbaatar, A., Grenke, J., Bao, T., et al. (2020). The effects of livestock grazing on biodiversity are multi-trophic: a meta-analysis. *Ecol Lett* 23, 1298–1309. doi:10.1111/ELE.13527.

Grass, I., Loos, J., Baensch, S., Batáry, P., Librán-Embid, F., Ficiciyan, A., et al. (2019). Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. *People Nat* 1, 262–272. doi:https://doi.org/10.1002/pan3.21.

Green, R. E., Cornell, S. J., Scharlemann, J. P. W., and Balmford, A. (2005). Farming and the fate of wild nature. *Science (80- )* 307, 550–555. doi:10.1126/SCIENCE.1106049/SUPPL_FILE/GREEN.SOM.PDF.

Hirsh-Pearson, K., Johnson, C. J., Schuster, R., Wheate, R. D., and Venter, O. (2022). Canada's human footprint reveals large intact areas juxtaposed against areas under immense anthropogenic pressure. *Facets* 7, 398–419. doi:10.1139/FACETS-2021-0063/SUPPL_FILE/FACETS-2021-0063_SUPPLEMENT4.PDF.

Jones, K. R., Venter, O., Fuller, R. A., Allan, J. R., Maxwell, S. L., Negret, P. J., et al. (2018). One-third of global protected land is under intense human pressure. *Science (80- )* 360, 788–791. doi:10.1126/science.aap9565.

Leslie, R. G., Mackey, B. G., and Preece, K. M. (1998). A computer-based methodology for the survey of wilderness in Australia. *Environ Conserv* 15, 225–232. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84994436816&partnerID=40&md5=ed6cb126bd75d0b6cf972608e3ca1584.

Lesslie, R. G., and Taylor, S. G. (1983). *Wilderness in South Australia : an inventory of the state's relatively high quality wilderness areas*. , eds. S. G. Taylor, U. of A. D. of Geography, and U. of A. C. for E. Studies Adelaide [S. Aust.]: Centre for Environmental Studies, University of Adelaide.

Lesslie, R. G., and Taylor, S. G. (1985). The wilderness continuum concept and its implications for Australian wilderness preservation policy. *Biol Conserv* 32, 309–333. doi:https://doi.org/10.1016/0006-3207(85)90021-7.

Liddicoat, C., Ciganovic, P., Sindicic, M., and Wright, M. (2022). Farm Dams. A guide to siting, design, construction and management on Eyre Peninsula. 88. Available at: https://cdn.environment.sa.gov.au/landscape/docs/ep/Farm-Dams-Guide.pdf.

Locke, H., Ellis, E. C., Venter, O., Schuster, R., Ma, K., Shen, X., et al. (2019). Three global conditions for biodiversity conservation and sustainable use: an implementation framework. *Natl Sci Rev* 6, 1080–1082. doi:10.1093/nsr/nwz136.

Maxwell, S. L., Fuller, R. A., Brooks, T. M., and Watson, J. E. M. (2016). Biodiversity: The ravages of guns, nets and bulldozers. *Nature* 536, 143–145. doi:10.1038/536143a.

Prowse, T. A. A., O'Connor, P. J., Collard, S. J., and Rogers, D. J. (2019). Eating away at protected areas: Total grazing pressure is undermining public land conservation. *Glob Ecol Conserv* 20, e00754. doi:https://doi.org/10.1016/j.gecco.2019.e00754.

Riggio, J., Baillie, J. E. M., Brumby, S., Ellis, E., Kennedy, C. M., Oakleaf, J. R., et al. (2020). Global human influence maps reveal clear opportunities in conserving Earth's remaining intact terrestrial ecosystems. *Glob Chang Biol* 26, 4344–4356. doi:10.1111/GCB.15109.

Sanderson, E. W., Jaiteh, M., Levy, M. A., Redford, K. H., Wannebo, A. V, and Woolmer, G. (2002). The Human Footprint and the Last of the Wild: The human footprint is a global map of human influence on the land surface, which suggests that human beings are stewards of nature, whether we like it or not. *Bioscience* 52, 891–904. doi:10.1641/0006-3568(2002)052[0891:THFATL]2.0.CO;2.

Sawyer, N. (2015). Wilderness quality mapping - the Australian experiences. in *Science and stewardship to protect and sustain wilderness values: Tenth World Wilderness Congress symposium*, eds. A. Watson, S. Carver, Z. Krenova, and B. McBride (Samanaca, Spain).

Small, C., Elvidge, C. D., Balk, D., and Montgomery, M. (2011). Spatial scaling of stable night lights. *Remote Sens Environ* 115, 269–280. doi:10.1016/J.RSE.2010.08.021.

Sonter, L. J., Ali, S. H., and Watson, J. E. M. (2018). Mining and biodiversity: key issues and research needs in conservation science. *Proc R Soc B* 285. doi:10.1098/RSPB.2018.1926.

Tratalos, J., Fuller, R. A., Warren, P. H., Davies, R. G., and Gaston, K. J. (2007). Urban form, biodiversity potential and ecosystem services. *Landsc Urban Plan* 83, 308–317. doi:10.1016/J.LANDURBPLAN.2007.05.003.

Trombulak, S. C., and Frissell, C. A. (2000). Review of ecological effects of roads on terrestrial and aquatic communities. *Conserv Biol* 14, 18–30. doi:10.1046/J.1523-1739.2000.99084.X.

Venter, O., Sanderson, E. W., Magrach, A., Allan, J. R., Beher, J., Jones, K. R., et al. (2016). Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nat Commun* 7, 12558. Available at: http://dx.doi.org/10.1038/ncomms12558.

Watson, J. E. M., Shanahan, D. F., Di Marco, M., Allan, J., Laurance, W. F., Sanderson, E. W., et al. (2016). Catastrophic Declines in Wilderness Areas Undermine Global

Environment Targets. *Curr Biol* 26, 2929–2934. doi:10.1016/j.cub.2016.08.049.

Watson, J. E. M., and Venter, O. (2019). Mapping the Continuum of Humanity's Footprint on Land. *One Earth* 1, 175–180. doi:10.1016/J.ONEEAR.2019.09.004.

Williams, B. A., Venter, O., Allan, J. R., Atkinson, S. C., Rehbein, J. A., Ward, M., et al. (2020). Change in Terrestrial Human Footprint Drives Continued Loss of Intact Ecosystems. *One Earth* 3, 371–382. doi:https://doi.org/10.1016/j.oneear.2020.08.009.

Woolmer, G., Trombulak, S. C., Ray, J. C., Doran, P. J., Anderson, M. G., Baldwin, R. F., et al. (2008). Rescaling the Human Footprint: A tool for conservation planning at an ecoregional scale. *Landsc Urban Plan* 87, 42–53. doi:10.1016/J.LANDURBPLAN.2008.04.005.

## Annex 1. Note on the difference between the past Australian National Wilderness Inventory and the Human Industrial and Intactness indices

The Australian National Wilderness Inventory (NWI) and the Human Industrial Index (HII) created here for South Australia use two distinct methodologies to assess the pressure that contemporary human industrial activities have on the natural environment. The underlying assumptions behind each method to score human pressures in the environment are different, as well as the datasets used (with different levels of accuracy and sources of errors). Thus, the NWI and the HII maps are not directly comparable, and they are particularly not suitable for making quantitative assessments of temporal changes in human pressures (that is, it is not sensible to assess changes in wilderness quality by comparing the current HII product with the previous NWI product). It also must be noted that the underlying data for the original NWI assessment could not be reproduced.

However, it is valuable to note that a recent evaluation (Riggio et al., 2020) of four different pressure maps produced with different methodologies -including a global HII (Venter et al. 2016)- found a strong agreement between all methods in the areas that were identified as having low and very low human influence. This suggests that the NWI and the HII maps are likely to have important agreement between those areas identified as having low human pressure (high wilderness quality), especially if mapped for similar points in time. Unfortunately, a quantitative assessment of the agreement between the NWI and the HII or the intactness map cannot be done given the absence of a geospatial layer of the current NWI. However, a simple visual inspection of the current NWI and the newly generated maps show similar patterns in terms of wilderness quality (human pressure) (Fig A1). The NWI map was obtained from the report “Data on significant wilderness areas in the Alinytjara Wilurara and South Australian Arid Lands NRM Regions” (Wilderness Advisory Committee 2014), it was georeferenced in ArcGIS 10.8.

An additional small note on the concept of remoteness: while the NWI directly weights pressure scores by the distance of a cell to the nearest pressure (reporting the highest value pressure in case of multiple pressures “affecting” that cell), the HII includes a remoteness element by assigning a pressure value to cells that are at a certain distance from roads and navigable waterways. Thus, although the methods are different, given that roads, railways, and waterways are the means of people reaching those areas where they carry out actions or build infrastructure that exert pressure on the environment (e.g., settlements and access points as defined in the NWI), the HII also incorporates an element of remoteness (via the measure of distance). This can be observed by overlaying the road network over the NWI map (Fig A3).

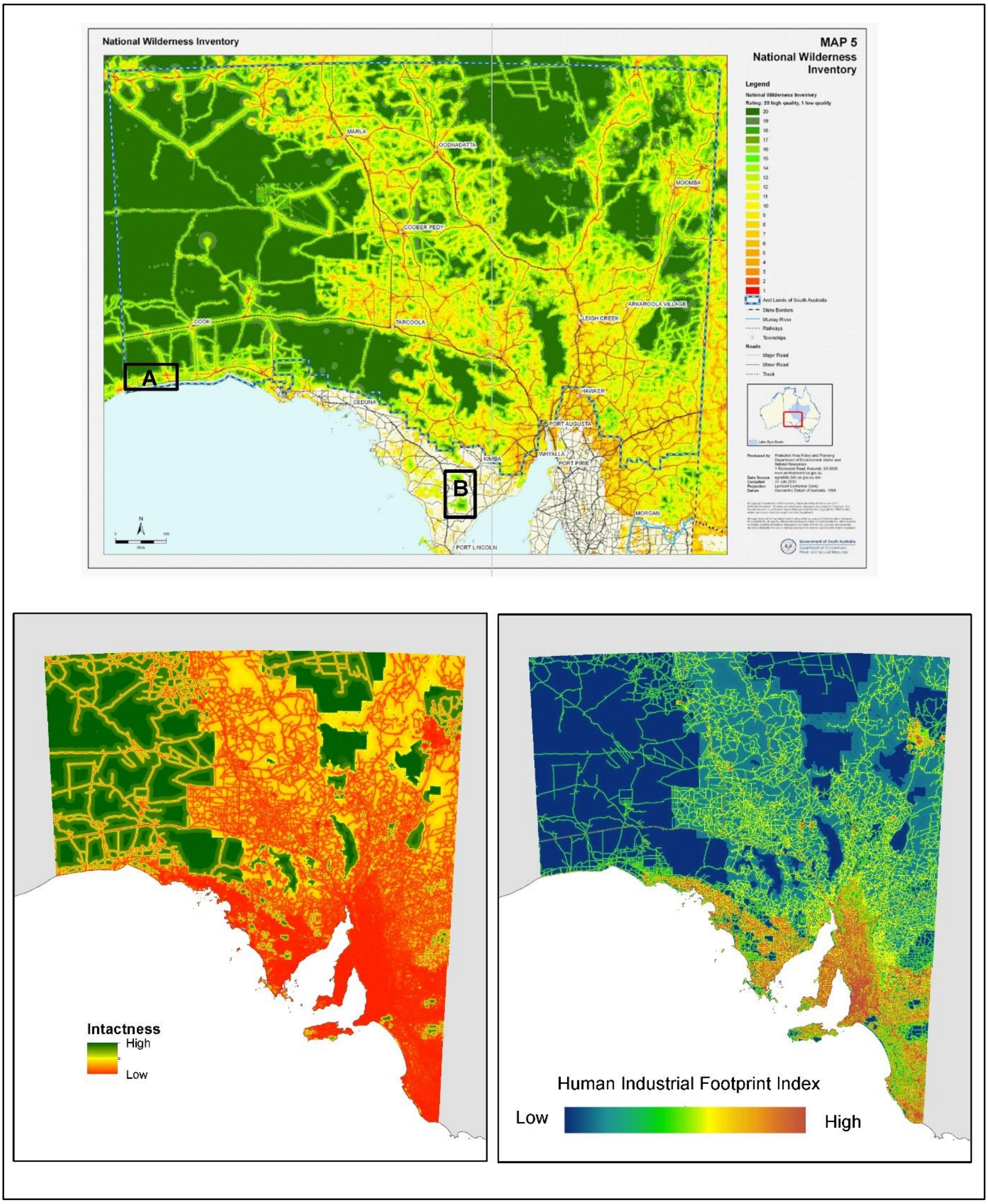


Figure A1. Visual comparison of the current NWI (top) and the HII (bottom right) and the Intactness index (bottom left) for South Australia. The NWI was obtained from a report from the Wilderness Advisory Committee (2014); values of 12 or more are in different tones of green. Boxes A and B correspond to areas in the next figure.

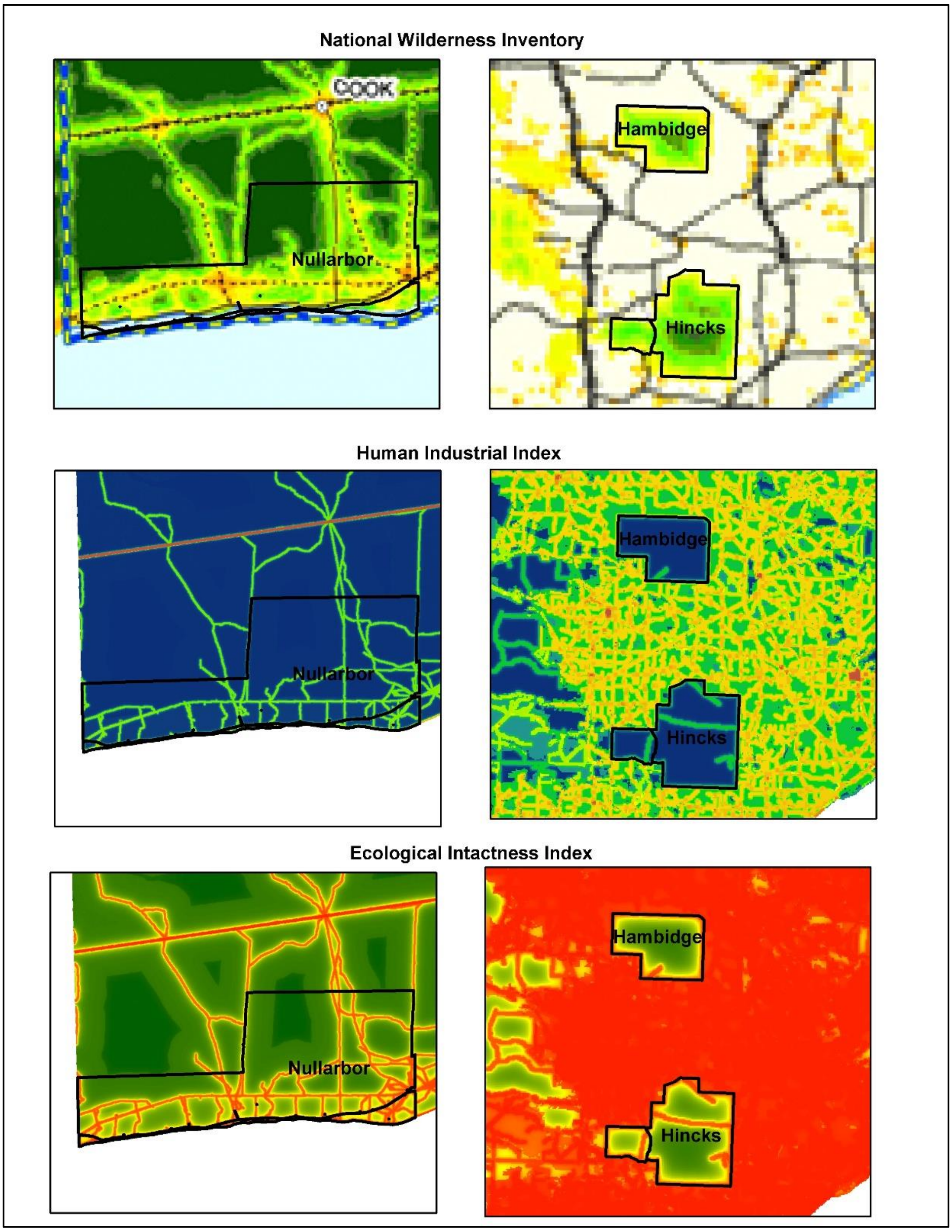


Figure A2. Visual comparison of the current NWI) and the HII and the Intactness index for two regions in South Australia. The NWI map was obtained  from a report from the Wilderness Advisory Committee (2014); values of 12 or more are in different tones of green.;. The images on the left correspond to Box A in Fig A1, and the images on the right correspond to Box B.

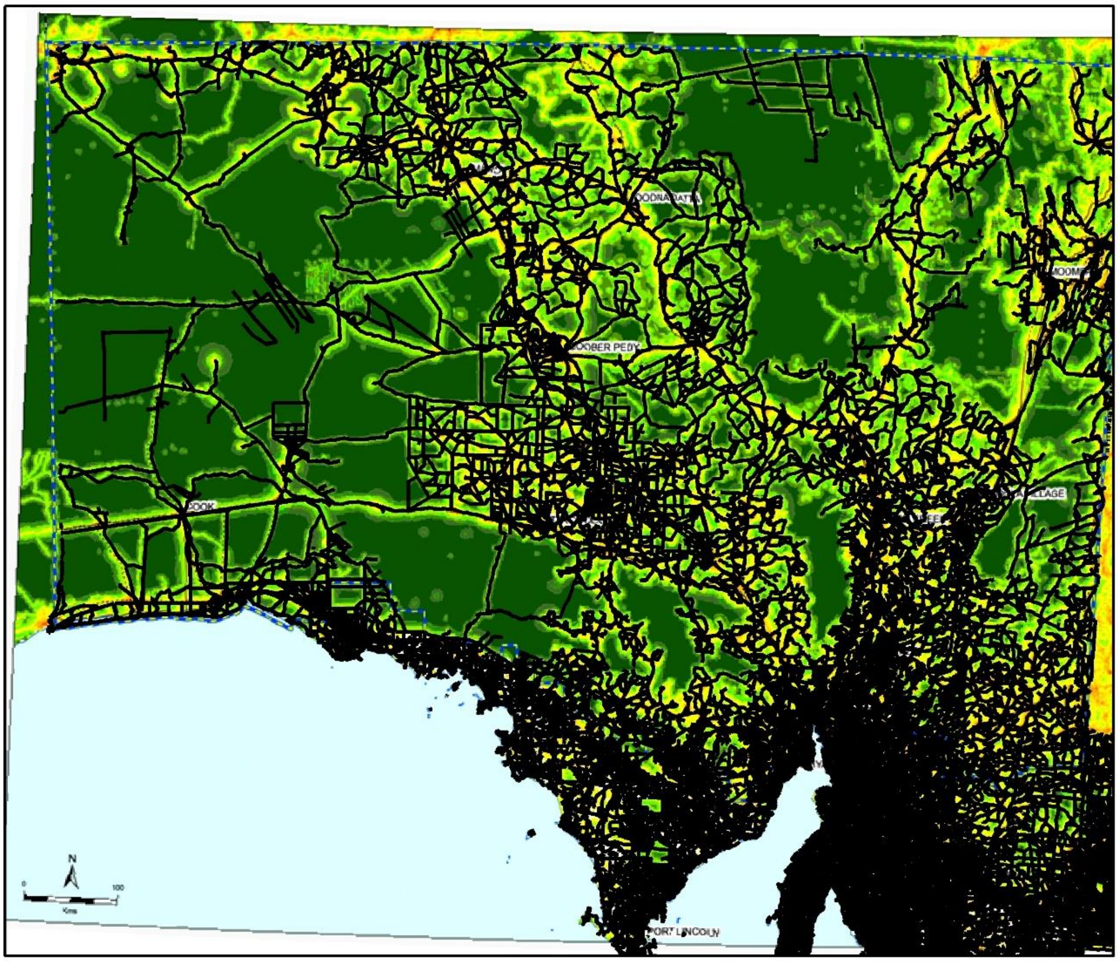

Fig 3A. Most areas with lower wilderness quality identified in the current NWI are in the vicinity of the road network. There are some isolated patches away from roads that are not dark green (the highest wilderness quality value), but in most cases they correspond with a tone of green (high wilderness quality). The NWI map was obtained from a report from the Wilderness Advisory Committee (2014); values of 12 or more are in different tones of green.

References

Riggio, J., Baillie, J. E. M., Brumby, S., Ellis, E., Kennedy, C. M., Oakleaf, J. R., et al. (2020). Global human influence maps reveal clear opportunities in conserving Earth's remaining intact terrestrial ecosystems. *Glob Chang Biol* 26, 4344–4356. doi:10.1111/GCB.15109.

Wilderness Advisory Committee. (2014). Data on significant wilderness areas in the Alinytjara Wilurara and South Australian Arid Lands NRM Regions

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