



Government of **Western Australia**
Department of **Water and Environmental Regulation**

Perth Air Emissions Study 2011–2012

Technical report 1:
Biogenic and Geogenic Emissions



Report

Department of Water and Environmental Regulation
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61 8 6364 7000
Facsimile +61 8 6364 7001
National Relay Service 13 36 77
www.dwer.wa.gov.au

© Government of Western Australia

June 2018

This work is copyright. You may download, display, print and reproduce this material in unaltered form only (retaining this notice) for your personal, non-commercial use or use within your organisation. Apart from any use as permitted under the *Copyright Act 1968*, all other rights are reserved. Requests and inquiries concerning reproduction and rights should be addressed to the Department of Water and Environmental Regulation.

Temporal and spatially allocated emission estimates produced for this study can be made available on request. Please contact npi@dwer.wa.gov.au with queries and requests for information.

Disclaimer

This document has been published by the Department of Water and Environmental Regulation. Any representation, statement, opinion or advice expressed or implied in this publication is made in good faith and on the basis that the Department of Water and Environmental Regulation and its employees are not liable for any damage or loss whatsoever which may occur as a result of action taken or not taken, as the case may be in respect of any representation, statement, opinion or advice referred to herein. Professional advice should be obtained before applying the information contained in this document to particular circumstances.

The Department of Water and Environmental Regulation was established by the Government of Western Australia on 1 July 2017. It is a result of the amalgamation of the Department of Environment Regulation, Department of Water and the Office of the Environmental Protection Authority. This publication may contain references to previous government departments and programs. Please email the Department of Water and Environmental Regulation to clarify any specific information.

This publication is available at our website <<https://www.dwer.wa.gov.au>> or for those with special needs it can be made available in alternative formats such as audio, large print, or Braille

Contents

Summary	vi
1 Introduction.....	1
1.1 Inventory scope	1
2 Study methodology.....	4
2.1 Meteorology	4
2.2 Marine aerosol	5
2.3 Windblown dust	8
2.4 Fires	26
2.5 Soils	40
2.6 Vegetation.....	53
3 Total emission estimates	66
3.1 Total biogenic and geogenic emissions	66
3.2 Spatial allocation summary.....	72
4 Key considerations	80
Appendices.....	81
References	85

Figures

Figure 1 – Perth Air Emissions Study 2011–2012 boundaries.....	2
Figure 2 – Grid coordinate system.....	3
Figure 3 – Annual average marine wind speed	6
Figure 4 – Spatial allocation of marine aerosol TSP emissions.....	7
Figure 5 – Soil erodibility factor	11
Figure 6 – Agricultural lands crop type coverage.....	12
Figure 7 – Climatic factor.....	14
Figure 8 – Agricultural land coverage	18
Figure 9 – Land development and site preparation coverage.....	19
Figure 10 – Unpaved road coverage	20
Figure 11 – Spatial allocation of agricultural land wind erosion TSP emissions	22
Figure 12 – Spatial allocation of land development wind erosion TSP emissions	23
Figure 13 – Spatial allocation of unpaved roads wind erosion TSP emissions.....	24
Figure 14 – Spatial allocation of total wind erosion TSP emissions.....	25
Figure 15 – Bushfire and prescribed burn areas between July 2011 and June 2012	30
Figure 16 – Spatial allocation of agricultural burning TSP emissions	36
Figure 17 – Spatial allocation of bushfire TSP emissions.....	37
Figure 18 – Spatial allocation of prescribed burning TSP emissions	38
Figure 19 – Spatial allocation of total fire TSP emissions.....	39
Figure 20 – Land use distribution	44
Figure 21 – Gridded land use temperature control factor for soil NO _x emissions.....	46
Figure 22 – Spatial allocation of soil NO _x emissions	51
Figure 23 – Spatial allocation of soil NH ₃ emissions.....	52
Figure 24 – Leaf area index.....	61

Figure 25 – Terrain height 62

Figure 26 – Spatial allocation of vegetation VOC emissions 65

Figure 27 – Biogenic and geogenic emission estimates: source contributions by mass.... 68

Figure 28 – Biogenic and geogenic TEP source contributions 71

Figure 29 – Spatial allocation of biogenic and geogenic VOC emissions 73

Figure 30 – Spatial allocation of biogenic and geogenic PM_{2.5} emissions 74

Figure 31 – Spatial allocation of biogenic and geogenic NO_x emissions..... 75

Figure 32 – Spatial allocation of biogenic and geogenic PM₁₀ emissions..... 76

Figure 33 – Spatial allocation of biogenic and geogenic CO emissions 77

Figure 34 – Spatial allocation of biogenic and geogenic SO₂ emissions 78

Figure 35 – Spatial allocation of biogenic and geogenic TEP score 79

Tables

Table 1 – Study grid corner coordinates	1
Table 2 – Marine aerosol emission estimates.....	5
Table 3 – Speciation of TSP for windblown dust	9
Table 4 – Soil erodibility factors.....	9
Table 5 – Surface roughness factors.....	10
Table 6 – Unsheltered field width factor variables used	15
Table 7 – Vegetative coverage factor data	16
Table 8 – Windblown dust emission estimates.....	21
Table 9 – Wind erosion emission source area.....	21
Table 10 – Agricultural fuel load input data	28
Table 11 – Agricultural burning emission factors.....	28
Table 12 – Bushfire and prescribed burning fuel load and burn efficiency factors.....	31
Table 13 – Bushfire and prescribed burning emission factors	32
Table 14 – Speciation profiles for fires	33
Table 15 – Fire emission estimates.....	33
Table 16 – Fire emission source area	35
Table 17 – Soil temperature calculation constants for each land use type	41
Table 18 – Area of land use categories in study area.....	43
Table 19 – Nitric oxide emission factors	45
Table 20 – Fertiliser use in study area.....	47
Table 21 – Agricultural ammonia emission factors	48
Table 22 – Fertiliser distribution by land use	48
Table 23 – Natural ammonia emission factors.....	49
Table 24 – Soil emission estimates	50
Table 25 – Area of vegetation types in study area.....	58
Table 26 – Tree canopy and uncut grass emission factors.....	59
Table 27 – Area of lawn mown: domestic lawn.....	60
Table 28 – Area of lawn mown: public open space lawn	63
Table 29 – Cut grass biomass attributes and VOC emission factor.....	63
Table 30 – Cut grass VOC speciation factors.....	64
Table 31 – Vegetation emission estimates	64
Table 32 – Biogenic and geogenic emission estimates: total	66
Table 33 – Biogenic and geogenic emissions estimates by source.....	69
Table 34 – NPI substance TEP rating	81

Summary

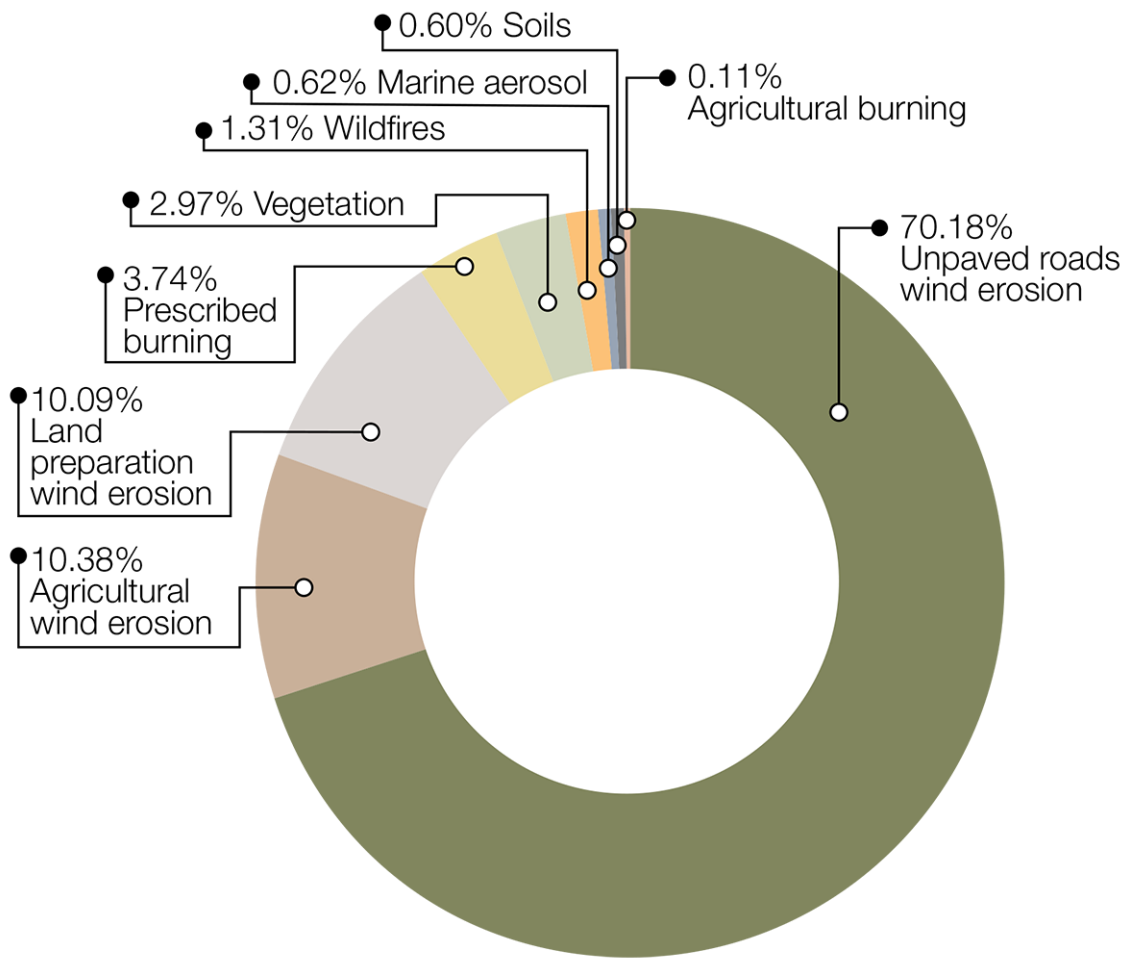
The Department of Water and Environmental Regulation (DWER) has completed an air emissions inventory of Perth for the 2011–12 financial year. The study area was generally consistent with the Australian Bureau of Statistics (ABS) Census Dataset: Greater Capital City Statistical Area – Greater Perth. The inventory estimated emissions for a variety of natural and anthropogenic emission sources.

This report summarises estimated emissions from biogenic and geogenic sources, including marine aerosols, wind erosion, bushfires and prescribed burning, soil denitrification and vegetation.

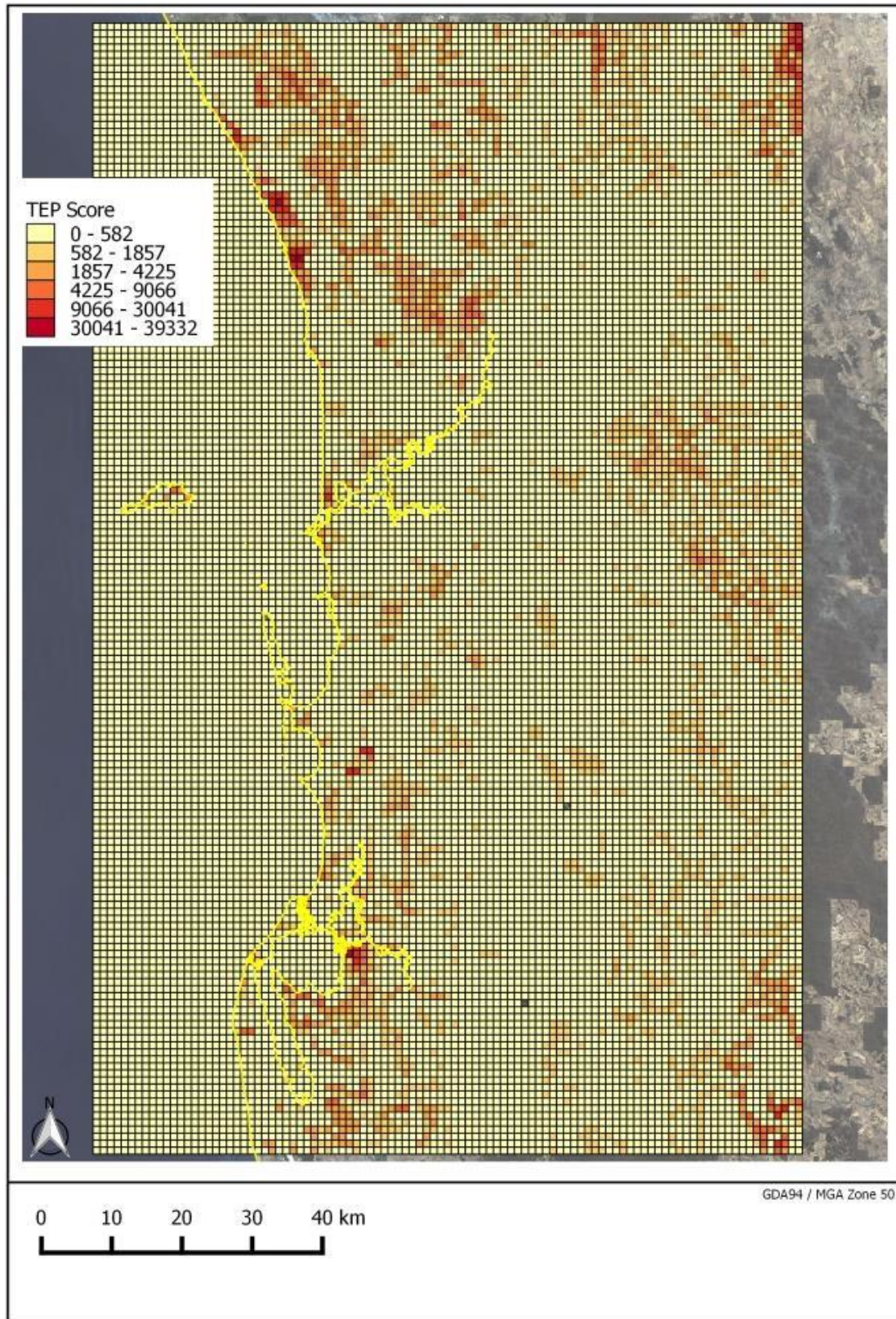
Emissions were estimated using the methodology published in the *2008 Calendar Year Air Emissions Inventory for the Greater Metropolitan Region in New South Wales* (NSW EPA 2012). Methodologies were adapted to address the availability of local data and, in some cases, were superseded by more relevant or recently developed methods. Emissions were spatially allocated with respect to land use, soil types, climate, vegetation groups, topography and relevant activities.

Based on a toxic equivalency potential (TEP) scoring system, emission estimates from biogenic and geogenic sources for 2011–12 showed that volatile organic compounds were the most significant major emission. Emission estimates of metals such as lead, mercury and cadmium (speciated from particulate emissions) were comparatively small, but were found to be significant pollutants due to their high toxicity.

The summary figures show the relative contribution from biogenic and geogenic emission sources to the overall TEP score, and the spatial allocation of the TEP score. Wind erosion made the largest contribution and represented 90 per cent of the emission risk from biogenic and geogenic sources. Unpaved road wind erosion was the single largest emission source.



Summary figure – relative TEP contributions from biogenic and geogenic sources



Summary figure – spatial allocation of biogenic and geogenic TEP score

1 Introduction

The Department of Water and Environmental Regulation (DWER) has completed an air emissions inventory of Perth for 2011–12.

This technical report presents the emission estimate methods, calculated emissions, and spatial allocation of emissions of biogenic and geogenic emission sources.

This technical report focuses on emissions estimated as a result of biogenic and geogenic activities. It is one of six reports prepared for the Perth Air Emissions Study 2011–2012:

1. *Perth Air Emissions Study 2011–2012: Summary of emissions*
2. **Technical report 1: Biogenic and geogenic emissions**
3. *Technical report 2: Domestic emissions*
4. *Technical report 3: Commercial and industrial emissions*
5. *Technical report 4: On-road vehicle emissions*
6. *Technical report 5: Off-road mobile emissions*

1.1 Inventory scope

This module is defined by the following study parameters:

Year

The data presented by this study represent emissions estimated for the 2011–12 financial year. This time period aligns with Australian Bureau of Statistics (ABS) census data and available datasets.

Where data are not available for 2011–12, data outside the study period have been used as being broadly representative of 2011–12.

Boundaries

This study includes Local Government Areas (LGAs) in the ABS *Census Dataset: Greater Capital City Statistical Area – Greater Perth* (ABS 2012). The grid covers an area of 100 kilometres west to east (Rottnest Island to Toodyay) and 160 kilometres north to south (Two Rocks to Waroona). The corner coordinates are presented in Table 1, and the study area is shown in Figure 1.

Table 1 – Study grid corner coordinates

	Easting* (m)	Northing* (m)
North-west	350000	6525000
North-east	450000	6525000
South-west	350000	6365000
South-east	450000	6365000

* Geocentric Datum of Australia 1994 (GDA94 MGA Zone 50).



Figure 1 – Perth Air Emissions Study 2011–2012 boundaries

Spatial allocation

The study used a one kilometre grid to spatially allocate emission estimates. This scale balances the resolution of fine data (roads, individual point sources etc.) and computationally demanding calculations.

Grid coordinates start at the upper left corner, as illustrated in Figure 2.

		Easting (m)			
		350000	351000	352000	353000
Northing (m)	6525000				
	6524000	(350, 6525)			
	6523000			(352, 6524)	
	6522000		(351, 6523)		

Figure 2 – Grid coordinate system

Emission substances

The substances of interest in this study module are those in the National Environment Protection (Ambient Air Quality) Measure. These include:

- carbon monoxide (CO);
- nitrogen dioxide (NO₂), as a subset of oxides of nitrogen (NO_x);
- particulate matter 2.5 µm (PM_{2.5});
- particulate matter 10 µm (PM₁₀); and
- sulfur dioxide (SO₂).

Ozone (O₃), as a proxy for photochemical smog, is a secondary pollutant resulting from the chemical transformation of pollutants in the atmosphere over time, and was not directly considered in this study. Instead, emissions of volatile organic compounds (VOCs) were estimated because these, along with oxides of nitrogen, are considered to be precursors to smog formation.

Other emissions estimated are included in the list of substances of interest to the National Pollutant Inventory (NPI):

- ammonia;
- heavy metals, including lead, cadmium, copper, chromium, nickel, selenium and zinc; and
- organic compounds, including speciated volatiles, polycyclic aromatic hydrocarbons (B[a]P_{eq}), and polychlorinated dioxins and furans (TEQ).

2 Study methodology

The biogenic and geogenic emissions inventory method has two discrete stages: the estimation of total biogenic and geogenic emissions, and the spatial allocation of those emissions. The methods were developed and used for data readily available at the time. Several assumptions have been made to supplement data gaps and are documented in the relevant sections.

The biogenic and geogenic emission sources considered in this inventory include:

- marine aerosol
- windblown dust (agricultural land, cleared land and unpaved roads)
- fires (agricultural burning, prescribed burns and bushfires)
- soils
- vegetation (tree canopy and grasses)

Some emission sources in this module are the result of human influences rather than being strictly 'natural' emissions. These emissions are included in this module because of the difficulty in separating natural and human influences from the activity data used, the nature of the emissions, or because this module is the most appropriate place in the inventory to which to allocate these emissions.

2.1 Meteorology

Gridded meteorological data used in this module have been generated using 'The Air Pollution Model' Version 4 (TAPM V4) (Hurley 2008). To generate the meteorology, the following inputs and settings were applied in the model:

- Centre coordinates 400,000 mE and 6,445,000 mS (UTM Zone 50)
- Three nested grids
 - outer grid resolution 27 kilometres¹
 - second grid resolution 10 kilometres
 - inner grid resolution three kilometres
- Model default vertical grid levels
- Date range 28/06/2011 to 30/06/2012 (two days 'wind up' at start)
- Default TAPM databases for synoptic scale meteorology and surface information

The three-kilometre inner grid data were manually allocated to one-kilometre grid cells to align with the study area grid.

¹ Outer grid had to be adjusted from the default 30 km to fit the grid within the 1500 km size limit of the model.

2.2 Marine aerosol

Marine aerosol emission estimates describe the particulate matter generated from the ocean/atmosphere interface. Surface winds pick up water droplets and carry the salt into the atmosphere where it can deposit on coastal environments downwind.

Emission estimation technique

Emissions for marine aerosol were estimated using the method established in the *2008 Calendar Year Air Emissions Inventory for the Greater Metropolitan Region in NSW* (NSW EPA 2012). The equations derived by NSW EPA were used in this study and are summarised below.

$$E_{PM2.5} = 1.59 \times 10^{-14} \times U^{3.41}$$

$$E_{PM10} = 1.10 \times 10^{-13} \times U^{3.41}$$

$$E_{TSP} = (1.30 \times 10^{-13} \times U^{3.41}) + (1.40 \times 10^{-13} \times U^{3.5}) + (2.70 \times 10^{-13} \times U^3)$$

Where:

- E = Total emissions of particulate size fraction (kg/yr)
 U = Wind speed at an elevation of 10 m from the water surface (m/s)

Activity data

Wind speed data were generated for each grid cell in the study area using TAPM V4, as described in Section 2.1. The annual average marine wind speed is presented in Figure 3.

To determine if a grid cell generated marine aerosol emissions, Landsat imagery was intersected with the study grid and visually inspected. Marine aerosol emissions were calculated for cells that were judged to be more than 50 per cent water.

Hourly average wind speed was used to estimate hourly emissions in each grid cell. Hourly emissions were then summed to obtain an annual emission estimate.

Emission estimates

Emissions of marine aerosols in the study area are summarised in Table 2.

Table 2 – Marine aerosol emission estimates

Source	Pollutant	Emissions (kg/yr)
Marine aerosol	Particulate matter 2.5 µm	1,281,315
	Particulate matter 10 µm	8,864,440
	Total suspended particulate (TSP)	33,388,229

Spatial allocation

The spatial allocation of marine aerosol emissions as total suspended particulate (TSP) is presented in Figure 4.

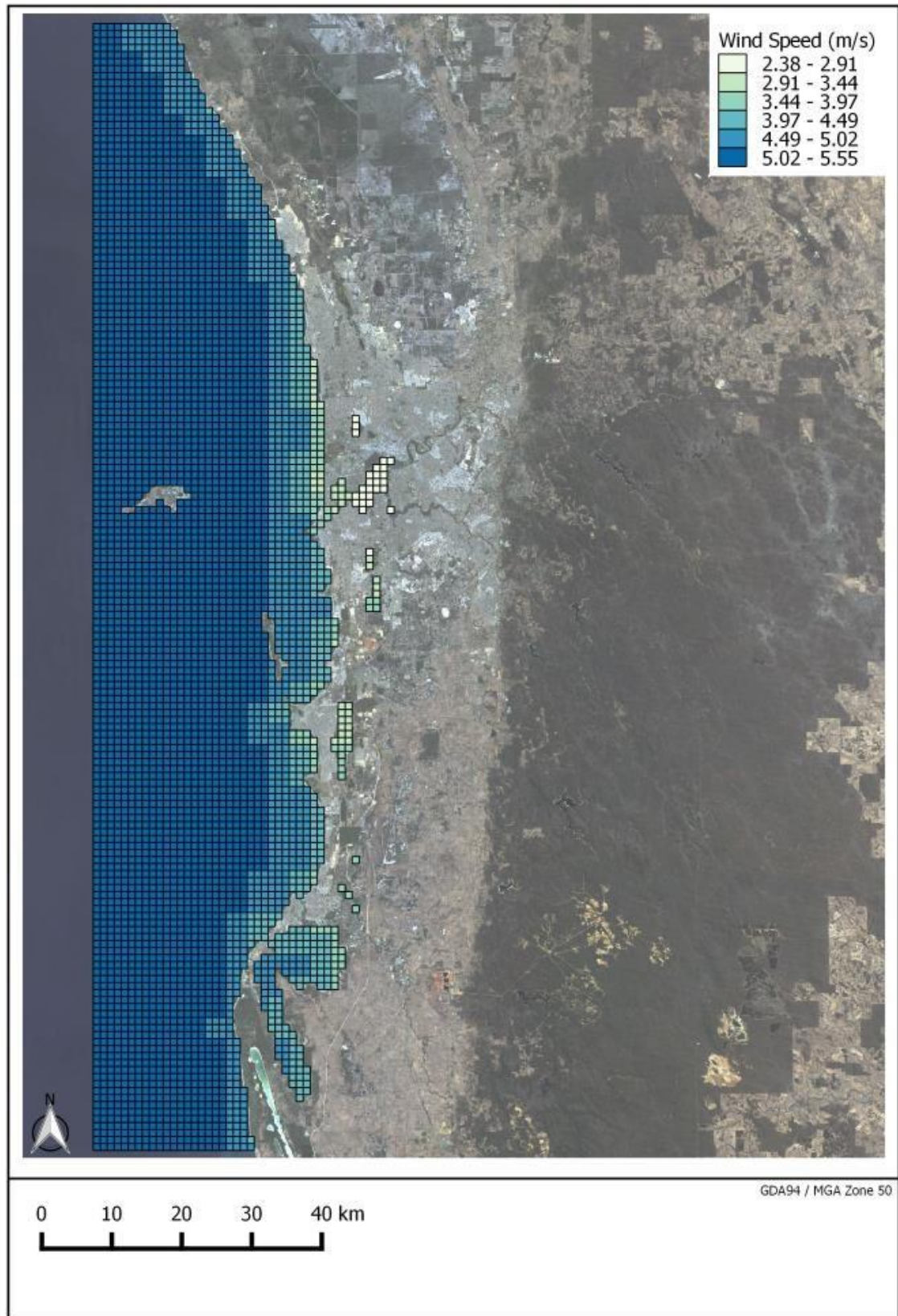


Figure 3 – Annual average marine wind speed

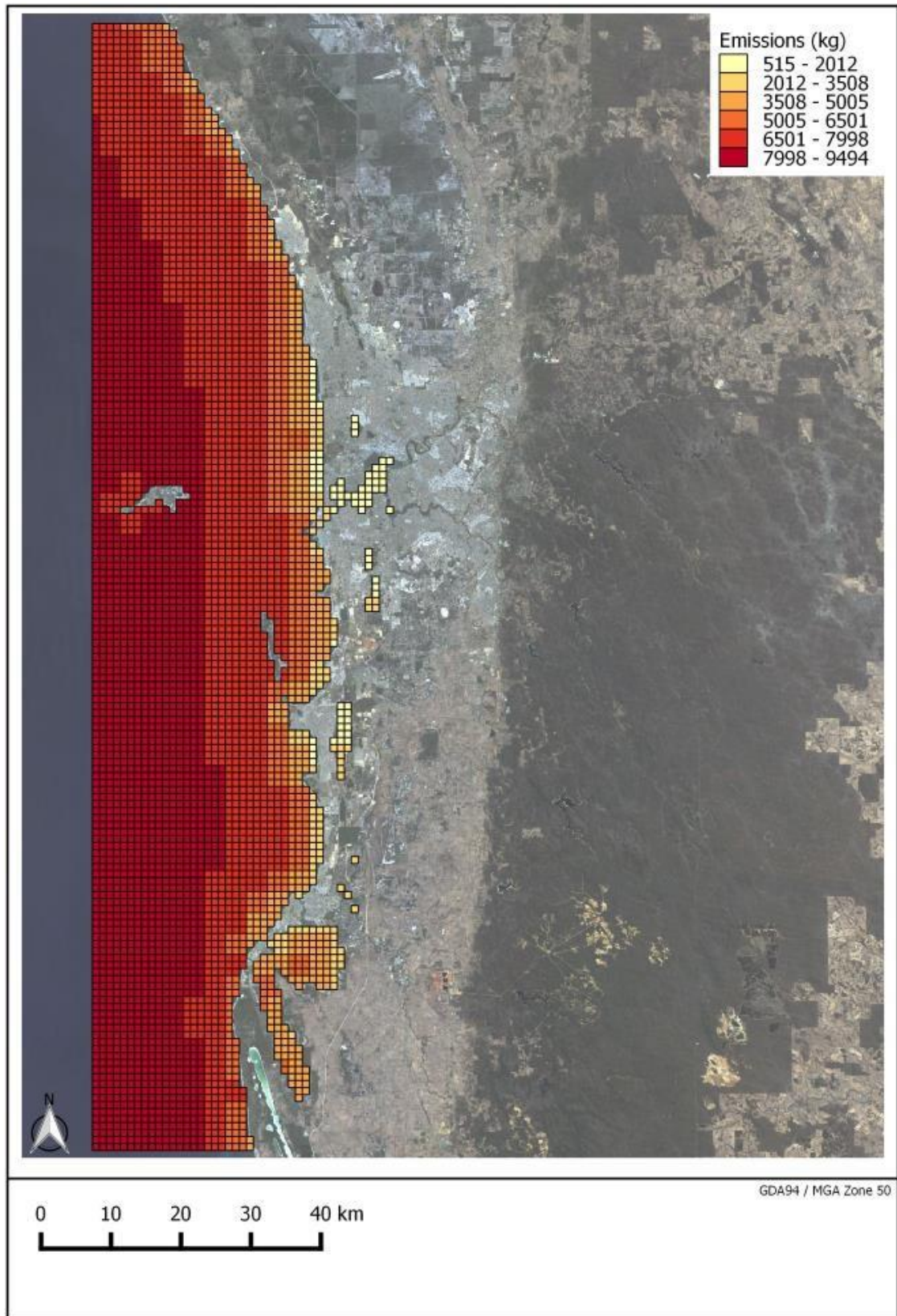


Figure 4 – Spatial allocation of marine aerosol TSP emissions

2.3 Windblown dust

Windblown dust emissions were estimated for particulate matter generated from exposed soils and surfaces. Three key sources of windblown dust were considered:

- Agricultural lands – cleared and prepared agricultural fields generate dust, with emissions reducing as crop coverage grows.
- Land development and site preparation services – preparing construction sites and new areas for development requires broadscale clearing and filling of land with sand which generates windblown dust.
- Unpaved roads – unpaved and unsealed road surfaces are pulverised by traffic, generating fine particulates which are distributed by winds.

Emission estimation technique

Emissions for agricultural lands and unpaved roads were estimated using the methods established in the *2008 Calendar Year Air Emissions Inventory for the Greater Metropolitan Region in NSW* (NSW EPA 2012).

The technique used to estimate land development and site preparation services was developed for this study.

Emissions from windblown dust were estimated using the following equation adapted from the California Air Resources Board (CARB 1997a, 1997b).

$$E_{i,j} = A \times I_j \times K_i \times C \times L'_i \times V'_{i,k} \times H_i \times 1000 \times CF$$

Where:

$E_{i,j}$	= Emissions of TSP from source (i) and soil type (j)	(kg/yr)
A	= Fraction of wind-eroded dust that becomes suspended and carried away by winds – 0.025 and 0.038 for agricultural lands and unpaved roads respectively	(–)
I_j	= Soil erodibility factor for soil type (j)	(tonne/ha/yr)
K_i	= Surface roughness factor for source type (i)	(–)
C	= Climatic factor	(–)
L'_i	= Unsheltered field width factor for source type (i)	(–)
$V'_{i,k}$	= Vegetative cover factor for source type (i) and month (k)	(–)
H_i	= Area of emission source (i)	(ha)
CF	= Emission control factor	(–)
i	= Source type (i.e. type of surface or crop coverage)	(–)
j	= Soil type	(–)
k	= Month	(–)

TSP emissions estimated using this equation are speciated using California Air Resources Board speciation profiles (CARB 2014a, 2014b) summarised in Table 3.

Table 3 – Speciation of TSP for windblown dust

Pollutant species	Agricultural lands (PMPROF 418)	Land development and site preparation services (PMPROF 420)	Unpaved roads (PMPROF 416)
Antimony and compounds	0.000006	0.00001	0.000007
Arsenic and compounds	0.000016	0.000017	0.000015
Cadmium and compounds	0.00002	0.000021	0.000025
Chromium (total)	0.000209	0.000224	0.000245
Cobalt and compounds	0.000087	0.000115	0.000149
Copper and compounds	0.000067	0.000102	0.000087
Lead and compounds	0.000062	0.000557	0.000901
Manganese and compounds	0.000953	0.000945	0.001051
Mercury and compounds	0.000011	0.000015	0.000015
Nickel and compounds	0.00005	0.000059	0.000063
Particulate matter 2.5 µm	0.0786	0.0489	0.0786
Particulate matter 10 µm	0.4543	0.4893	0.5943
Selenium and compounds	0.000002	0.000002	0.000001
Zinc and compounds	0.000164	0.000518	0.000622

Activity data

Soil erodibility factor (I)

The soil erodibility factors used in this inventory were derived from the *Digital Atlas of Australian Soils* dataset (BRS 1991). The principal profile form (PPF) in the dataset was used to determine the medium texture and clay content for each soil type. This data allowed a texture grade to be assigned to each soil (CSIRO 2000).

The texture grades were matched against the soil erodibility factors presented in USEPA (1974), shown in Table 4 below.

Table 4 – Soil erodibility factors

Soil texture class (USEPA)	Erodibility (tons/acre/year)	Erodibility (tonnes/ha/year) ²
Sand	220	535
Loamy sand	134	326
Sandy loam	86	209
Clay	86	209
Silty clay	86	209
Loam	56	136

² Converted from imperial units (tons/acre/year) to metric units (tonnes/hectare/year) using $1 \times 2.471/1.016$

Soil texture class (USEPA)	Erodibility (tons/acre/year)	Erodibility (tonnes/ha/year) ²
Sandy clay loam	56	136
Sandy clay	56	136
Silt loam	47	114
Clay loam	47	114
Silty clay loam	38	92
Silt	38	92

The soil erodibility factors used for each study area grid cell are presented in Figure 5. The lower erodibility values seen along coasts and waterbodies are due to a smaller ratio of land to water for each grid cell. The relatively high erodibility of soil in the study area is attributed to high sand content in most soils.

Surface roughness factor (K)

The surface roughness factor is a 0 to 1 scaling factor applied to windblown dust from agricultural lands and is based on the crop type coverage. Unpaved roads and construction sites were assigned a value of 1 as they are generally very smooth surfaces.

The surface roughness factor was calculated using crop coverage data from the *2005–06 Landuse of Australia, Version 4* dataset (BRS 2010). The area of agricultural land in the study area for each crop type is shown in Figure 6.

Equivalent crop types were selected to allow assignment of surface roughness factors presented in USEPA (1974) and in Table 5.

Table 5 – Surface roughness factors

Landuse of Australia V4 crop type	USEPA (1974) crop equivalent	Surface roughness (K)
Oil seeds	Canola	0.5
Legumes	Beans	0.5
Cereals	Wheat	0.6
Hay and silage	Grain hays	0.8

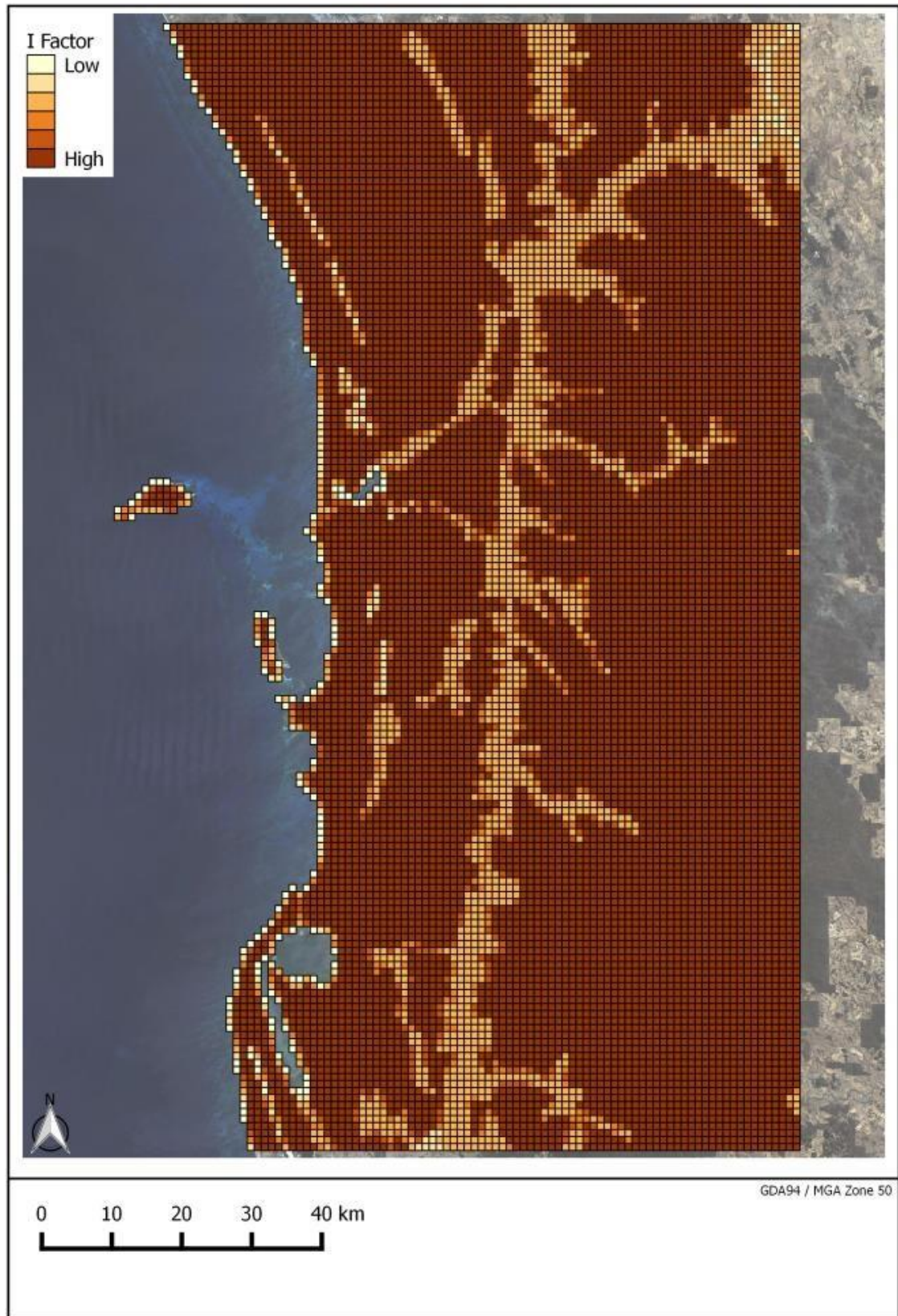


Figure 5 – Soil erodibility factor



Figure 6 – Agricultural lands crop type coverage

Climatic factor (C)

The climatic factor accounts for the influence of weather on windblown dust emissions. The climatic factor is derived from California Air Resources Board (CARB 1997a, 1997b) and is calculated using the following formula:

$$C = 0.0828 \times \left(\frac{WS^3}{PE^2} \right)$$

Where:

C	= Climatic factor	(–)
WS	= Annual average wind speed	(km/h)
PE	= Annual Thornthwaite's precipitation-evaporation (PE) index	(–)

Gridded hourly wind speed was generated using TAPM V4 as described in Section 2.1 and averaged over the entire year to obtain gridded annual average wind speeds.

The Thornthwaite's PE index factor was calculated with the following equation, converted by NSW EPA (2012) from imperial to metric units:

$$PE = \sum_{k=1}^{12} \left(1.64 \times \left(\frac{P_k}{T_k + 12.2} \right)^{\frac{10}{9}} \right)$$

Where:

PE	= Annual Thornthwaite's PE index	(–)
P _k	= Average monthly rainfall	(mm)
T _k	= Average monthly temperature	(°C)
k	= Month of the year	(–)

Gridded hourly rainfall and temperature were generated using TAPM V4, as described in Section 2.1. Average monthly rainfall values of less than 12.5 millimetres were set to 12.5 millimetres to avoid unrealistic climatic factor values during dry months. Hourly rainfall and temperature data were averaged in each grid cell for each month to calculate a monthly PE value. Monthly PE values were summed in each grid cell to produce the gridded PE value used to calculate the climatic factor (C).

The gridded climatic factor data for the study area is presented in Figure 7.

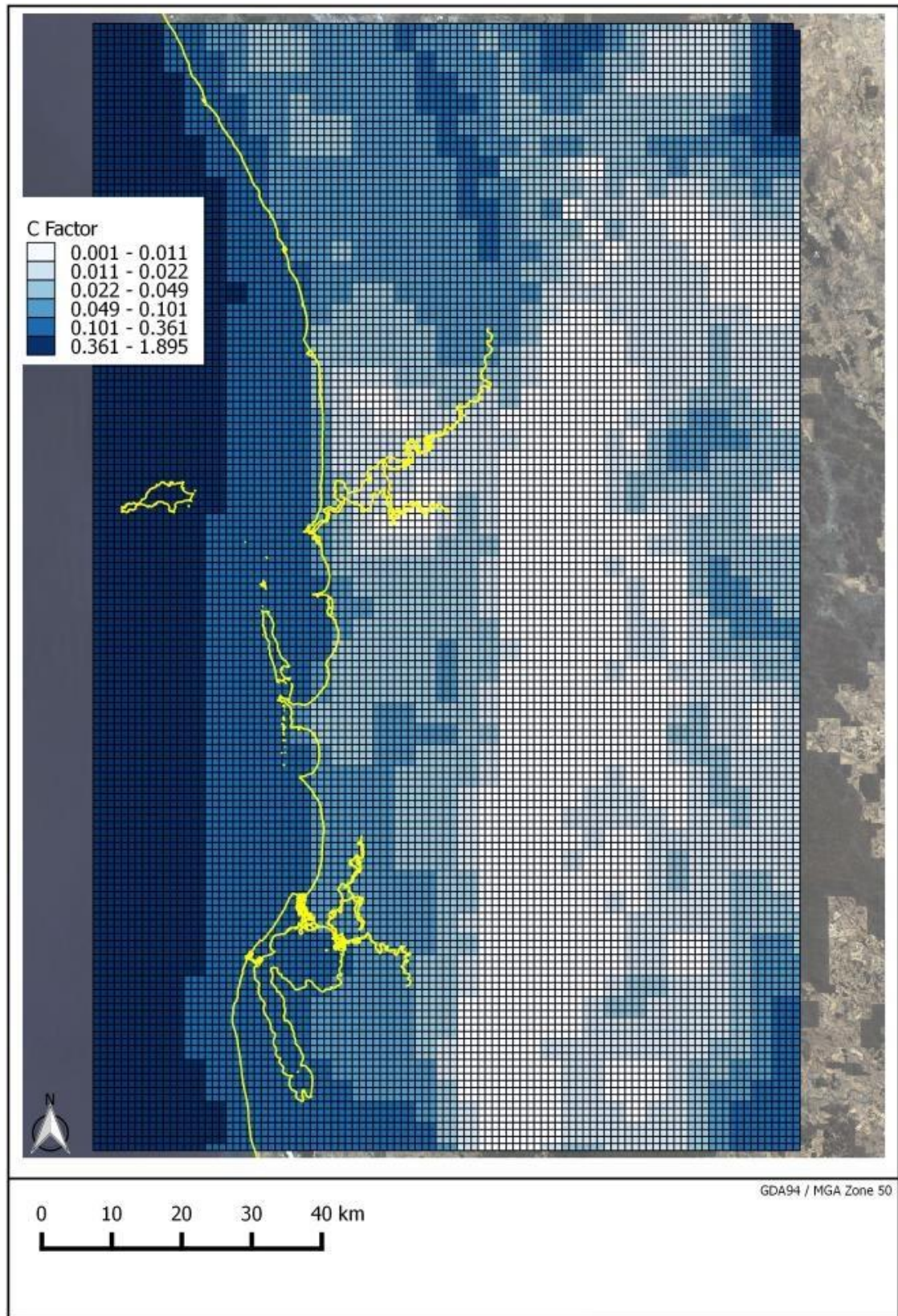


Figure 7 – Climatic factor

Unsheltered field width factor (L')

The unsheltered field width factor accounts for the exposure of fields to the prevailing wind direction. USEPA (1974) provides default unsheltered field width values for individual crop types based on typical field sizes in flat terrain without significant natural vegetation.

The default field widths (L) were used to calculate the unsheltered field width factor (L') through a logarithmic function (NSW EPA 2012):

$$L'_i = 1 - 10^{(-1.8467 \times 10^{-7} \times (I_j K_i)^2 \times L_i) + (6.1213 \times 10^{-6} \times (I_j K_i) \times L_i) - (6.876 \times 10^{-4} \times L_i) - (3.3161 \times 10^{-3} \times (I_j K_i)) - 0.0336}$$

Where:

L'_i	= Unsheltered field width factor for crop type or activity (i)	(–)
I_j	= Soil erodibility factor for soil type (j)	(t/ha/yr)
K_i	= Surface roughness factor for crop type or activity (i)	(–)
L_i	= Unsheltered field width for crop type or activity (i)	(m)
i	= Crop type or activity	(–)
j	= Soil type	(–)

Variables used to estimate the unsheltered field width factor are presented in Table 6. The 'I x K' variable used for agricultural lands and unpaved roads were set to 80 and 40 respectively – regardless of soil type and surface roughness factors for crop types and road surface. This was a simplification to account for changes made to surface soil as a result of farming activity.

Table 6 – Unsheltered field width factor variables used

Crop type or activity	I x K variable	Unsheltered field width L (m)	Unsheltered field width factor L'
Oil seeds	80	304.8	0.8092
Legumes	80	304.8	0.8092
Cereals	80	609.6	0.9276
Hay and silage	80	609.6	0.9276
Site preparation ³	493	–	0.99
Unpaved roads	40	7.88	0.3271

³ Given the significant variation in potential 'field width' for cleared construction areas and that the surface is assumed to be 100 per cent sand (i.e. highly erodible), the L' factor was given a default value of 0.99 for this emission source.

Vegetative cover factor (V')

The vegetative cover factor applies to agricultural land windblown dust and accounts for the mitigating effects of vegetation coverage as crops grow. The vegetative cover factor is calculated using the following equations (CARB 1997a):

Pre-harvest: $V'_{i,k} = e^{-0.201 \times CC_k^{0.7366}}$

Post-harvest: $V'_{i,k} = e^{-0.0438 \times SC_k}$

Where:

- $V'_{i,k}$ = Vegetative cover factor for crop type (i) and month (k) (–)
- CC_k = Proportion of ground covered by crop canopy (%)
- SC_k = Proportion of ground covered by crop debris (%)
- i = Crop type (–)
- k = Month (–)

Crop coverage was determined using the Crop Calendar data published by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES 2012) set to Western Australia’s Swan region. Data were supplemented with cropping information compiled by NSW EPA (2012). To apply the V' factor in calculations across the gridded study area, a weighted V' factor was generated for the total area covered by each crop type in the study area (ABS 2013). Data used to calculate the monthly V' factor are shown in Table 7.

Table 7 – Vegetative coverage factor data

Month	Canola		Lupins		Wheat		Oats		Weighted V' factor
	CC/SC (%)	V'	CC/SC (%)	V'	CC/SC (%)	V'	CC/SC (%)	V'	
July	50	0.028	50	0.028	25	0.116	50	0.028	0.085
August	50	0.028	50	0.028	50	0.028	75	0.008	0.027
September	75	0.008	75	0.008	75	0.008	100	0.003	0.008
October	75	0.008	100	0.003	75	0.008	5	0.803	0.026
November	100	0.003	100	0.003	88	0.004	5	0.803	0.022
December	100	0.003	5	0.803	88	0.004	5	0.803	0.088
January	5	0.803	5	0.803	100	0.003	5	0.803	0.285
February	5	0.803	5	0.803	5	0.803	5	0.803	0.803
March	5	0.803	5	0.803	5	0.803	5	0.803	0.803
April	5	0.803	5	0.803	25	0.116	5	0.803	0.358
May	25	0.116	25	0.116	25	0.116	5	0.803	0.132
June	25	0.116	25	0.116	25	0.116	25	0.116	0.116
Crop area (ha)	1,200		400		110.5		3,145		

Area of emission source (H)

The area of agricultural activity was sourced from the *2005–06 Landuse of Australia, Version 4* dataset (BRS 2010). Areas labelled ‘agriculture’ were used, as shown in Figure 8.

The area of land development and site preparation activity for 2011–12 were derived from a ‘Lots Granted Final Approval’ dataset provided by the former Department of Planning (now the Department of Planning Lands and Heritage). The following assumptions were made in the use of this dataset:

- All lots granted approval were completely cleared, and were cut and filled with sand. No attempt was made to apply a reduction factor for lots that may not have been cleared, cut and filled.
- Land was cleared for the whole 2011–12 year with no dust management controls applied.

Land development activity for 2011–12 in the study area is presented in Figure 9.

Unpaved road coverage in the study area is presented in Figure 10.

Emission control factor (CF)

The emission control factor accounts for any dust mitigation that may be applied to the emission source.

No controls were applied for agricultural lands or unpaved roads.

A control factor of 0.5 was applied to land development and site preparation emissions. The value of 0.5 was based on the dust control factor for water suppression used by the National Pollutant Inventory (NPI 2012) and was intended to represent the range of controls applied to minimise dust from site clearing and preparation activities.

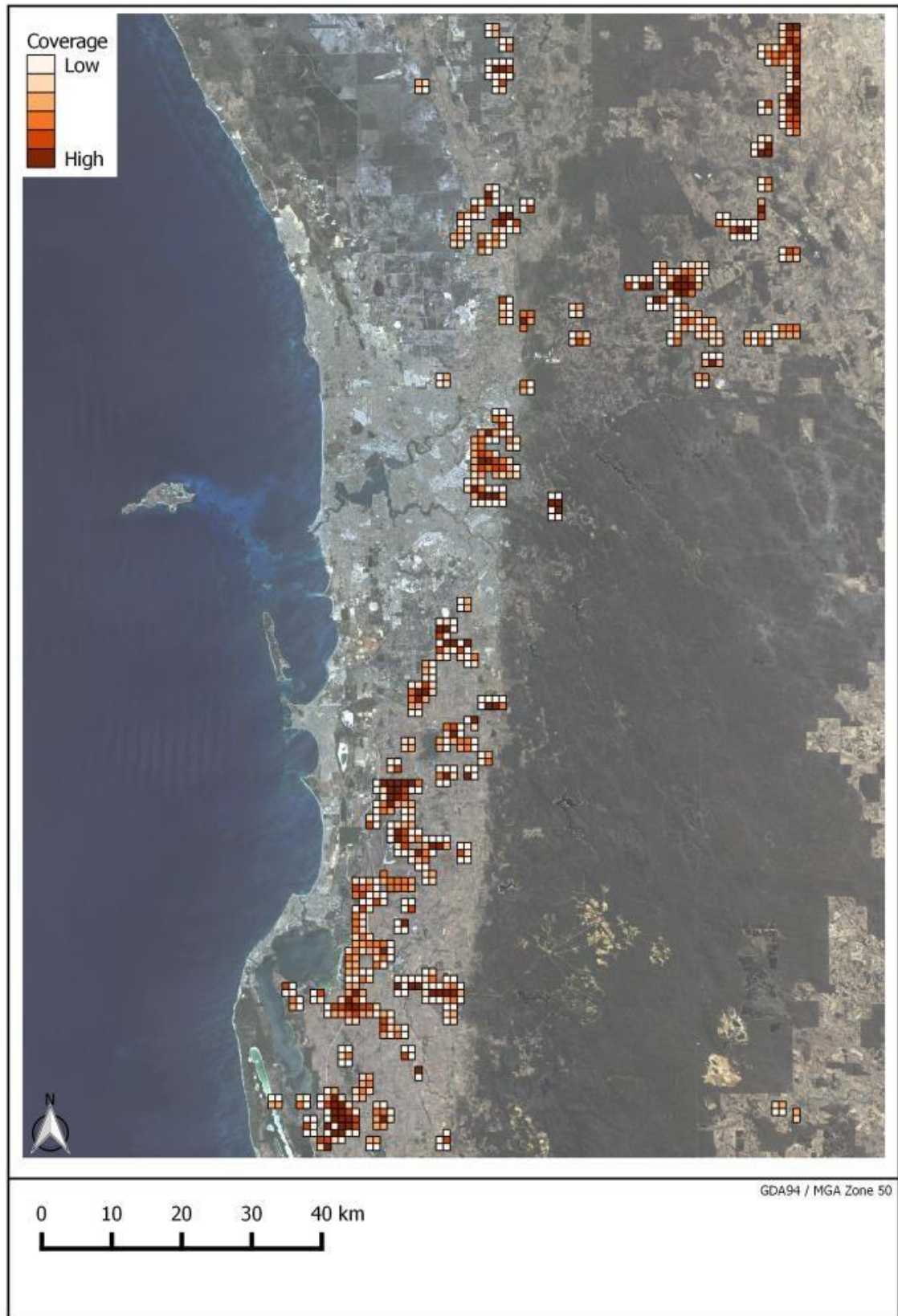


Figure 8 – Agricultural land coverage



Figure 9 – Land development and site preparation coverage

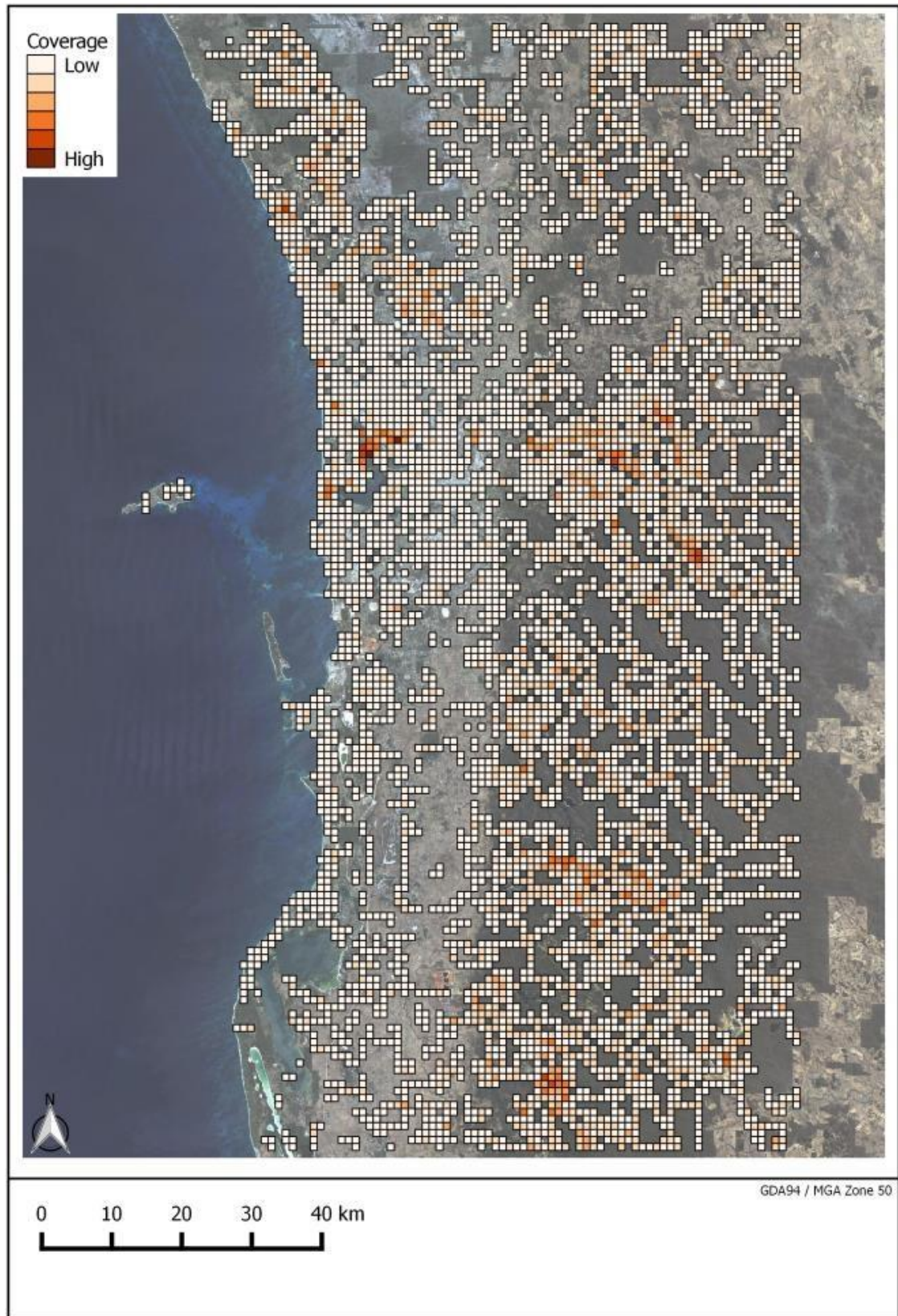


Figure 10 – Unpaved road coverage

Emission estimates

Emissions of key pollutants from windblown dust in the study area are summarised in Table 8.

Table 8 – Windblown dust emission estimates

Pollutant	Emissions (kg/yr)			
	Agricultural lands	Land development and site preparation	Unpaved roads	Total
Antimony and compounds	25.7	12.8	42.4	80.8
Arsenic and compounds	68.4	21.7	90.9	181
Cadmium and compounds	85.5	26.8	151	264
Chromium (total)	894	286	1,485	2,665
Cobalt and compounds	372	147	903	1,422
Copper and compounds	287	130	527	944
Lead and compounds	265	711	5,460	6,436
Manganese and compounds	4,076	1,207	6,369	11,652
Mercury and compounds	47.0	19.2	90.9	157
Nickel and compounds	214	75.3	382	671
Particulate matter 2.5 µm	336,154	62,448	476,299	874,901
Particulate matter 10 µm	1,942,938	624,861	3,601,332	6,169,131
Selenium and compounds	8.55	2.55	6.06	17.2
Total suspended particulate (TSP)	4,276,772	1,277,050	6,059,789	11,613,611
Zinc and compounds	701	662	3,769	5,132

Spatial allocation

The spatial allocation of wind erosion emissions is shown in Figure 11 through to Figure 14. The emission source areas are summarised in Table 9.

Table 9 – Wind erosion emission source area

Activity	Area (km ²)
Agricultural lands	307
Land development and site preparation activity	22.1
Unpaved roads	41.0

Unpaved road emissions are the most extensive, producing low-level coverage over the study area. Areas of high wind erosion in the north-east corner of the study area are attributable to the climatic factor in that area and relative intensity of agricultural activity. The coastal areas experience wind erosion where significant areas of land development exist.

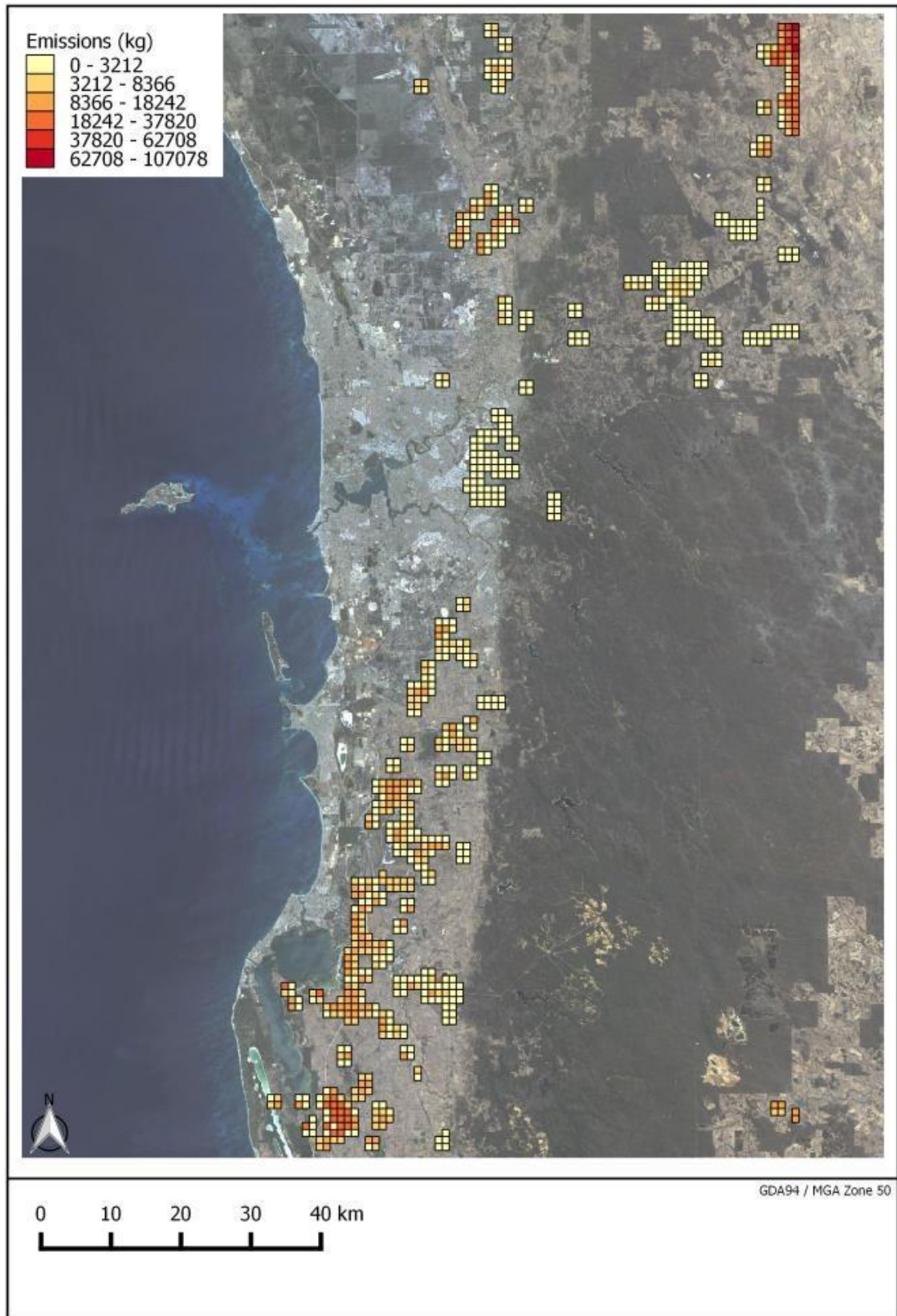


Figure 11 – Spatial allocation of agricultural land wind erosion TSP emissions

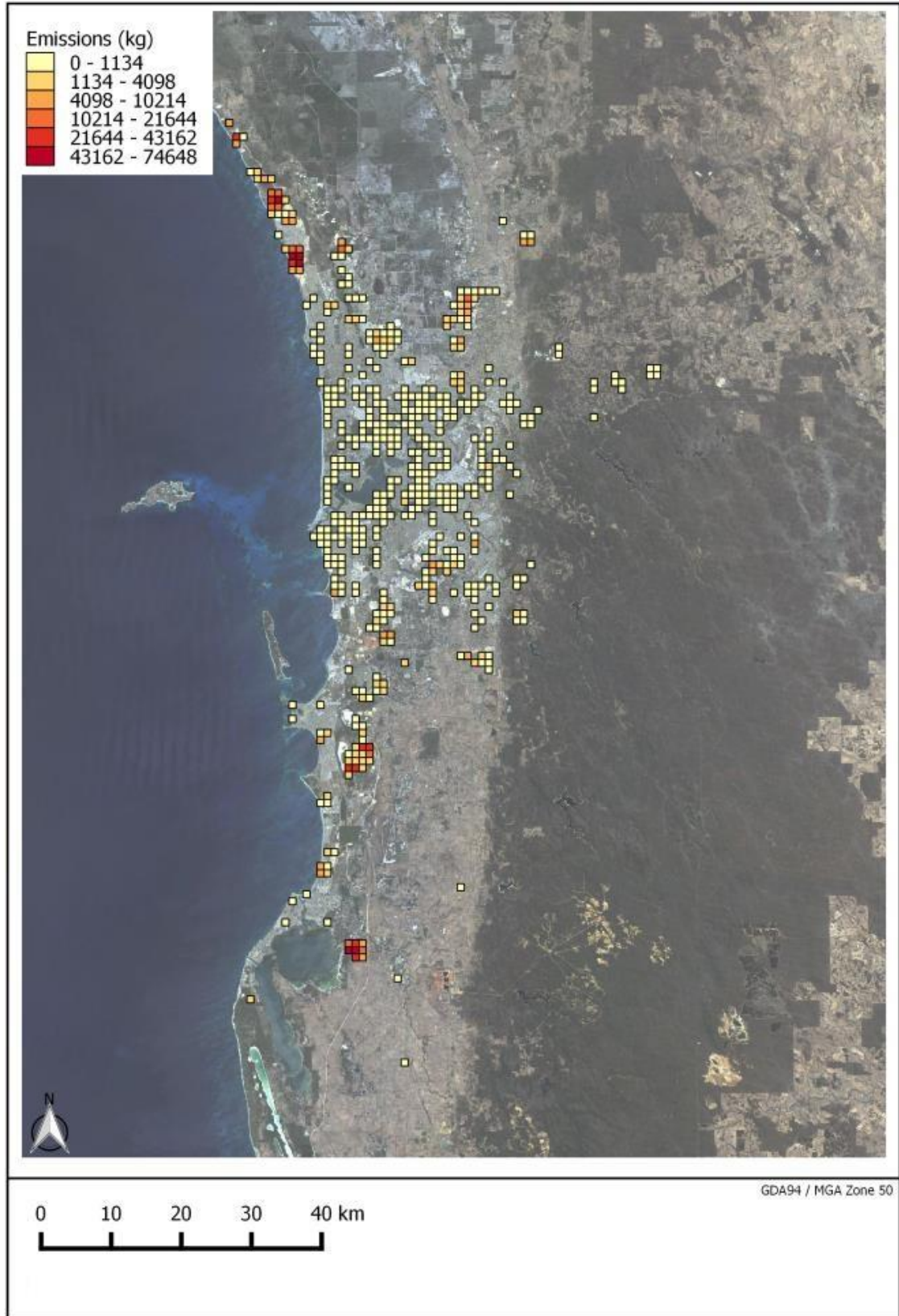


Figure 12 – Spatial allocation of land development wind erosion TSP emissions

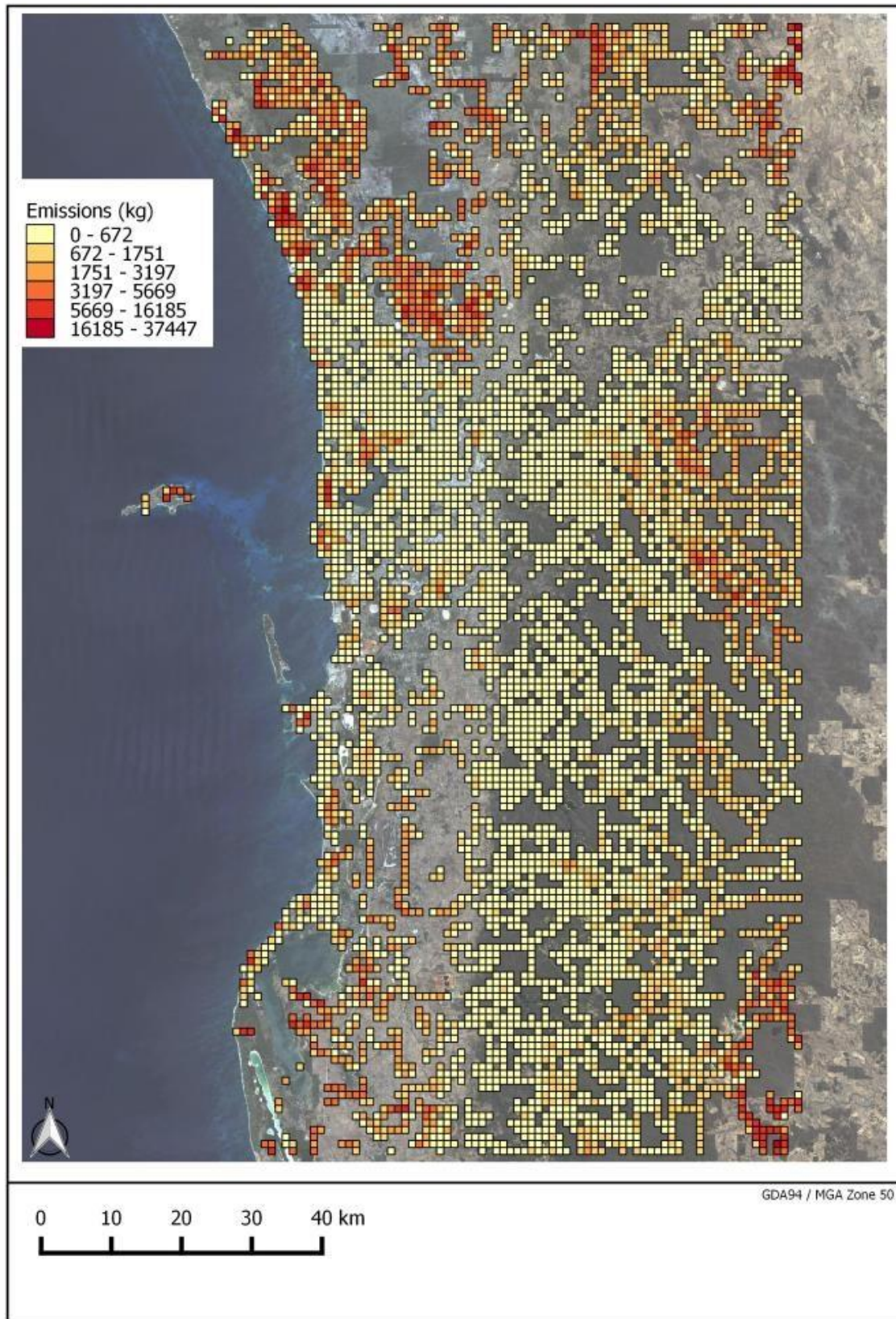


Figure 13 – Spatial allocation of unpaved roads wind erosion TSP emissions

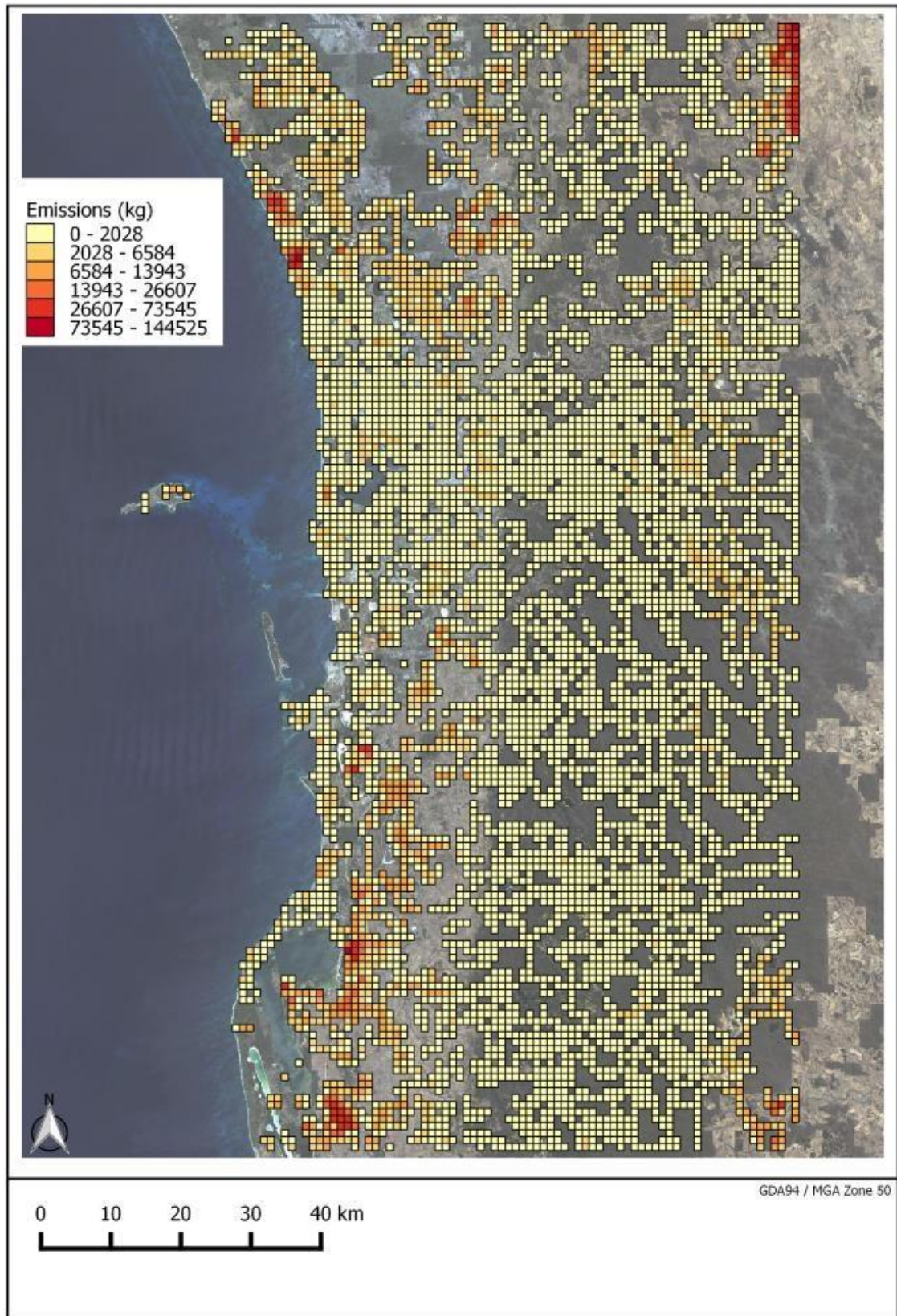


Figure 14 – Spatial allocation of total wind erosion TSP emissions

2.4 Fires

Emissions from the burning of vegetation are considered in this inventory. The emission sources considered for fire emissions include:

- Agricultural burning – the creation of windrows and burning of post-harvest crop residues is a common weed management practice.
- Bushfires – the study area is subject to bushfires of variable scale caused by natural events and human activity.
- Prescribed burning – the intentional burning of vegetation undertaken to manage fuel load.

While some of these emission sources are not biogenic and are caused by human activity, they have been included in the biogenic inventory because of their similar emissions profiles and wide geographical coverage, as well as for consistency with the approach in the *2008 Calendar Year Air Emissions Inventory for the Greater Metropolitan Region in NSW* (NSW EPA 2012).

Backyard fires and small-scale domestic burning were excluded from this study because the necessary survey data do not currently exist and emissions from these sources are likely to be insignificant compared with included sources. However, it is recognised that these emissions are likely to be closer to populated areas and occur more frequently, making them of potential significance.

Emission estimation technique

Emissions from agricultural burning are estimated using the following equation adapted from the California Air Resources Board (CARB 2005).

$$E_{h,j} = FL_i \times EF_{h,i}$$

Where:

$E_{h,i}$	= Emissions of substance (h) from crop type (i)	(kg/yr)
FL_i	= Fuel loading	(tonne crop residue burnt/yr)
$EF_{h,i}$	= Emission factor for substance (h) and crop type (i)	(kg/tonne crop residue burnt)
h	= Substance	(–)
i	= Crop type	(–)

The fuel loading (FL) component of the formula was determined using the method published by NSW EPA (2012) and relies on greenhouse data published by the Australian Department of the Environment (DotE 2014).

$$FL_i = P_i \times R_i \times S_i \times DM_i \times Z_i \times F_i$$

Where:

FL _i	= Fuel loading	(tonne crop residue burnt/yr)
P _i	= Crop type (i) production	(tonne/yr)
R _i	= Residue to crop ratio for crop type (i)	(kg residue/kg crop)
S _i	= Fraction of crop type (i) residue remaining at time of burning	(kg residue/kg residue)
DM _i	= Dry matter content for crop type (i)	(kg dry residue/kg residue)
Z _i	= Residue burning efficiency for crop type (i)	(kg residue burned/kg residue)
F _i	= Fraction of crop type (i) harvest burnt	(ha burned/ha harvested)
i	= Crop type	(–)

Emissions from bushfires and prescribed burning are estimated using the following equation adapted from the California Air Resources Board (CARB 2004, 2006).

$$E_{h,i} = A_i \times FL_i \times Z_i \times EF_{h,i}$$

Where:

E _{h,i}	= Emissions of substance (h) from fire type (i)	(kg/yr)
A _i	= Area of burning for fire type (i)	(ha/yr)
FL _i	= Fuel loading for fire type (i)	(tonne dry vegetation burnt/ha vegetation)
Z _i	= Burning efficiency for fire type (i)	(kg vegetation burnt/kg vegetation)
EF _{h,i}	= Emission factor for substance (h) and fire type (i)	(kg/tonne)
h	= Substance	(–)
i	= Fire type	(–)

Only fires that occurred within the study area during the study period were considered.

Activity data

Agricultural fuel loading (FL)

Crop production (P factor) data for the study area were sourced from the ABS *Agricultural Commodities Australia, 2011–12* dataset (ABS 2013). The Perth and Mandurah values in this dataset were used as representative of the study area.

The R, S, DM, Z and F factors were sourced from crop and pasture attribute data published by the Australian Department of the Environment (DotE 2014). The relevant factors used for each crop type in this study are presented in Table 10.

Table 10 – Agricultural fuel load input data

Crop	P (tonnes/yr)	R (kg residue/kg crop)	S (kg residue/kg residue)	DM (kg residue/kg residue)	Z (kg residue/kg residue)	F (ha burned/ha harvested)
Canola	2,400	1.5	0.5	0.8	0.96	0.08
Lupins	600	1.5	0.5	0.8	0.96	0.08
Oats	162	1.5	0.5	0.8	0.96	0.23
Wheat	10,779	1.5	0.5	0.9	0.96	0.23
Hay and silage	33,764	1.5	0.5	0.8	0.96	0.08

Agricultural emission factors (EF)

Emission factors for agricultural burning were sourced from the California Air Resources Board (CARB 1996, 2005) and Department of the Environment (DotE 2014). Emission factors used are presented in Table 11.

Table 11 – Agricultural burning emission factors

Crop	Emission factor (kg/t)									
	TSP ⁴	PM ₁₀	PM _{2.5}	NO _x	SO ₂	VOC	CO	NH ₃	PAH ⁵	PCDF ⁶
Canola	7.22	7.10	6.78	2.00	0.27	4.79	50.9	0.80	0.0031	8.2x10 ⁻¹⁰
Lupins	7.22	7.10	6.78	2.00	0.27	4.79	50.9	0.80	0.0031	8.2x10 ⁻¹⁰
Oats	9.39	9.24	8.79	2.01	0.27	4.60	60.7	0.96	0.0031	8.2x10 ⁻¹⁰
Wheat	4.81	4.73	4.51	1.92	0.40	3.39	55.2	0.87	0.00088	8.2x10 ⁻¹⁰
Hay and silage	7.22	7.10	6.78	2.00	0.27	4.79	50.9	0.80	0.0031	8.2x10 ⁻¹⁰

⁴ TSP emission factors derived from PM₁₀ factors using the CARB PMSIZE 430 speciation data (CARB 2014a).

⁵ PAH emission factors derived from CARB (1996), Table 4.5.4, using only PAHs specified by the NPI (2014)

⁶ PCDF emission factors sourced from DEH (2004), Table 4.87, page 56.

Bushfire and prescribed burning area (A)

The area of land in the study area that was burnt during the study period was sourced from the Department of Parks and Wildlife (now the Department of Biodiversity, Conservation and Attractions) spatial database. A map of the burnt areas considered in this study is presented in Figure 15.

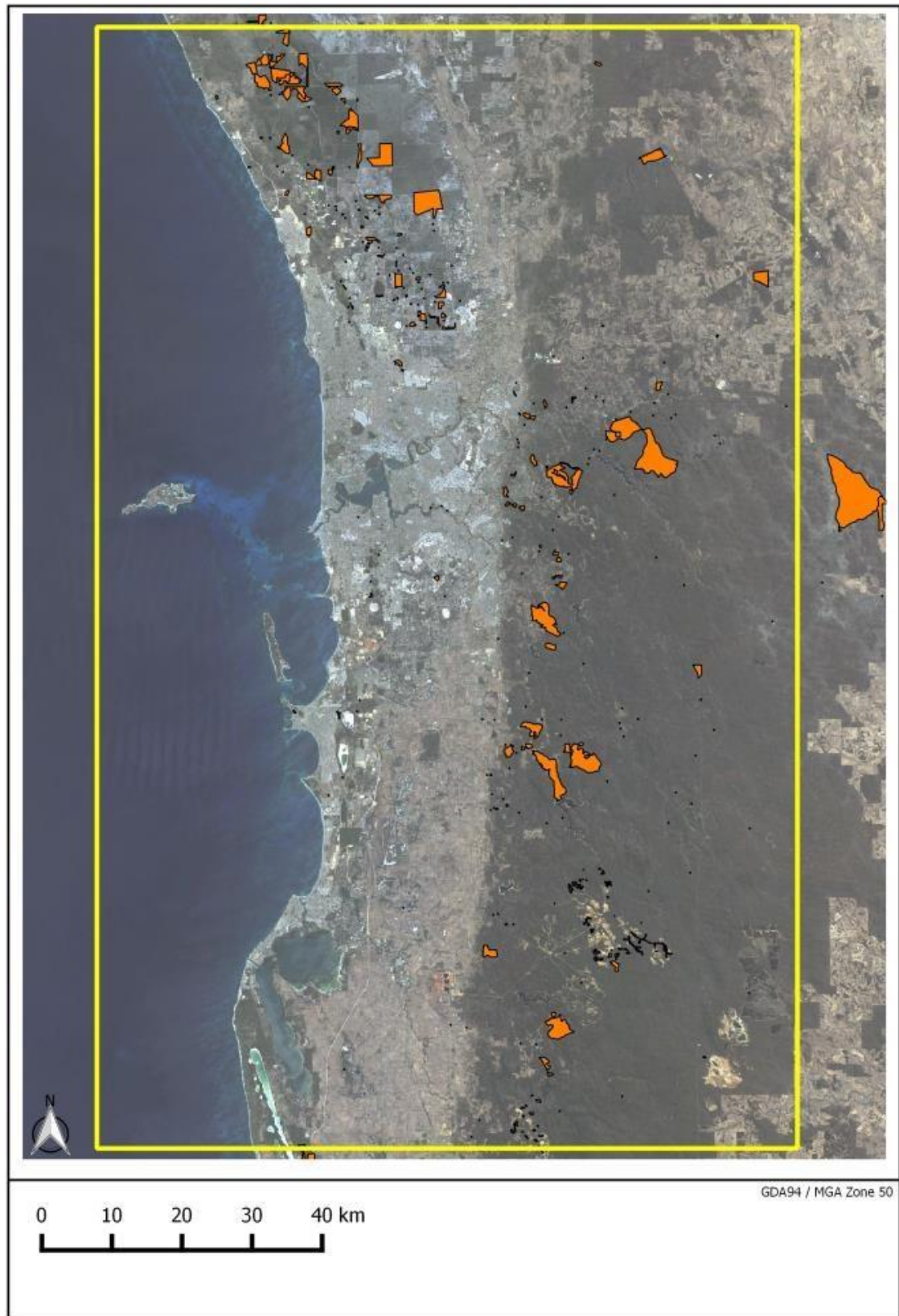


Figure 15 – Bushfire and prescribed burn areas between July 2011 and June 2012

Bushfire and prescribed burning fuel load (FL) and burn efficiency (Z)

Fuel load and burn efficiency factors for bushfire and prescribed burning were sourced from the Australian Department of the Environment (DotE 2014) and are presented in Table 12.

Table 12 – Bushfire and prescribed burning fuel load and burn efficiency factors

Fire type	Fuel loading (tonnes burnt/ha vegetation)	Burn efficiency (kg burnt/kg vegetation)
Bushfire	33.4	0.72
Prescribed burn	12.0	0.42

Bushfire and prescribed burning emission factors (EF)

Emission factors for bushfire and prescribed burning were sourced from the California Air Resources Board (1996, 2004) and Department of the Environment (DotE 2014).

The CARB (2004) emission factors are available in ‘wet’, ‘mod’ and ‘dry’. This study used the more conservative dry factors. Emission factors describe the various forest components that fuel fires. To develop an emission factor, a fire component weighting was calculated using the fire example provided by CARB (2004).

Emission weightings and factors used are presented in Table 13.

Table 13 – Bushfire and prescribed burning emission factors

Fire component	Weighting factor	Emission factors (kg/t)									
		TSP ⁷	PM ₁₀	PM _{2.5}	VOC	NH ₃	NO _x	SO ₂	CO	PAH ⁸	PCDF ⁹
Litter	0.034		4.15	3.53	1.65	0.22	3.66	1.12	23.4		
Wood 0–1 inch	0.019		4.15	3.53	1.65	0.22	3.66	1.12	23.4		
Wood 1–3 inch	0.026		6.25	5.31	3.48	0.49	3.57	1.12	49.7		
Wood 3+ inch	0.265		8.53	7.23	5.45	0.76	3.44	1.07	77.9		
Herb	0.005		11.2	9.51	7.77	1.12	3.30	1.03	111		
Shrub	0.006		11.2	9.51	7.77	1.12	3.30	1.03	111		
Regen	0.003		11.2	9.51	7.77	1.12	3.30	1.03	111		
Duff	0.463		13.6	11.5	9.87	1.43	3.17	0.98	141		
Canopy foliage	0.140		11.2	9.51	7.77	1.12	3.30	1.03	111		
Canopy branchwood	0.039		11.2	9.51	7.77	1.12	3.30	1.03	111		
Calculated emission factor		11.3	11.1	9.41	7.69	1.10	3.30	1.02	110	0.00012	4.4 x10 ⁻¹⁰ 8.5 x10 ⁻¹⁰

⁷ TSP emission factors derived from PM₁₀ factors using the CARB PMSIZE 460 speciation data (CARB 2014a)

⁸ PAH emission factors derived from CARB (1996), Table 4.5.6, using only PAHs specified by the NPI (2014)

⁹ PCDF emission factors sourced from DEH (2004), Table 4.87, page 56. 4.4 x 10⁻¹⁰ is for bushfires, 8.5 x 10⁻¹⁰ is for prescribed burns

Emission speciation

Emissions of particulate matter and volatile organic compounds (VOCs) from agricultural burning, bushfires and prescribed burns were speciated using California Air Resources Board speciation profiles (CARB 2014a, 2014b, 2015), summarised in Table 14.

Table 14 – Speciation profiles for fires

Pollutant species	Agricultural burning (PMPROF 430)	Prescribed burning (PMPROF 460, ORGPORF 307)
TSP speciation		
Antimony and compounds	0.000051	0.000042
Arsenic and compounds	0.000007	0.000004
Cadmium and compounds	0.000050	0.000028
Chromium (total)	0.000021	0.000011
Cobalt and compounds	0.000003	0.000002
Copper and compounds	0.000013	0.000019
Lead and compounds	0.000012	0.000098
Manganese and compounds	0.000471	0.000246
Mercury and compounds	0.000013	0.000006
Nickel and compounds	0.000009	0.000004
Selenium and compounds	0.000006	0.000004
Zinc and compounds	0.000169	0.001931
VOC speciation		
1,3-Butadiene (vinyl ethylene)	–	0.0094

Emission estimates

Emissions of key pollutants from fires in the study area are summarised in Table 15.

Table 15 – Fire emission estimates

Pollutant	Emissions (kg/yr)			
	Agricultural burning	Bushfires	Prescribed burning	Total
Ammonia (total)	2,783	37,270	91,160	131,213
Antimony and compounds	1.03	16.0	39.2	56.2
Arsenic and compounds	0.14	1.53	3.73	5.40
1,3-Butadiene (vinyl ethylene)	–	2,443	5,976	8,419
Cadmium and compounds	1.01	10.7	26.1	37.8
Carbon monoxide	176,121	3,717,462	9,092,660	12,986,243
Chromium (total)	0.42	4.19	10.3	14.9

Cobalt and compounds	0.06	0.76	1.87	2.69
Copper and compounds	0.26	7.25	17.7	25.2
Lead and compounds	0.24	37.4	91.4	129
Manganese and compounds	9.49	93.8	229	332
Mercury and compounds	0.26	2.29	5.60	8.15
Nickel and compounds	0.18	1.53	3.73	5.44
Oxides of nitrogen	6,523	111,599	272,963	391,085
Particulate matter 2.5 µm	18,912	318,048	777,924	1,114,884
Particulate matter 10 µm	19,825	374,793	916,717	1,311,335
Polychlorinated dioxins and furans (TEQ)	0.0000027	0.000015	0.000070	0.000088
Polycyclic aromatic hydrocarbons (B[a]P _{eq})	6.74	4.16	10.2	21.1
Selenium and compounds	0.12	1.53	3.73	5.38
Sulfur dioxide	1,113	34,632	84,708	120,453
Total suspended particulate (TSP)	20,153	381,352	932,760	1,334,265
Total volatile organic compounds	13,664	259,900	635,697	909,261
Zinc and compounds	3.41	736	1,801	2,540

Spatial allocation

The spatial allocation of fire emissions are presented in Figure 16 through to Figure 19. The emission source areas are summarised in Table 16.

Table 16 – Fire emission source area

Activity	Area (km ²)
Agricultural burning	307
Bushfires	14.1
Prescribed burning	164

Agricultural burning emissions were distributed evenly across the areas identified as agricultural in the *2005–06 Landuse of Australia, Version 4* dataset (BRS 2010), mapped earlier in Figure 6.

Bushfire emissions were distributed evenly across the areas identified in the former Department of Parks and Wildlife (now the Department of Biodiversity, Conservation and Attractions) fire history dataset for 2011–12. The intensity of the activity in the study area's north-west corner reflected the large area burnt, with small isolated emission areas the result of very small contained bushfires.

Prescribed burning emissions were distributed evenly across the areas identified in the former Department of Parks and Wildlife fire history dataset for 2011–12.

The north-west corner had higher emissions compared with the rest of the study area as a result of a concentration of bushfires and prescribed burning in that area. Agricultural emissions were much lower on a cell by cell basis compared with bushfires and prescribed burning.

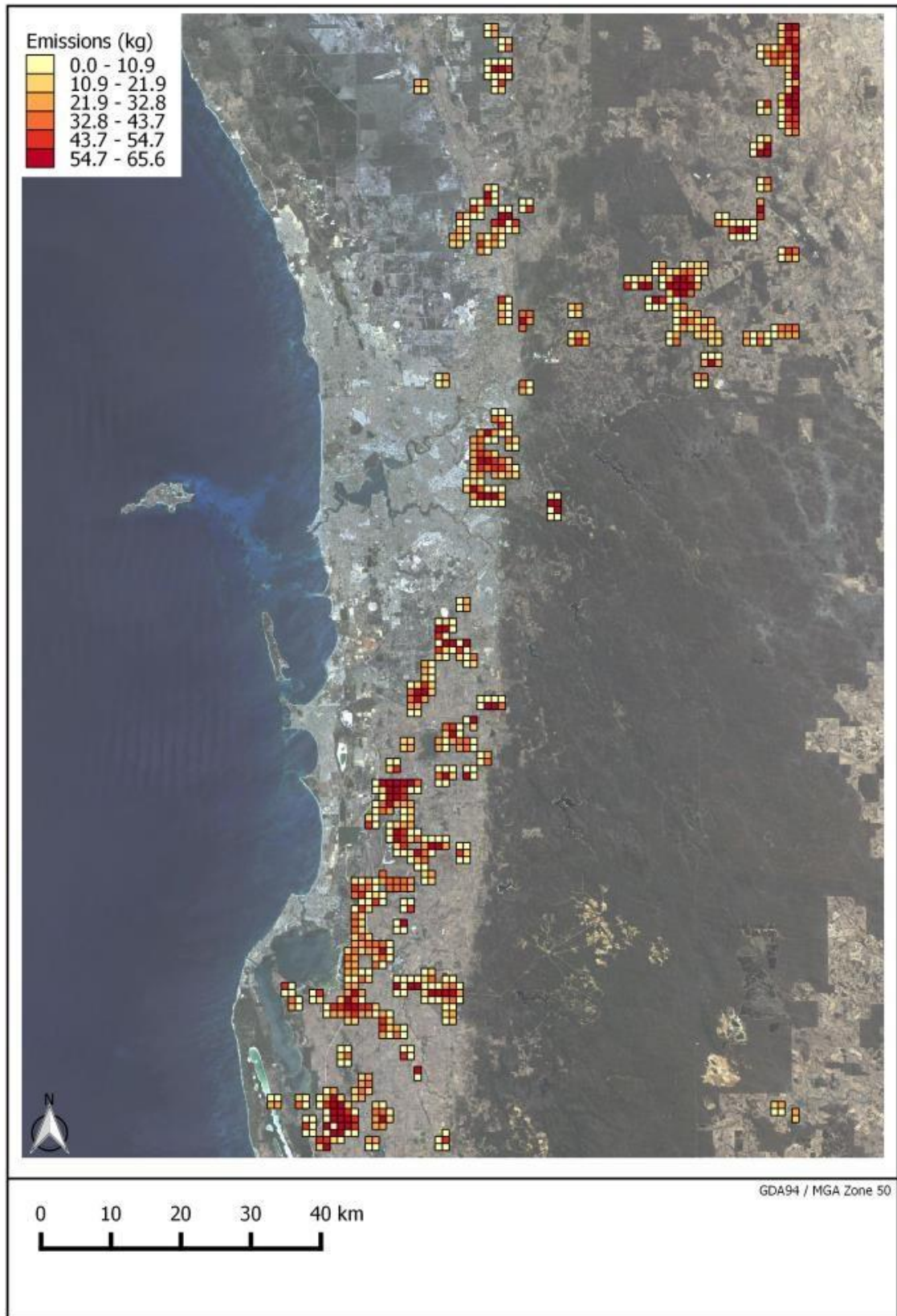


Figure 16 – Spatial allocation of agricultural burning TSP emissions

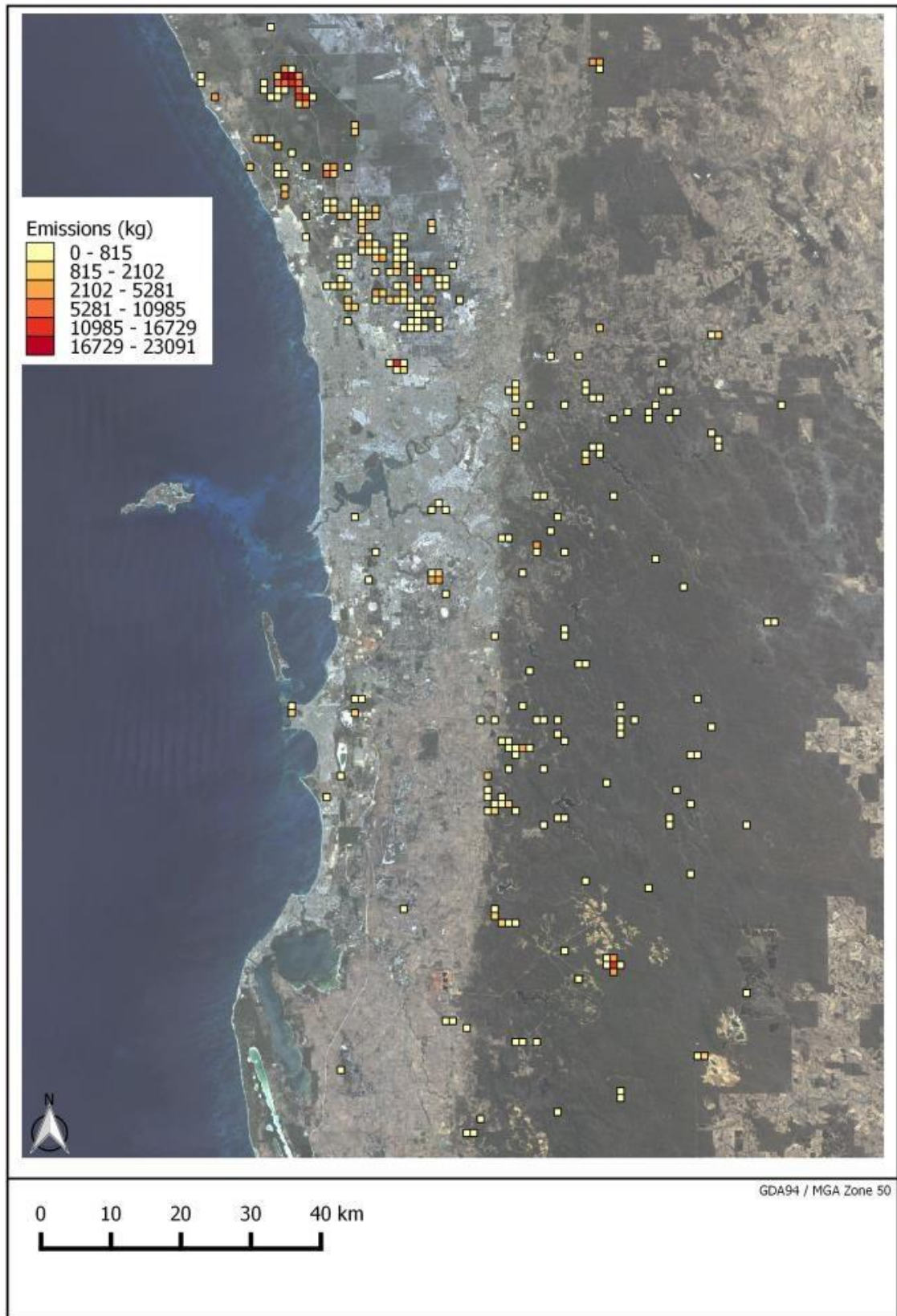


Figure 17 – Spatial allocation of bushfire TSP emissions

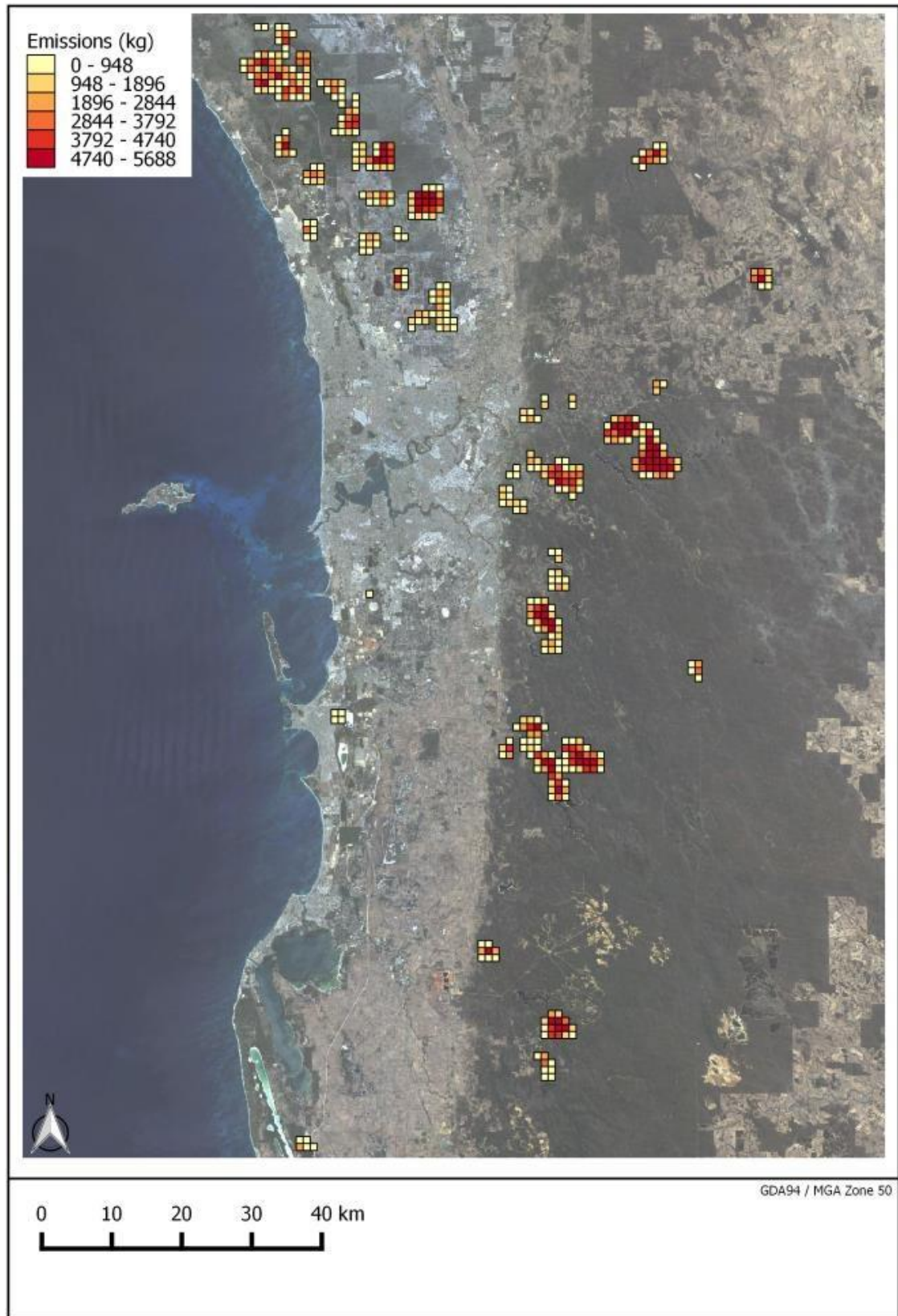


Figure 18 – Spatial allocation of prescribed burning TSP emissions

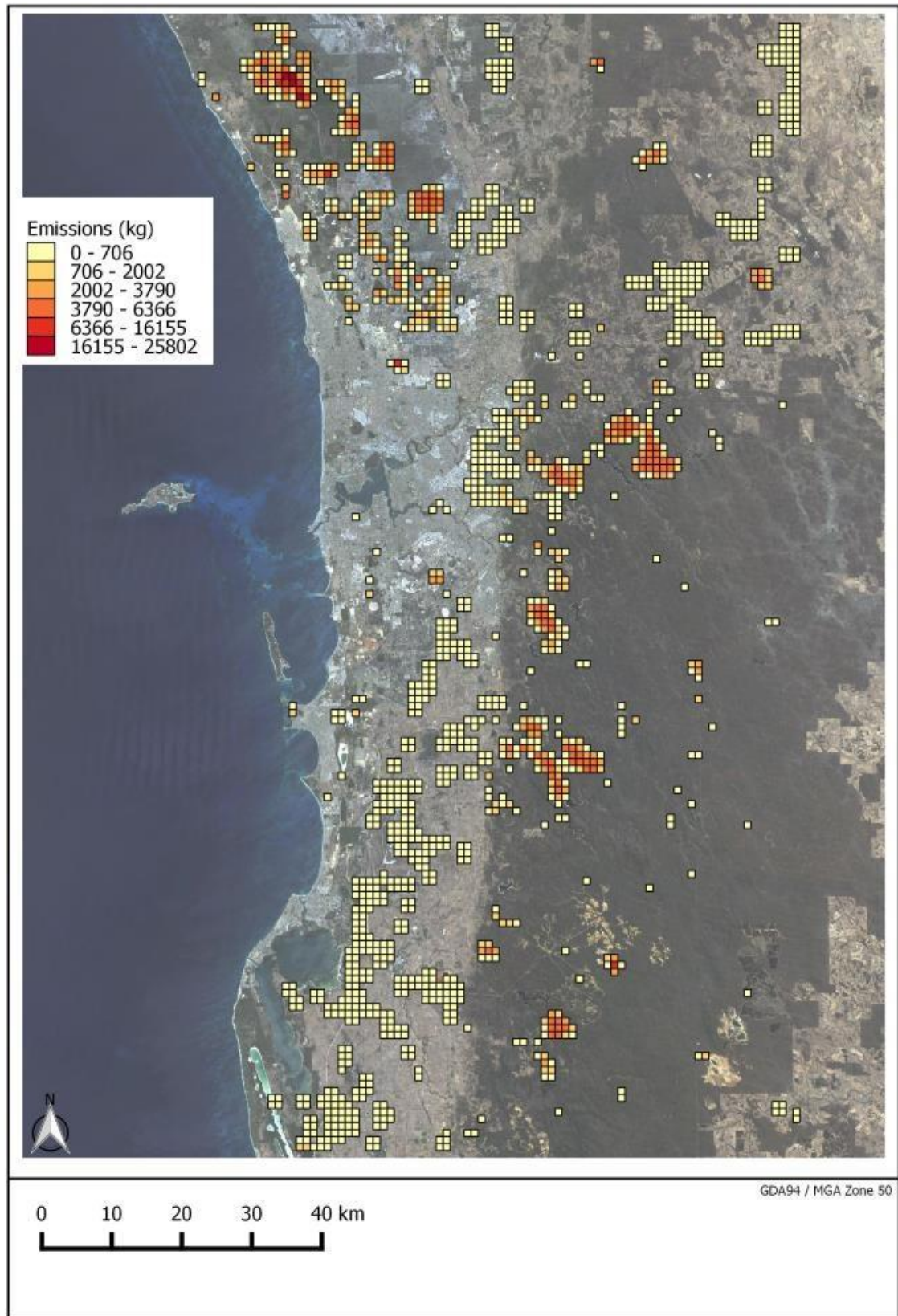


Figure 19 – Spatial allocation of total fire TSP emissions

2.5 Soils

Oxides of nitrogen (NO_x) and ammonia (NH₃) emissions from the denitrification of soils are considered in this inventory. These emissions occur as a result of the natural nitrogen cycle of the environment and from the addition of nitrogen fertilisers as part of agricultural activities.

Emission estimation technique

Emissions of oxides of nitrogen (NO_x) were estimated using the following equation adapted from the USEPA (Radian 1996) and *2008 Calendar Year Air Emissions Inventory for the Greater Metropolitan Region in NSW* (NSW EPA 2012).

$$E_{NO_x} = \frac{\sum_{t=1}^n (A_l \times EF_{NO,l} \times CF_l \times 10^{-9})}{0.65}$$

Where:

E _{NO_x}	= Emissions of oxides of nitrogen (NO _x)	(kg/yr)
A _l	= Area of land use type (l)	(m ²)
EF _{NO,l}	= Emission factor for nitric oxide (NO) and land use type (l)	(µg/m ² /hr)
CF _l	= Temperature correction factor for land use type (l)	(–)
n	= Hours (8784 for 2011–12)	(–)
t	= Time interval	(hr/yr)
l	= Land use type	(–)
10 ⁻⁹	= Conversion factor	(kg/µg)
0.65	= NO to NO _x conversion factor ¹⁰	(–)

The temperature correction factor (CF) was calculated with the following equation (Radian 1996).

$$CF_l = e^{(0.071 \times T_{s,l})}$$

Where:

CF _l	= Temperature correction factor for land use type (l)	(–)
T _{s,l}	= Soil temperature for land use type (l)	(°C)
l	= Land use type	(–)

¹⁰ The 0.65 NO:NO_x ratio was developed by calculating the NO emission rates and comparing them to the NO_x emission rates presented in NSW EPA (2012), Table 3-67. The value is an approximation across all land use types (except agriculture due to different crop compositions between the study areas).

The soil temperature (T_s) was estimated from ambient air temperature using the following equation presented by NSW EPA (2012).

$$T_{s,l} = (K_{1,l} \times T_a) + K_{2,l}$$

Where:

$T_{s,l}$	= Soil temperature for land use type (l)	(°C)
$K_{1,l}$	= Constant 1 for land use type (l)	(–)
T_a	= Ambient air temperature	(°C)
$K_{2,l}$	= Constant 2 for land use type (l)	(–)
l	= Land use type	(–)

The constants K_1 and K_2 for each land use type were adopted from NSW EPA (2012) and are presented in Table 17.

Table 17 – Soil temperature calculation constants for each land use type

Land use	K_1	K_2
Agricultural	1.03	2.9
Forest	0.84	3.6
Grassland	0.66	8.8
Urban	0.66	8.8
Water	–	–
Wetland	0.92	4.4

Emissions of ammonia from agricultural activities were estimated using the following equation adapted from the USEPA (Batty et al. 2004).

$$E_{NH3,l} = NFC_i \times EF_{NH3,i} \times F_l$$

Where:

$E_{NH3,l}$	= Emissions of ammonia from land use type (l)	(kg/yr)
NFC_i	= Total consumption of fertiliser type (i)	(tonnes N/yr)
$EF_{NH3,i}$	= Emission factor for ammonia for fertiliser type (i)	(kg/tonne N)
F_l	= Fraction of nitrogen fertiliser use (NFC) applied to each land use type (l)	(tonne N/tonne N)
l	= Land use type	(–)
i	= Fertiliser type	(–)

Emissions of ammonia from natural processes were estimated using the following equation adapted from the USEPA (Battye et al. 2004).

$$E_{NH3,l} = EF_{NH3,l} \times A_l \times 31622400 \times 10^{-12}$$

Where:

$E_{NH3,l}$	=	Emissions of ammonia from land use type (l)	(kg/yr)
$EF_{NH3,l}$	=	Emission factor for ammonia for land use type (l)	(ng/m ² /s)
A_l	=	Area of land use type (l)	(m ²)
31622400	=	Seconds in 2011–12	(s/yr)
10^{-12}	=	Conversion factor	(kg/ng)
l	=	Land use type	(–)

Activity data

Area of land use (A)

The land use data used for NO_x and NH₃ emission estimates was sourced from the *2005–06 Land use of Australia, Version 4* dataset (BRS 2010). The land use map is presented in Figure 20 and shows the area of the six main land use categories. The total area of each land use category is summarised in Table 18.

Table 18 – Area of land use categories in study area

Landuse	Landuse type	Area (km ²)
Agriculture	Cropping	305
	Irrigated cropping	2.49
	Irrigated perennial horticulture	89.3
	Irrigated seasonal horticulture	8.40
	Perennial horticulture	26.1
	Seasonal horticulture	1.05
	Total	432
Forest	Managed resource protection	50.5
	Nature conservation	1,563
	Other minimal use	1,398
	Plantation forestry	396
	Irrigated plantation forestry	1.05
	Production forestry	3,204
	Total	6,612
Grassland	Grazing natural vegetation	400
	Grazing modified pastures	2,396
	Irrigated modified pastures	32.5
	Total	2,828
Urban	Intensive animal production	170
	Intensive horticulture	20.0
	Manufacturing and industrial	5.25
	Mining	17.7
	Residential	1,241
	Services/other	276
	Transport and communication	18.9
	Total	1,665
Water	Lake	46.6
	Reservoir/dam	32.3
	River	32.5
	Total	111
Wetland	Total	19.9
Total		11,752

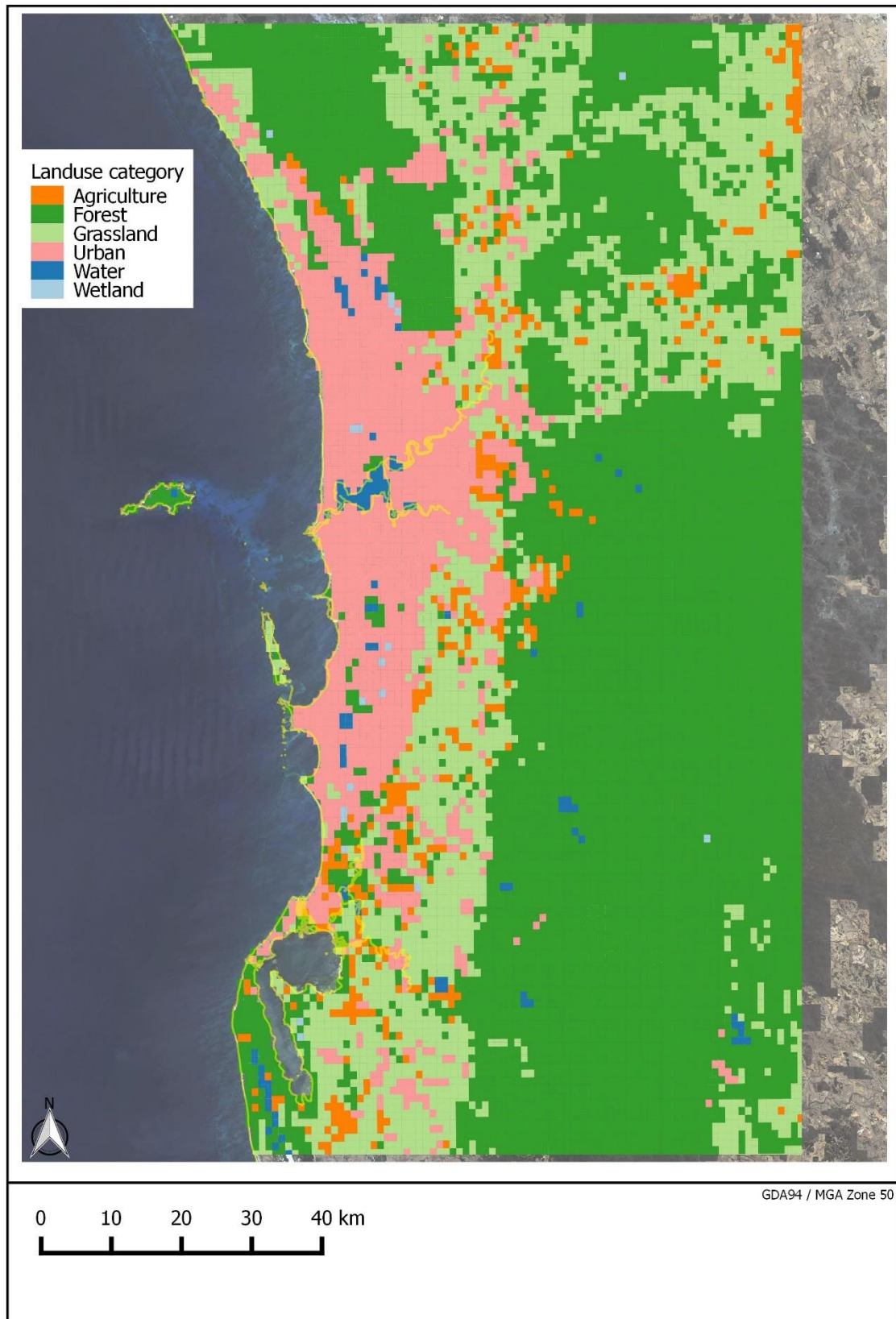


Figure 20 – Land use distribution

Nitric oxide emission factors (EF)

Emission factors for nitric oxide (NO) were sourced from the USEPA (Radian 1996). Emission factors used are presented in Table 19. The agricultural NO flux applied was weighted with respect to production of crops in the study area.

Table 19 – Nitric oxide emission factors

Land use		Production (tonnes/yr)	NO flux ($\mu\text{g}/\text{m}^2/\text{hr}$) ¹¹	Radian (1996) Veg ID code	NO _x flux ($\mu\text{g}/\text{m}^2/\text{hr}$)
Agriculture	Oats	162	257	Oats	116
	Wheat	10,779	193	Whea	
	Lupin	600	13	Mscp	
	Canola	2,400	13	Mscp	
	Alfalfa	510	13	Alfa	
	Hay	11,198	13	Hay	
	Pasture	22,056	58	Past	
Forest		4.5	Assorted ¹²	6.92	
Grassland		58	Gras	89.2	
Urban		12	Uoth	18.5	
Water		0	Wate	0	
Wetland		0.2	Wetf	0.31	

Temperature control factor (CF)

The temperature control factor was developed from ambient air temperature data generated using TAPM V4 (see Section 2.1) and the *2005–06 Land use of Australia, Version 4* dataset (BRS 2010). A map of the calculated temperature control factors is presented in Figure 21.

¹¹ Emission factors sourced from Table 3-1 in Radian (1996)

¹² Factor applied was the most common across all 'forest' vegetation types

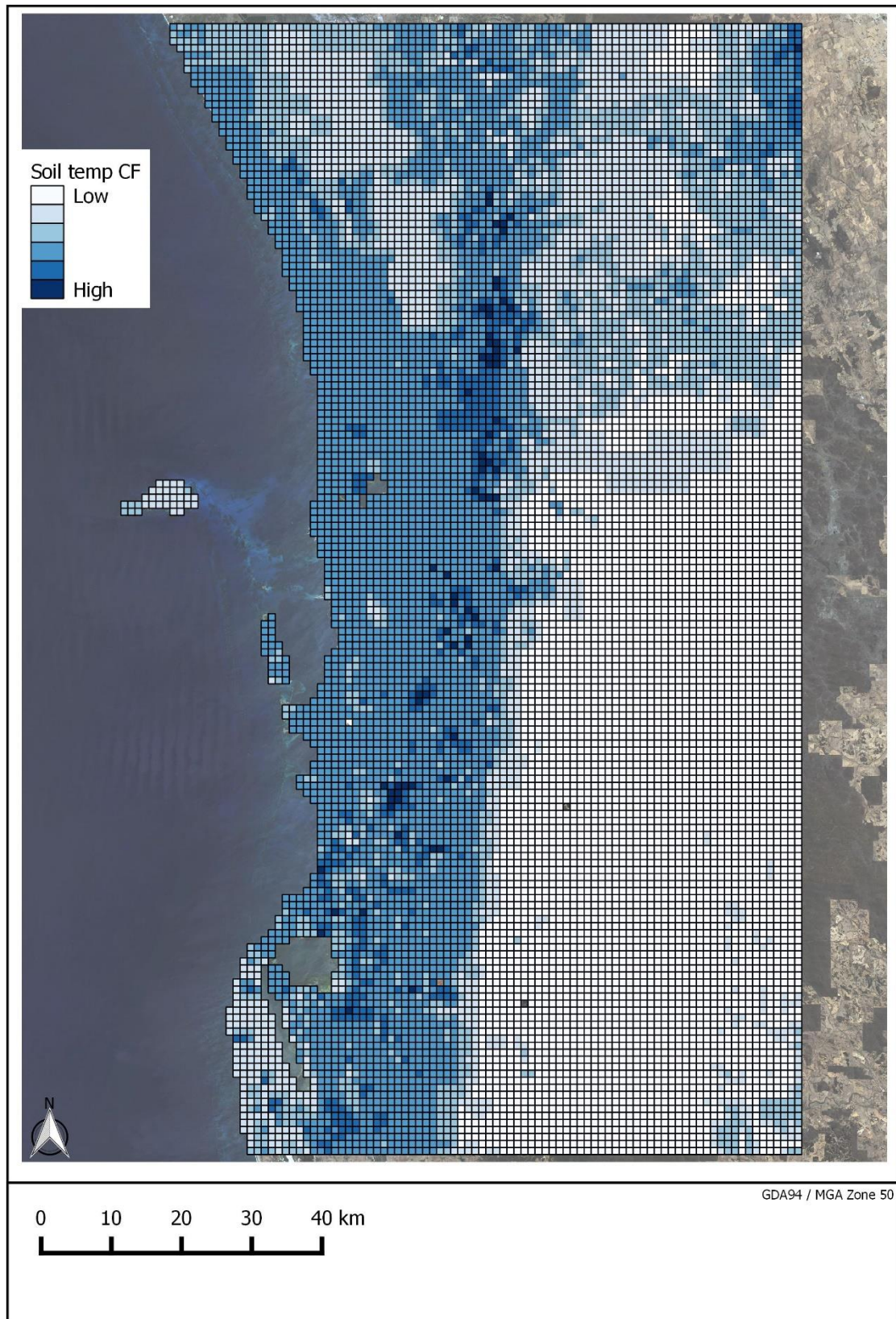


Figure 21 – Gridded land use temperature control factor for soil NO_x emissions

Total consumption of fertiliser (NFC)

Fertiliser use for all of Australia was sourced from the International Fertilizer Industry Association (IFA 2015). Fertiliser data used in this study is summarised in Table 20. To scale fertiliser use from all of Australia to the study area, the area of farmland in Australia was sourced from ABS and the relative proportion of total farmland in the study area (0.04 per cent) was applied to total fertiliser use (ABS 2013).

Table 20 – Fertiliser use in study area

IFA fertiliser type	Use in Australia (kilotonnes/yr)			Study area (tonnes/yr)
	2011	2012	2011–12	
Ammonia direct application	90	74	82	0.033
Ammonium sulfate	90	70.8	80.4	0.032
Urea	586	703	644	0.26
Nitrogen solutions	100	85.3	92.7	0.037
Ammonium phosphate (N)	165	144	154	0.062
N K compound (N)	1	1	1	0.00040
N P K compound (N)	67	21.2	44.1	0.018
Total N straight	866	933	899	0.36
Total N compound	233	166	200	0.080
Grand total N	1099	1099	1099	0.44

Agricultural ammonia emission factors (EF)

Emission factors for agricultural ammonia were sourced from the USEPA (Battye et al. 2004) and are presented in Table 21. Ammonia emission factors for Group II soils were applied for this study¹³.

Table 21 – Agricultural ammonia emission factors

Fertiliser type		NH ₃ emission factor (kg/t N)		
IFA name	USEPA name	Group I soil	Group II soil	Group III soil
Ammonia direct application	Anhydrous ammonia	48	48	48
Ammonium sulfate	Ammonium sulfate	182	121	61
Urea	Urea	242	182	182
Nitrogen solutions	Nitrogen solutions	97	97	97
Ammonium phosphate (N)	Monoammonium phosphate	61	61	61
N K compound (N)	Potassium nitrate	12	12	12
N P K compound (N)	Mix	36	24	12

Fraction of nitrogen fertiliser use (F)

The fraction of nitrogen fertiliser applied to different land use activities was sourced from the Department of the Environment (DotE 2014) and is presented in Table 22. Data used are specific to Western Australia.

Table 22 – Fertiliser distribution by land use

Land use		2011	2012	2011–12
Land use of Australia type	DotE land use type			
Cropping	Non-irrigated crops	0.0027	0.0017	0.0022
Grazing modified pastures	Non-irrigated pasture	0.0018	0.0016	0.0017
Irrigated cropping	Irrigated crops	0.3793	0.3721	0.3757
Irrigated modified pastures	Irrigated pasture	0.599	0.6098	0.6044
Irrigated perennial horticulture	Horticultural crops	0.0171	0.0143	0.0157
Irrigated seasonal horticulture				
Perennial horticulture				
Seasonal horticulture				

¹³ Group I: Warm, temperate areas with a large proportion of calcareous soils

Group II: Temperate and warm-temperate areas with some calcareous soils (or managed with soil pH>7), but with large areas of acidic soils

Group III: Temperate and cool-temperate areas with largely acidic soils

Natural ammonia emission factors (EF)

Emission factors for naturally occurring ammonia were sourced from the USEPA (Battye et al. 2004) and NSW EPA (2012). Factors used are presented in Table 23. Water and wetlands have no identified ammonia emission factors.

Table 23 – Natural ammonia emission factors

Land use	Land use type	Emission factors (ng/m ² /s)
Forest	Managed resource protection	1.2
	Nature conservation	
	Other minimal use	
	Plantation forestry	
	Irrigated plantation forestry	
	Production forestry	
Grassland	Grazing natural vegetation	0.9
Urban	Intensive animal production	0.31 ¹⁴
	Intensive horticulture	
	Manufacturing and industrial	
	Mining	
	Residential	
	Services	
	Transport and communication	

¹⁴ Value derived by NSW EPA (2012), Table 3-57, and is the 'grassland' factor scaled to account for the ratio of domestic and public open area lawn coverage to urban land use area in that particular study.

Emission estimates

Emissions of key pollutants from soils in the study area are summarised in Table 24.

Table 24 – Soil emission estimates

Pollutant	Emissions (kg/yr)		
	Natural	Agricultural	Total
Ammonia (total)	278,360	59,980	338,340
Oxides of nitrogen	14,817,220 ¹⁵		14,817,220

Spatial allocation

The spatial allocation of soil emissions is presented in Figure 22 and Figure 23.

Soil oxides of nitrogen emissions were shown to align with the 'grassland' and 'agriculture' land use areas (Figure 20). This reflects the significantly higher emission factors associated with these land use areas (Table 19).

Soil ammonia emissions were significantly higher in the cropping and pasture areas defined in the *2005–06 Land use of Australia, Version 4* dataset as 'irrigated'. The higher emissions in these areas were due to the greater fertiliser use (Table 22).

¹⁵ As a result of the temperature control factor calculations, it was not possible to separate natural and agricultural emissions for oxides of nitrogen.

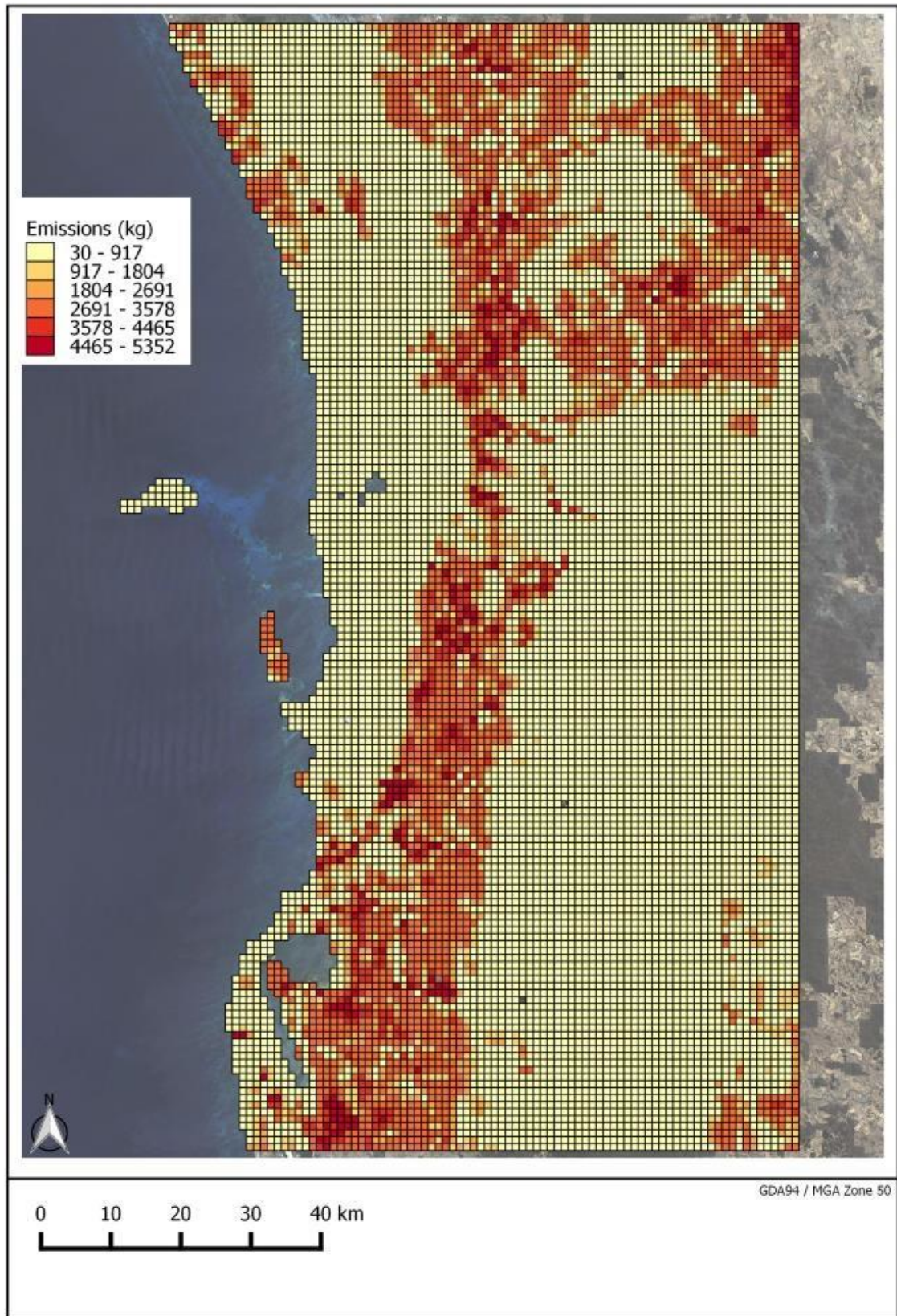


Figure 22 – Spatial allocation of soil NO_x emissions

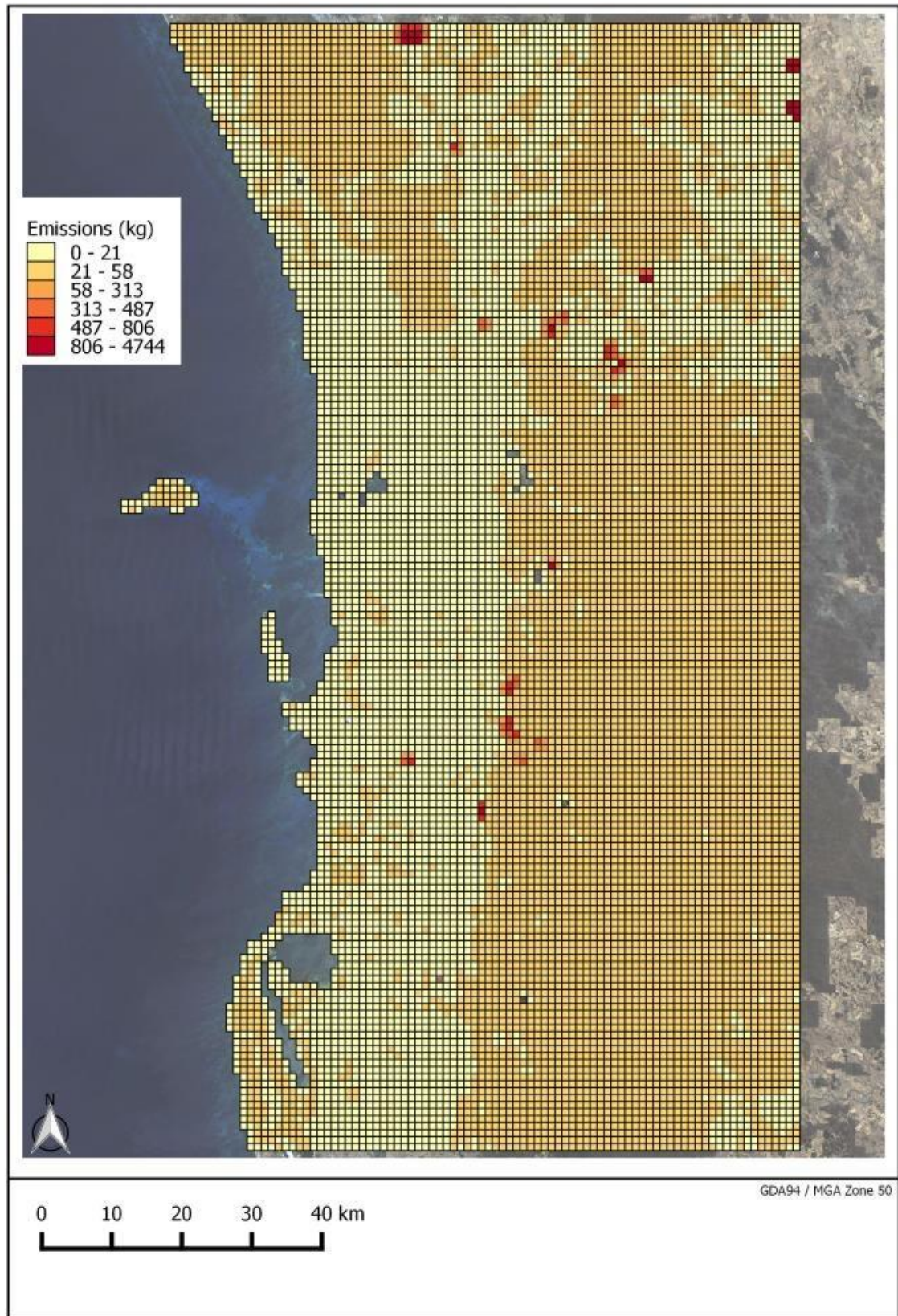


Figure 23 – Spatial allocation of soil NH₃ emissions

2.6 Vegetation

Vegetation emissions estimates account for the contribution of volatile organic compounds (VOCs) to the environment from tree canopies, uncut grass and cut grass.

Emission estimation technique

Emissions of VOCs from tree canopies and uncut grass were estimated using the following equation adapted from the USEPA (Radian 1996) and the California Air Resources Board (CARB 2003).

$$E_h = \sum_{t=1}^n (A_v \times EF_{h,v} \times CF_h \times 10^{-9})$$

Where:

E_h	= Emissions of substance type (h)	(kg/yr)
A_v	= Area of vegetation type (v)	(m ²)
$EF_{h,v}$	= Emission factor for substance type (h) from vegetation type (v)	(µg/m ² /hr)
CF_h	= Environmental correction factor for substance type (h)	(–)
n	= Hours (8784 for 2011–12)	(–)
t	= Time interval	(hr/yr)
v	= Vegetation type	(–)
h	= Substance	(–)
10^{-9}	= Conversion factor	(kg/µg)

The environmental correction factor (CF) applied was dependent on the emission. For tree canopies and uncut grass, VOCs emissions were estimated from the total of isoprene and monoterpene emissions.

Isoprene emissions are light- and temperature-dependent and were corrected with the following equations (Guenther et al. 1993; CARB 2003; CAWCR 2009).

$$CF_{iso} = CL_{iso} \times CT_{iso}$$

$$CL_{iso} = \frac{\alpha c_{L,1} L}{\sqrt{1 + \alpha^2 L^2}}$$

$$CT_{iso} = \frac{e^{\frac{c_{T,1}(T-T_s)}{(RT_s T)}}}{1 + e^{\frac{c_{T,2}(T-T_M)}{(RT_s T)}}$$

Where:

CF_{iso}	= Environmental correction factor for isoprene	(-)
CL_{iso}	= Light correction factor for isoprene	(-)
CT_{iso}	= Temperature correction factor for isoprene	(-)
	= 0.0027	(-)
$c_{L,1}$	= 1.066	(-)
L	= Ambient sunlight in the photosynthetically active radiation (PAR) range (400–700 nm)	($\mu\text{mol}/\text{m}^2/\text{s}$)
$c_{T,1}$	= 95,000	(J/mol)
T	= Ambient temperature	(K)
T_s	= 303	(K)
R	= 8.314	(J/K.mol)
$c_{T,2}$	= 230,000	(J/mol)
T_M	= 314	(K)

Monoterpene emissions are temperature-dependent and were corrected with the following equation (Guenther et al. 1993; CARB 2003; CAWCR 2009).

$$CF_{mono} = e^{(\beta(T-T_s))}$$

Where:

CF_{mono}	= Environmental correction factor for monoterpene	(-)
	= 0.09	(1/K)
T	= Ambient temperature	(K)
T_s	= 303	(K)

The ambient sunlight data (PAR) used in the isoprene correction factor was calculated using the following equations (Zhang et al. 2001; CAWCR 2009).

$$L = R_{dir}(\cos(\delta)/\cos(\theta)) + L_{shade}$$

$$L_{shade} = R_{diff}e^{(-0.65 \times LAI_z^{1.5})} + 0.07R_{dir}(1.1 - 0.1 \times LAI_z)e^{-\cos(\theta)}$$

Where:

L	= Ambient sunlight (PAR) on sunlight leaves	($\mu\text{mol}/\text{m}^2/\text{s}$)
R _{dir}	= Direct PAR at the top of the canopy	($\mu\text{mol}/\text{m}^2/\text{s}$)
	= Mean angle between leaves and sun – 60°	(°)
	= Solar zenith angle	(°)
L _{shade}	= Ambient sunlight (PAR) on shaded leaves	($\mu\text{mol}/\text{m}^2/\text{s}$)
R _{diff}	= Diffuse PAR at the top of the canopy	($\mu\text{mol}/\text{m}^2/\text{s}$)
LAI _z	= Leaf area index at height (z)	(–)
z	= Canopy height	(m)

The direct and diffuse PAR values used in the above equation were calculated using the following equations (Weiss & Norman 1985).

$$R_{dir} = 600e^{(-0.185(\frac{P}{P_0})^m)} \cos(\theta)$$

$$R_{diff} = 0.4(600 - R_{dir}) \cos(\theta)$$

$$m = \frac{1}{\cos(\theta)}$$

Where:

R _{dir}	= Direct PAR at the top of the canopy	($\mu\text{mol}/\text{m}^2/\text{s}$)
P	= Atmospheric pressure at terrain height	(Pa)
P ₀	= Atmospheric pressure at sea level – 101,325 Pa	(Pa)
m	= Optical air mass	(–)
	= Solar zenith angle	(°)
R _{diff}	= Diffuse PAR at the top of the canopy	($\mu\text{mol}/\text{m}^2/\text{s}$)

The barometric formula below was used to calculate atmospheric pressure at terrain height.

$$P = P_0 \left(\frac{T_0}{T_0 + L_0(h - h_0)} \right)^{\frac{gM}{RL_0}}$$

Where:

P	= Atmospheric pressure at terrain height	(Pa)
P ₀	= Atmospheric pressure at sea level – 101,325 Pa	(Pa)
T ₀	= Standard temperature at sea level – 288.15 K	(K)
L ₀	= Temperature lapse rate – -0.0065 K/m	(K/m)
h	= Terrain height	(m)
h ₀	= Sea level – 0 m	(m)
g	= Acceleration due to gravity – 9.8 m/s ²	(m/s ²)
M	= Molar mass of ‘air’ – 0.028964 kg/mol	(kg/mol)
R	= Universal gas constant – 8.31432	(N.m/mol.K)

Emissions of VOCs from cut grass were estimated using the following equation from the *2008 Calendar Year Air Emissions Inventory for the Greater Metropolitan Region in NSW* (NSW EPA 2012).

$$E_{VOC,i} = A_i \times (B_m - B_m^0) \times EF_{VOC} \times 10^{-3}$$

$$B_m = D \times f \times B_m^0$$

Where:

E _{VOC,i}	= Emissions of VOCs from source type (i)	(kg/yr)
A _i	= Area of lawn mown for source type (i)	(m ² /yr)
B _m	= Maximum potential leaf biomass before mowing	(g leaf biomass/m ²)
B _m ⁰	= Basal leaf biomass after mowing	(g leaf biomass/m ²)
EF _{VOC}	= Emission factor for VOCs	(g/g leaf biomass/mow)
D	= Leaf biomass removed	(g leaf biomass/m ² /mow)
f	= Frequency of mowing	(mows/yr)
i	= Source type	(–)
10 ⁻³	= Conversion factor	(kg/g)

Activity data

Area of vegetation type (A)

Vegetation coverage in the study area was estimated using the Western Australia Pre-European Vegetation dataset from the former Department of Agriculture and Food (now the Department of Primary Industries and Regional Development). The vegetation codes in this dataset were converted into structural and flora descriptions (Beard et al. 2013).

To adjust the Western Australia Pre-European Vegetation dataset for anthropogenic influences, the *2005–06 Land use of Australia, Version 4* dataset was intersected to allocate land use data to vegetation data. Vegetation areas coinciding with ‘urban’ and ‘water’ land use were removed from tree canopy and uncut grass emission estimates.

Any areas with flora descriptors not associated with vegetation (e.g. ‘freshwater lakes’, ‘salt pans’) had emissions set to zero.

To assign emission factors to different vegetation groups, the vegetation structural and flora descriptions were aligned with vegetation ID descriptions presented by the USEPA (Radian 1996).

For vegetation areas overlapping with ‘agricultural’ areas or ‘grassland’ used for grazing purposes, land use commodity data were used to assign an appropriate vegetation ID description.

The area of each different vegetation group is presented in Table 25. For areas with multiple flora species, multiple USEPA vegetation ID descriptions were assigned.

Table 25 – Area of vegetation types in study area

Vegetation flora description OR Land use commodity type	USEPA vegetation ID description (Radian 1996)	Area (km ²)
Wattle, casuarina and tea tree (<i>Acacia</i> – <i>allocasuarina</i> – <i>melaleuca</i> alliance)	Acacia, Casuarina	3.32
Other wattle (<i>Acacia</i> spp.), banksia (<i>Banksia</i> spp.), peppermint (<i>Agonis flexuosa</i>), cypress pine (<i>Callitris</i> spp.), casuarina (<i>Allocasuarina</i> spp.), York gum (<i>Eucalyptus loxophleba</i>)	Acacia, Casuarina, Eucalyptus	608
Wattle (<i>Acacia rostellifera</i>), Rottneet pine (<i>Callitris preissii</i>), moort (<i>Eucalyptus platypus</i>) or mixed tropical forest	Acacia, Casuarina, Eucalyptus, Mixed forest (G94)	13.4
Legumes	Alfalfa	8.15
Stone fruit	Prunus (cherry)	50.5
Citrus	Citrus (orange)	3.51
Jarrah (<i>Eucalyptus marginata</i>), marri (<i>Corymbia calophylla</i>) and wandoo (<i>E. wandoo</i>) Mainly jarrah (<i>E. marginata</i>) and marri (<i>C. calophylla</i>) Wheatbelt – York gum (<i>E. loxophleba</i>), salmon gum (<i>E. salmonophloia</i>) etc. Goldfields – gimlet (<i>E. salubris</i>), redwood (<i>E. transcontinentalis</i>) etc. Riverine – rivergum (<i>E. camaldulensis</i>) Tropical – Darwin stringybark (<i>E. tetradonta</i>) and woollybutt (<i>E. miniata</i>)	Eucalyptus	5,976
Jarrah (<i>Eucalyptus marginata</i>), banksia (<i>Banksia</i> spp.) or casuarina (<i>Allocasuarina</i> spp.)	Eucalyptus and Casuarina	104
(Mainly in the south-west) Cyperaceae, Restionaceae, Juncaceae	Grass	8.16
Pastures and crops for hay	Hay	244
Apples, pears and other pome fruit	Malus (apple)	18.5
Cereals, oilseeds, and other non-cereal crops	Misc. crops	75.0
Undefined woodland	Mixed forest (G94)	84.0
Agricultural commodities without corresponding USEPA veg ID	Other (assume grass)	40.7
Grazing	Pasture	2,419
Vegetables	Potato	9.45
Heath, scrub, low shrubs of mixed composition	Scrub woodland (G94)	164
Mixed heath with scattered tall shrubs <i>Acacia</i> spp., Proteaceae and Myrtaceae	Scrub woodland (G94) and Eucalyptus	7.04

Emission factors for vegetation type (EF)

Emission factors for isoprene and monoterpene from vegetation areas identified in Table 25 were sourced from the USEPA (Radian 1996) and are detailed in Table 26. Where multiple vegetation ID descriptions applied, the emission factor used was the average of those ID descriptions.

Table 26 – Tree canopy and uncut grass emission factors

USEPA vegetation ID description (Radian 1996)	Isoprene flux ($\mu\text{g}/\text{m}^2/\text{hr}$)	Monoterpene flux ($\mu\text{g}/\text{m}^2/\text{hr}$)
Acacia, Casuarina	14,915	1,212
Acacia, Casuarina, Eucalyptus	19,860	1,233
Acacia, Casuarina, Eucalyptus, Mixed forest (G94)	17,757	1,208
Alfalfa	19	8
Asimina (paw paw)	43	43
Citrus (orange)	43	680
Eucalyptus	29,750	1,275
Eucalyptus and Casuarina	29,750	659
Grass	56	141
Hay	38	95
Malus (apple)	43	43
Misc. crops	8	19
Mixed forest (G94)	11,450	1,134
Other (assume grass)	56	141
Pasture	56	141
Potato	10	24
Scrub woodland (G94)	2,700	349
Scrub woodland (G94) and Eucalyptus	16,225	812

Ambient temperature (T)

Ambient temperature data were generated using TAPM V4, as described in Section 2.1. Hourly averaged temperature data were used for emission estimates.

Solar zenith angle (θ)

The hourly solar zenith angle was calculated for the study area using the Solar Calculations tool published by the US National Oceanic and Atmospheric Administration (NOAA 2010) available on its website¹⁶. The solar zenith angle was calculated for the centre point of the study area and applied for all grid cells.

¹⁶ https://www.esrl.noaa.gov/gmd/grad/solcalc/NOAA_Solar_Calculations_day.xls

Leaf area index (LAI)

The leaf area index (LAI) data used in this study were developed using Landsat imagery from 2011 and 2012. Satellite imagery was converted into LAI data using the methodology from Boer et al. (2008). The 2011 and 2012 datasets were averaged to generate a 2011–12 dataset. The LAI map for the study area is presented in Figure 24.

The LAI data is satellite-image based and does not account for LAI at various canopy heights. Emission estimates for isoprene are based on direct sunlight with no adjustment for light reduction as a result of shading. As a result, emission estimates are considered conservative.

Terrain height (h)

Terrain height data used in this study were sourced from the NASA Shuttle Radar Topography Mission (SRTM) (NASA 2011). The SRTM dataset used had a resolution of three arc seconds (90 metres) and was aggregated to align with the one kilometre resolution used in this study. The terrain map for the study area is presented in Figure 25.

Area of lawn mown (A)

For cut grass emission estimates, two emission sources were considered: domestic lawns and public open space lawns.

To estimate domestic lawns, this study used the domestic survey data that NSW EPA collected for its 2008 inventory study (NSW EPA 2012). It was assumed that domestic lawn coverage and mowing behaviours in the NSW EPA inventory area were similar to the Perth study area. The domestic lawn mown area estimated for this study is presented in Table 27.

Table 27 – Area of lawn mown: domestic lawn

Parameter	Value
Number of free standing dwellings – NSW EPA (2008)	1,256,021
Residential cut grass area (m ²) – NSW EPA (2008)	1,014,914,751
Area lawn mown per residence (m ² /yr)	808
Lawn mowing frequency (mows/yr)	20.89
Area lawn per residence (m ²)	38.7
Number of free standing dwellings – Perth study area (ABS 2011)	562,375
Area of domestic lawn – Perth study area (m ²)	21,753,054
Area of domestic lawn mown – Perth study area (m ² /yr)	454,421,290

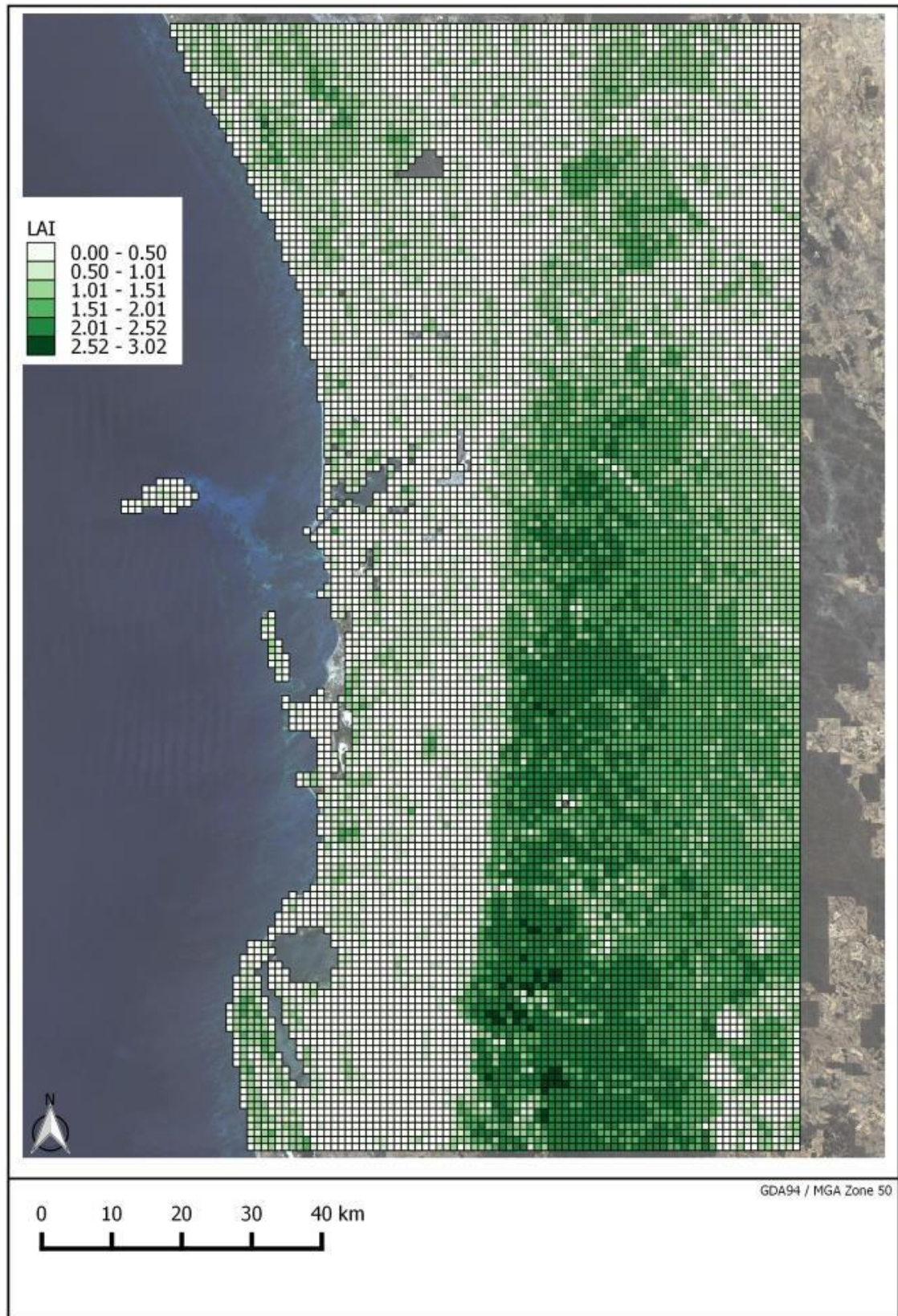


Figure 24 – Leaf area index

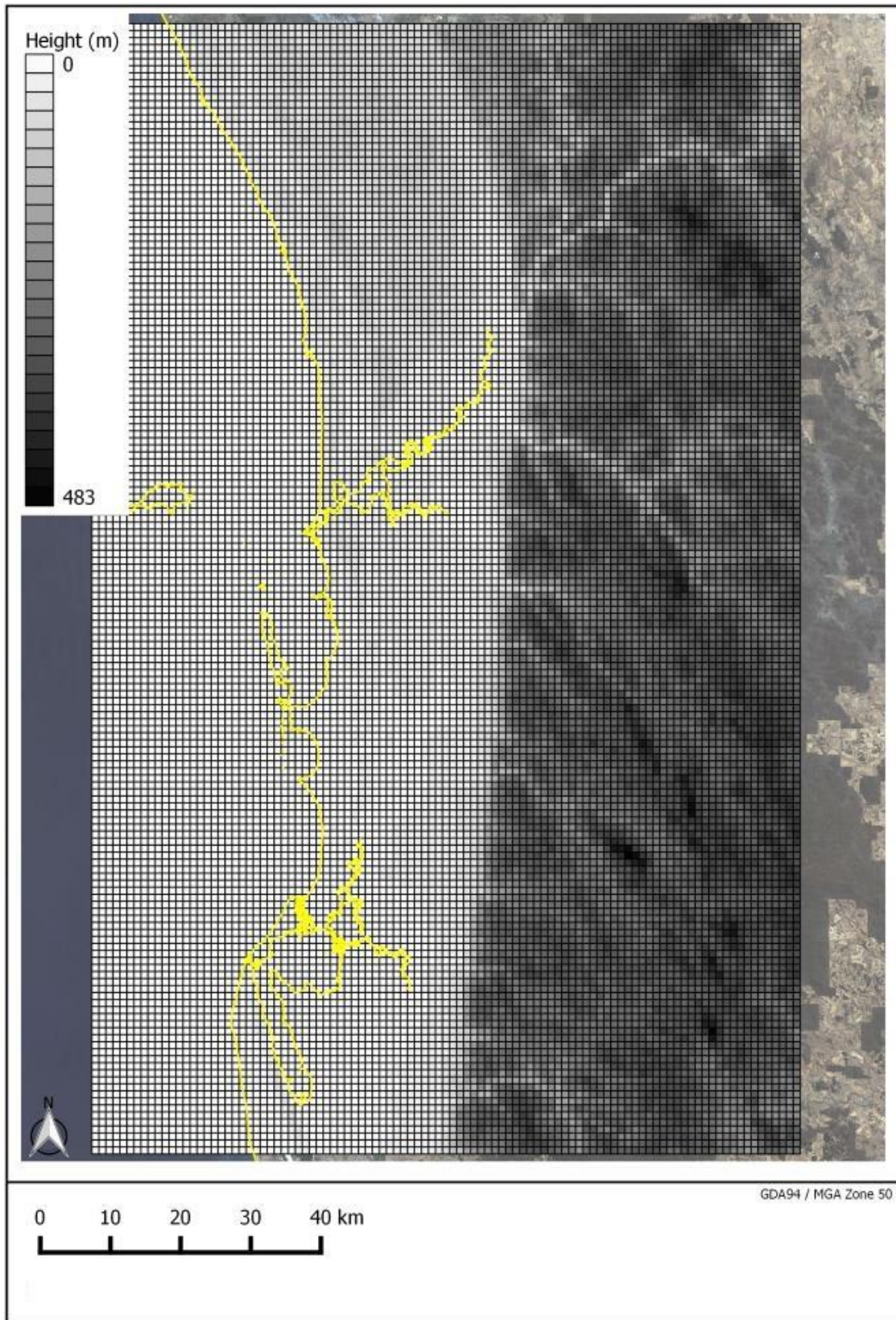


Figure 25 – Terrain height

The Western Australian Planning Commission's Liveable Neighbourhoods guidelines were used to establish a public open space lawn area to be applied for emission estimates. These guidelines recommend that at least 10 per cent of urban development be allocated as public open space (WAPC 2009).

To calculate the amount of public open space in the study area, 10 per cent of the area defined as 'urban' within the *2005–06 Land use of Australia, Version 4* dataset was used. To account for public open space without lawn, the estimated public open space area was reduced by 75 per cent. The mowing frequency for domestic lawn (NSW EPA 2012) was used for public open space. The estimated public open space lawn area is outlined in Table 28.

Table 28 – Area of lawn mown: public open space lawn

Parameter	Value
<i>2005–06 Land use of Australia, Version 4</i> dataset – Urban area within study area (m ²)	1,729,900,585
Urban area within study area allocated as public open space (m ²)	172,990,058
Public open space area estimated as lawn (m ²)	43,247,515
Lawn mowing frequency (mows/yr)	20.89
Area of public open space lawn mown – Perth study area (m ² /yr)	903,440,580

Emission factors for cut grass (EF) and biomass data (B)

The biomass variables and volatile organic compound (VOC) emission factor used to calculate cut grass emissions were sourced from the *2008 Calendar Year Air Emissions Inventory for the Greater Metropolitan Region in NSW* (NSW EPA 2012) and are presented in Table 29.

Table 29 – Cut grass biomass attributes and VOC emission factor

Parameter	Value
Maximum potential leaf biomass before lawn mowing (g leaf biomass/m ²) – (B _m)	936
Basal leaf biomass after lawn mowing (g leaf biomass/m ²) – (B _m ⁰)	100
Leaf biomass removed (g leaf biomass/m ² /mow) – (D)	40
VOC emission factor for cut grass (g VOC/g leaf biomass/mow) – (EF _{VOC})	0.002

Volatile organic compound speciation for cut grass

Cut grass VOC emissions were speciated using the factors presented in Table 30 (Kirstine et al. 1998).

Table 30 – Cut grass VOC speciation factors

Substance	VOC fraction
Acetaldehyde	0.0421
Acetone	0.0154
Ethanol	0.0061
Methanol	0.1598

Emission estimates

Emissions of key pollutants from vegetation in the study area are summarised in Table 31.

Table 31 – Vegetation emission estimates

Pollutant	Emissions (kg/yr)		
	Tree canopies and uncut grass	Cut grass	Total
Acetaldehyde	–	95,582	95,582
Acetone	–	34,963	34,963
Ethanol	–	13,849	13,849
Methanol	–	362,801	362,801
Total volatile organic compounds	165,324,757	2,270,345	167,595,102

Spatial allocation

The spatial allocation of vegetation VOC emissions is presented in Figure 26.

Both spatial allocation of tree canopy and uncut grass emissions are described earlier in this section.

Allocation of domestic cut grass emissions was based on the number of single dwellings in each suburb of the study area. Dwelling type data were sourced from the 2011 ABS census mesh block data (ABS 2011).

Allocation of public open space cut grass emissions was proportionate to the population density of each grid cell. Population density was determined using the 2011 ABS census mesh block data (ABS 2011).

Vegetation VOC emissions align strongly with the ‘forest’ land use areas (Figure 20), which reflects the higher emission rates from forest-type vegetation groups compared with other vegetation groups as presented in Table 26.

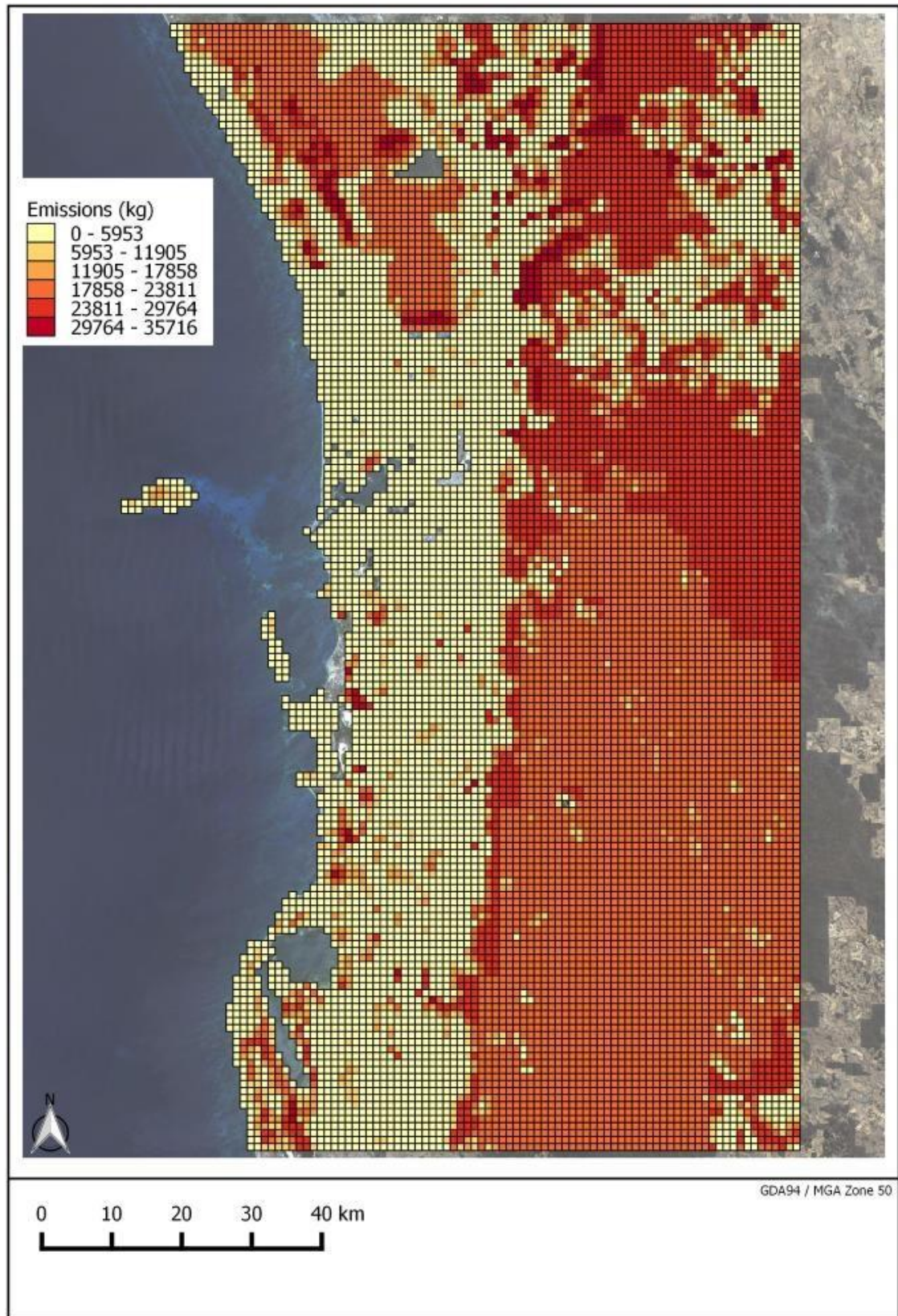


Figure 26 – Spatial allocation of vegetation VOC emissions

3 Total emission estimates

This section presents cumulative and comparative emission estimates for biogenic and geogenic activities.

To assess the relative risk for all emission estimates, toxic equivalency potential (TEP) scores were calculated. TEP is a technique increasingly being used by Australian and international environment agencies for comparing substances that have varying toxicities. TEP provides a screening-level evaluation of substances according to their effect on human health, and can be calculated in two ways. The ‘non-cancer risk’ score converts emissions to toluene-equivalents and is an assessment of the potential impact of toxins on general human health. The ‘cancer risk’ score converts emissions to benzene-equivalents and is an assessment of the potential impact of carcinogenic toxins (Scorecard 2015)¹⁷.

This study assessed TEP using the non-cancer risk score to indicate the more general health risk. TEP is calculated by multiplying the emission estimates for substances by their corresponding non-cancer risk score. A list of NPI substances and their associated risk scores is included in Appendix A.

3.1 Total biogenic and geogenic emissions

Emissions estimated and TEP scores for all biogenic and geogenic sources are presented in Table 32.

Table 32 – Biogenic and geogenic emission estimates: total

Substance	Emissions (tonnes/year)	Toxic equivalency potential (TEP) score
Key pollutants		
Total volatile organic compounds	168,504	168,504
Particulate matter 2.5 µm	3,271	55,609
Oxides of nitrogen	15,208	33,458
Particulate matter 10 µm	16,345	24,517
Carbon monoxide	12,986	1,818
Sulfur dioxide	120	373
Other NPI-listed pollutants¹⁸		
Lead and compounds	6.57	3,807,915
Mercury and compounds	0.17	826,219
Cadmium and compounds	0.30	573,137
Polychlorinated dioxins and furans (TEQ)	0.000000088	77,301
Cobalt and compounds	1.42	44,161
Arsenic and compounds	0.19	15,660

¹⁷ Further information on how TEP is calculated can be found on the Scorecard website at: http://scorecard.goodguide.com/env-releases/def/tep_caltox.html

¹⁸ ‘Polycyclic aromatic hydrocarbons’ include a range of organic compounds of varying toxicities. It does not have an assigned TEP score. Ethanol and TSP also do not have a TEP score.

Substance	Emissions (tonnes/year)	Toxic equivalency potential (TEP) score
Copper and compounds	0.97	12,600
Manganese and compounds	12.0	9,348
Chromium (total)	2.68	8,306
Nickel and compounds	0.68	2,164
Ammonia (total)	470	1,784
Zinc and compounds	7.67	1,458
Antimony and compounds	0.14	1,110
Acetaldehyde	95.6	889
Selenium and compounds	0.023	54.1
Methanol	363	32.7
1,3-Butadiene (vinyl ethylene)	8.42	18.5
Acetone	35.0	1.75
Total suspended particulate (TSP)	46,336	N/A
Ethanol	13.8	N/A
Polycyclic aromatic hydrocarbons (B[a]P _{eq})	0.021	N/A

The relative contribution of all biogenic and geogenic emission sources to key pollutants are summarised in Figure 27 and Table 33. The relative contribution of biogenic and geogenic emission sources to the overall TEP is presented in Figure 28.

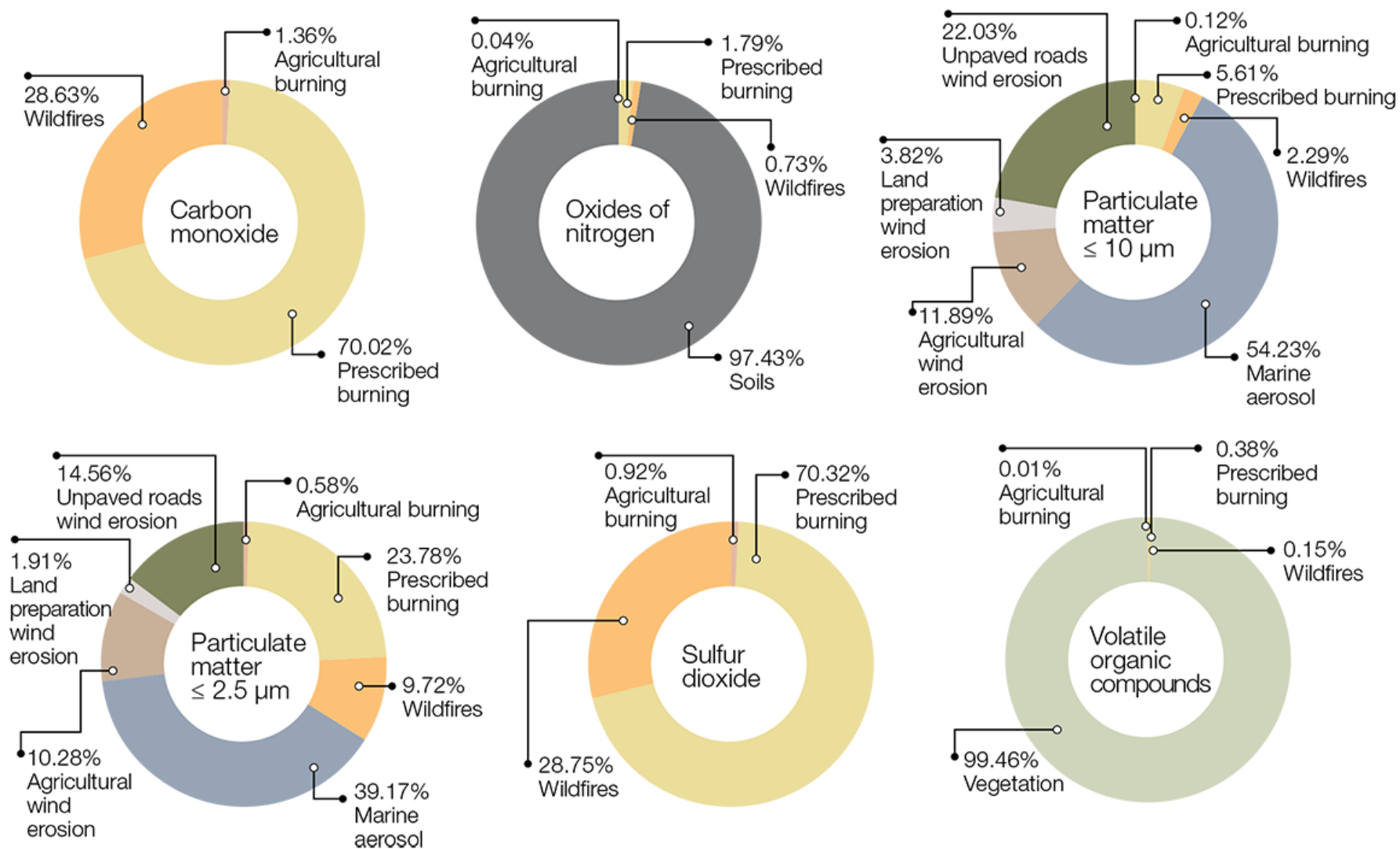


Figure 27 – Biogenic and geogenic emission estimates: source contributions by mass

Table 33 – Biogenic and geogenic emissions estimates by source

Substance	Emissions (tonnes/year)									Emissions (tonnes/year)
	Agricultural burning	Prescribed burning	Wildfires	Marine aerosol	Soils	Vegetation	Agricultural wind erosion	Land prep wind erosion	Unpaved roads wind erosion	
Key pollutants										
Carbon monoxide	176	9,093	3,717							12,986
Oxides of nitrogen	6.52	273	112		14,817					15,208
Particulate matter 2.5 µm	18.9	778	318	1,281			336	62.4	476	3,271
Particulate matter 10 µm	19.8	917	375	8,864			1,943	625	3,601	16,345
Sulfur dioxide	1.11	84.7	34.6							120
Total volatile organic compounds	13.7	636	260			167,595				168,504
Other NPI-listed pollutants										
Acetaldehyde						95.6				95.6
Acetone						35.0				35.0
Ammonia (total)	2.78	91.2	37.3		338					470
Antimony and compounds	0.0010	0.039	0.016				0.026	0.013	0.042	0.14
Arsenic and compounds	0.00014	0.0037	0.0015				0.068	0.022	0.091	0.19
1,3-Butadiene (vinyl ethylene)		5.98	2.44							8.42
Cadmium and compounds	0.0010	0.026	0.011				0.086	0.027	0.15	0.30
Cobalt and compounds	0.000060	0.0019	0.00076				0.37	0.15	0.90	1.42
Copper and compounds	0.00026	0.018	0.0072				0.29	0.13	0.53	0.97
Chromium (total)	0.00042	0.010	0.0042				0.89	0.29	1.48	2.68

Substance	Emissions (tonnes/year)									Emissions (tonnes/year)
	Agricultural burning	Prescribed burning	Wildfires	Marine aerosol	Soils	Vegetation	Agricultural wind erosion	Land prep wind erosion	Unpaved roads wind erosion	
Ethanol						13.8				13.8
Lead and compounds	0.00024	0.091	0.037				0.27	0.71	5.46	6.57
Manganese and compounds	0.0095	0.23	0.094				4.08	1.21	6.37	12.0
Mercury and compounds	0.00026	0.0056	0.0023				0.047	0.019	0.091	0.17
Methanol						363				363
Nickel and compounds	0.00018	0.0037	0.0015				0.21	0.075	0.38	0.68
Polychlorinated dioxins and furans (TEQ)	0.0000000027	0.000000070	0.000000015							0.000000088
Polycyclic aromatic hydrocarbons (B[a]P _{eq})	0.0067	0.010	0.0042							0.021
Selenium and compounds	0.00012	0.0037	0.0015				0.0086	0.0026	0.0061	0.023
Total suspended particulate (TSP)	20.2	933	381	33,388			4,277	1,277	6,060	46,336
Zinc and compounds	0.0034	1.80	0.74				0.70	0.66	3.77	7.67
Total TEP for each source	6,215	211,668	74,347	35,079	33,884	168,518	588,165	571,670	3,976,893	5,666,440

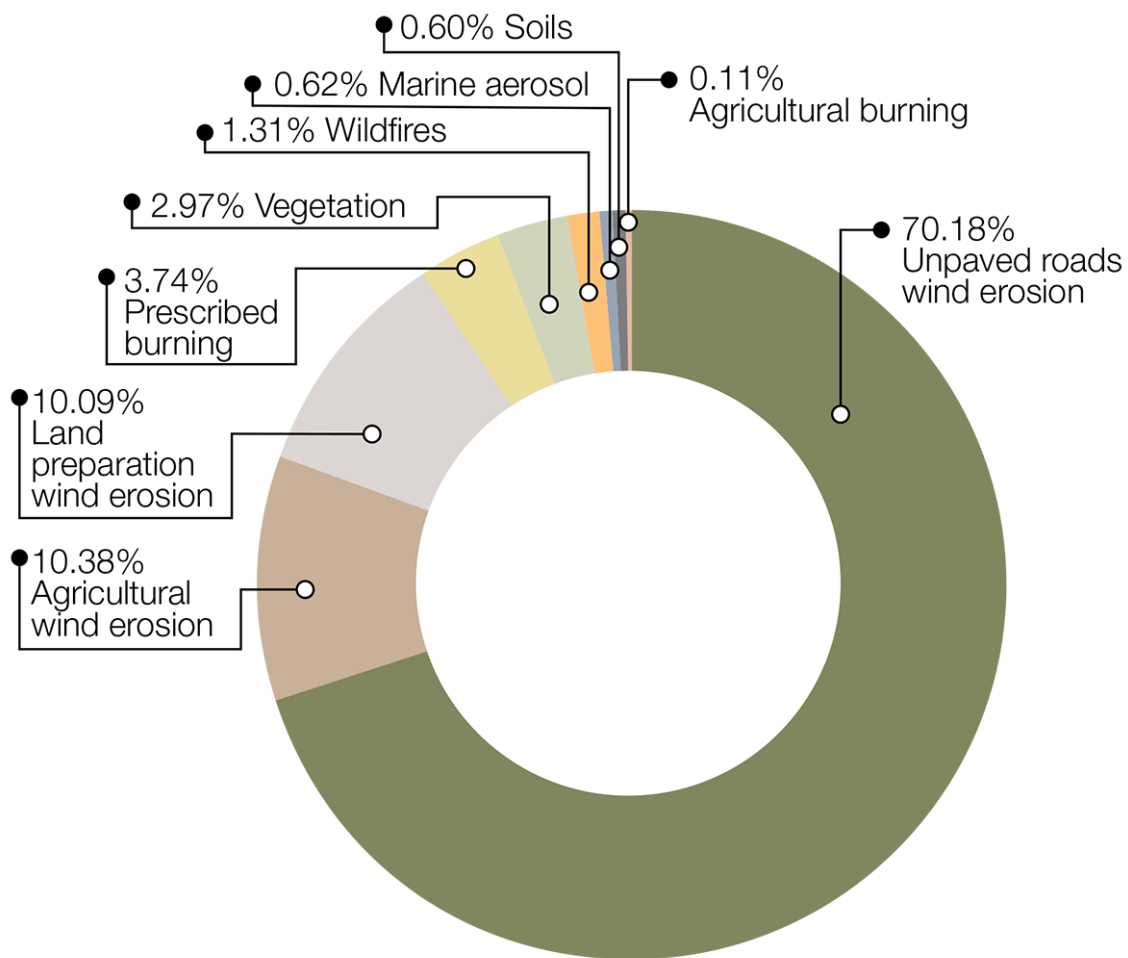


Figure 28 – Biogenic and geogenic TEP source contributions

The most significant emission risks were from heavy metals (e.g. lead, mercury and cadmium) (Table 32). These emissions were estimated from speciation of metals in dust, and represent the trace amounts of these substances that exist in crustal particulate. Wind-blown dust, mostly from unpaved road wind erosion, was the primary source of trace metals. Figure 28 shows that wind erosion sources make up 90 per cent of the emission risk from biogenic and geogenic sources.

VOCs were the most significant key pollutant and one of the primary emission risks from biogenic and geogenic sources. Vegetation sources produced nearly all VOC emissions from species such as *Acacia*, *Casuarina* and *Eucalyptus* within the study area. While VOC emissions from vegetation were noteworthy, Figure 28 shows vegetation sources contributed only three per cent of the total emissions risk from biogenic and geogenic sources.

The results show soil was the most significant source of biogenic and geogenic NO_x emissions (97 per cent). Marine aerosol was the main source of PM₁₀ emissions (54 per cent), which was more significant for coastal receptors than inland receptors. Wind erosion was also a significant source of PM₁₀ emissions (38 per cent). PM_{2.5} was generated by fires (34 per cent), marine aerosol (39 per cent) and wind erosion (27 per cent). Fire was the only source of CO and SO₂ emissions.

3.2 Spatial allocation summary

Emissions

Spatial allocation of key pollutant emissions from all biogenic and geogenic sources is presented from Figure 29 through to Figure 34.

The VOC emissions presented in Figure 29 align with the vegetation VOC emission allocation presented earlier in Figure 26. Non-vegetation VOC sources did not have a significant influence on the overall distribution of VOC emissions from biogenic and geogenic sources.

Particulate emissions presented in Figure 30 and Figure 32 show the influence of fire-generated particles (Figure 19). Particulate emissions from fires, while lower than marine aerosol and wind erosion emissions, were concentrated in a smaller area. Particulate emissions from windblown dust sources along the coast are also visible.

The NO_x emissions presented in Figure 31 followed the distribution pattern in Figure 22. The concentration of emissions in the study area's north-west corner area is attributed to bushfire activity (see Figure 17).

As fire activity was the only source of CO and SO₂, the distribution presented in Figure 33 and Figure 34 aligned with the fire emissions profile presented earlier in Figure 19.

TEP score

The TEP of biogenic and geogenic emission sources was calculated and spatially allocated to the study area. The cumulative TEP score for the study area is shown in Figure 35. The areas with higher TEP scores aligned with wind erosion sources, reflecting the trace levels of heavy metals in these sources (heavy metals have significantly larger TEP scores compared with other emitted substances from biogenic and geogenic sources).

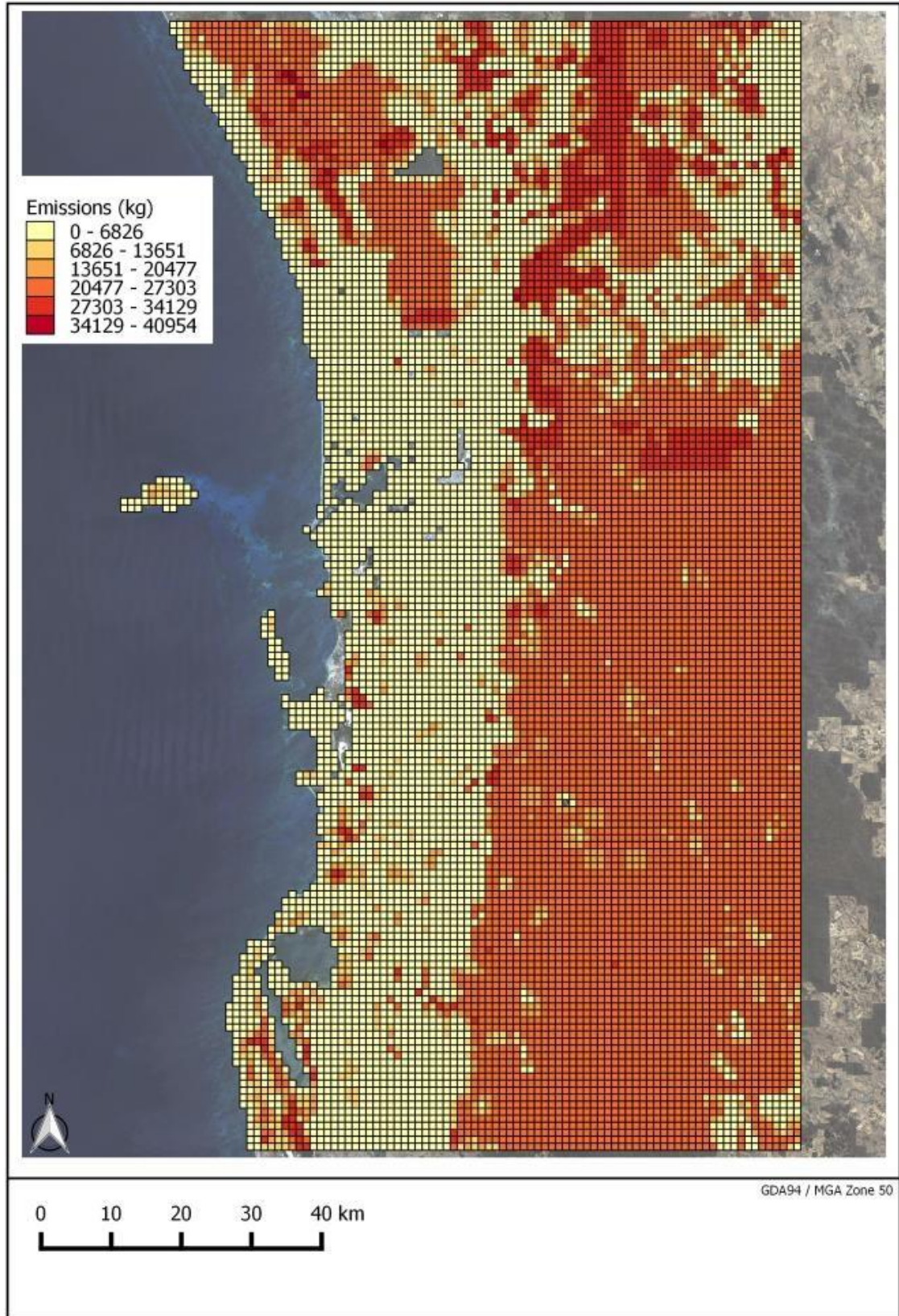


Figure 29 – Spatial allocation of biogenic and geogenic VOC emissions

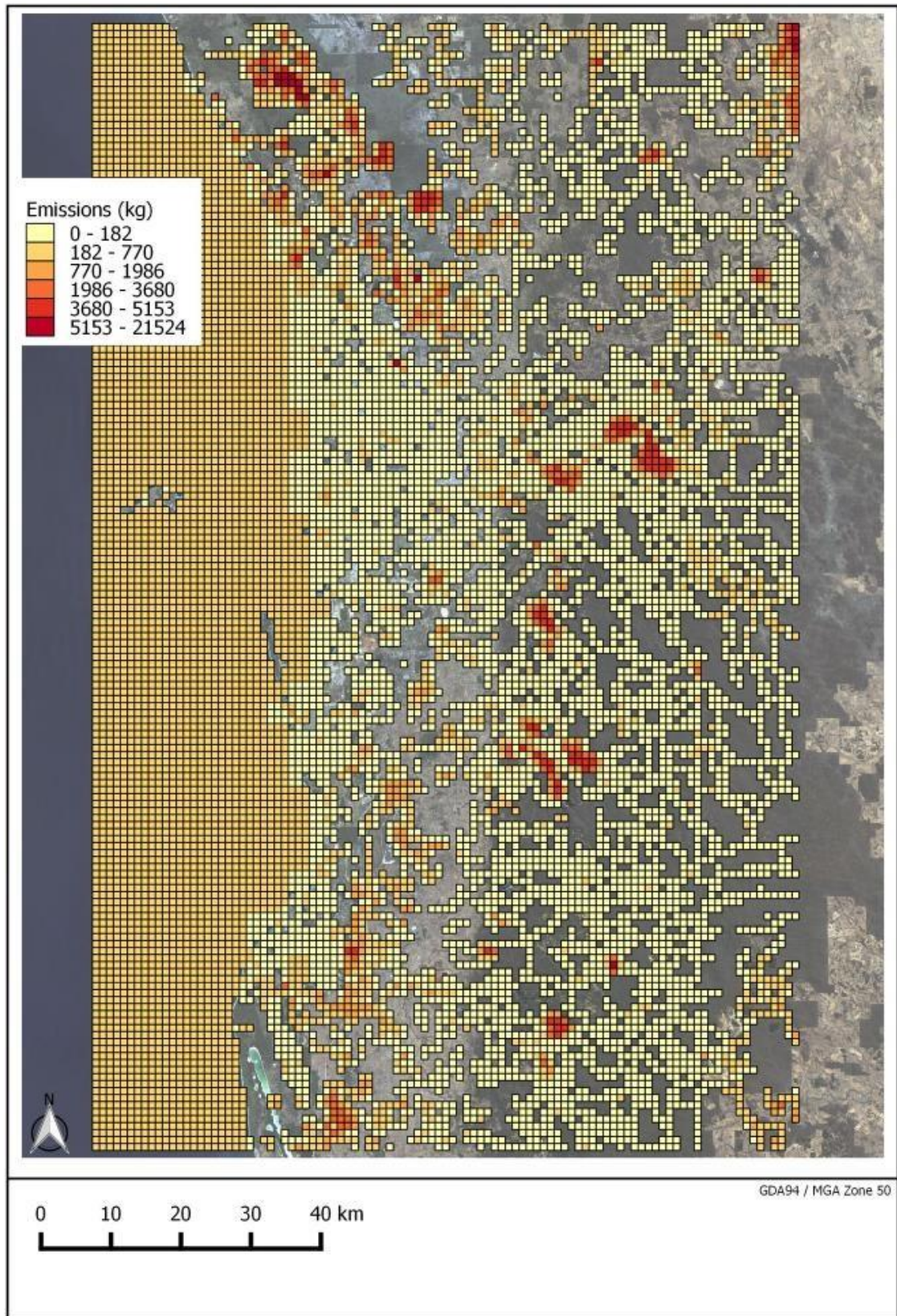


Figure 30 – Spatial allocation of biogenic and geogenic $PM_{2.5}$ emissions

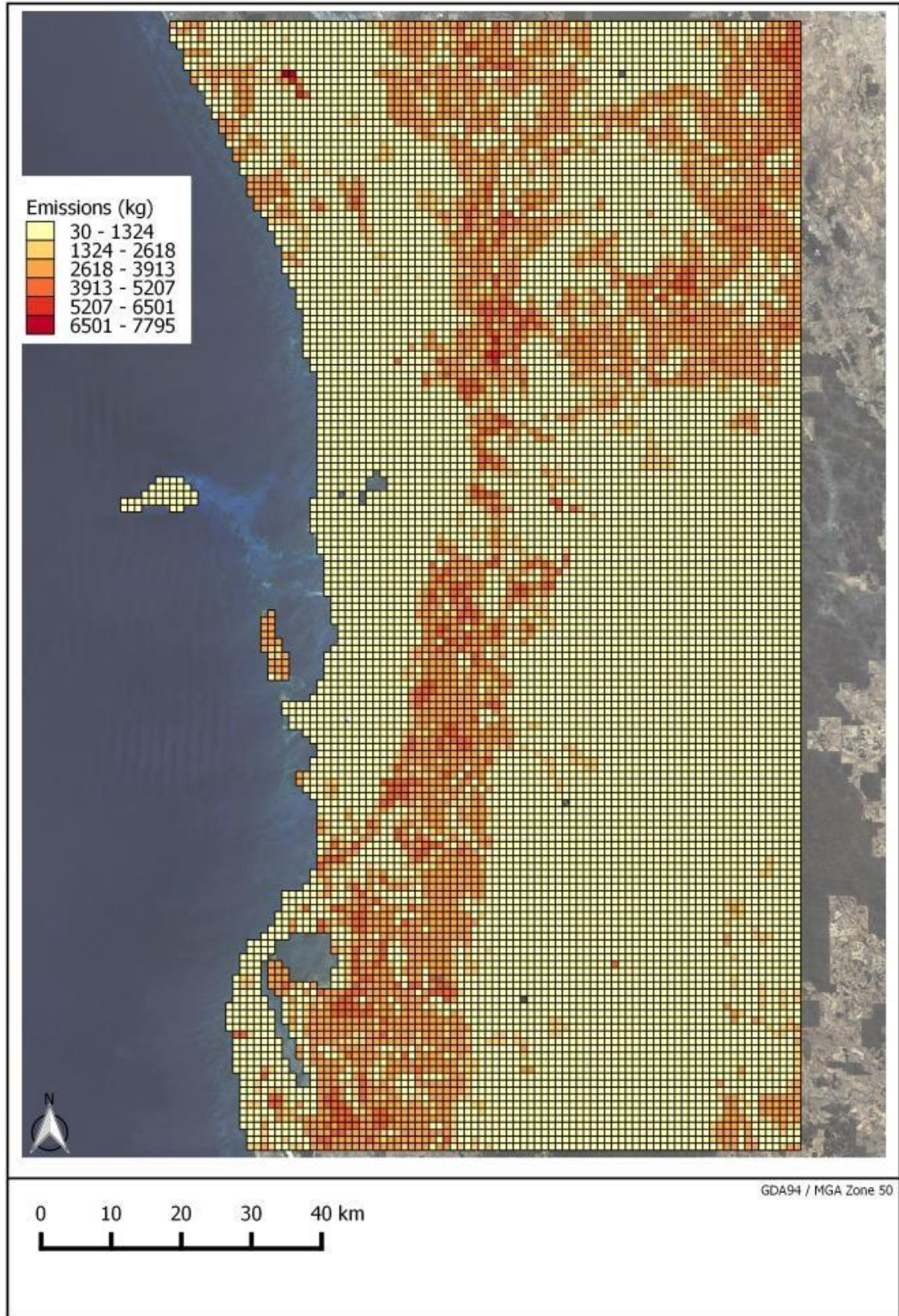


Figure 31 – Spatial allocation of biogenic and geogenic NO_x emissions

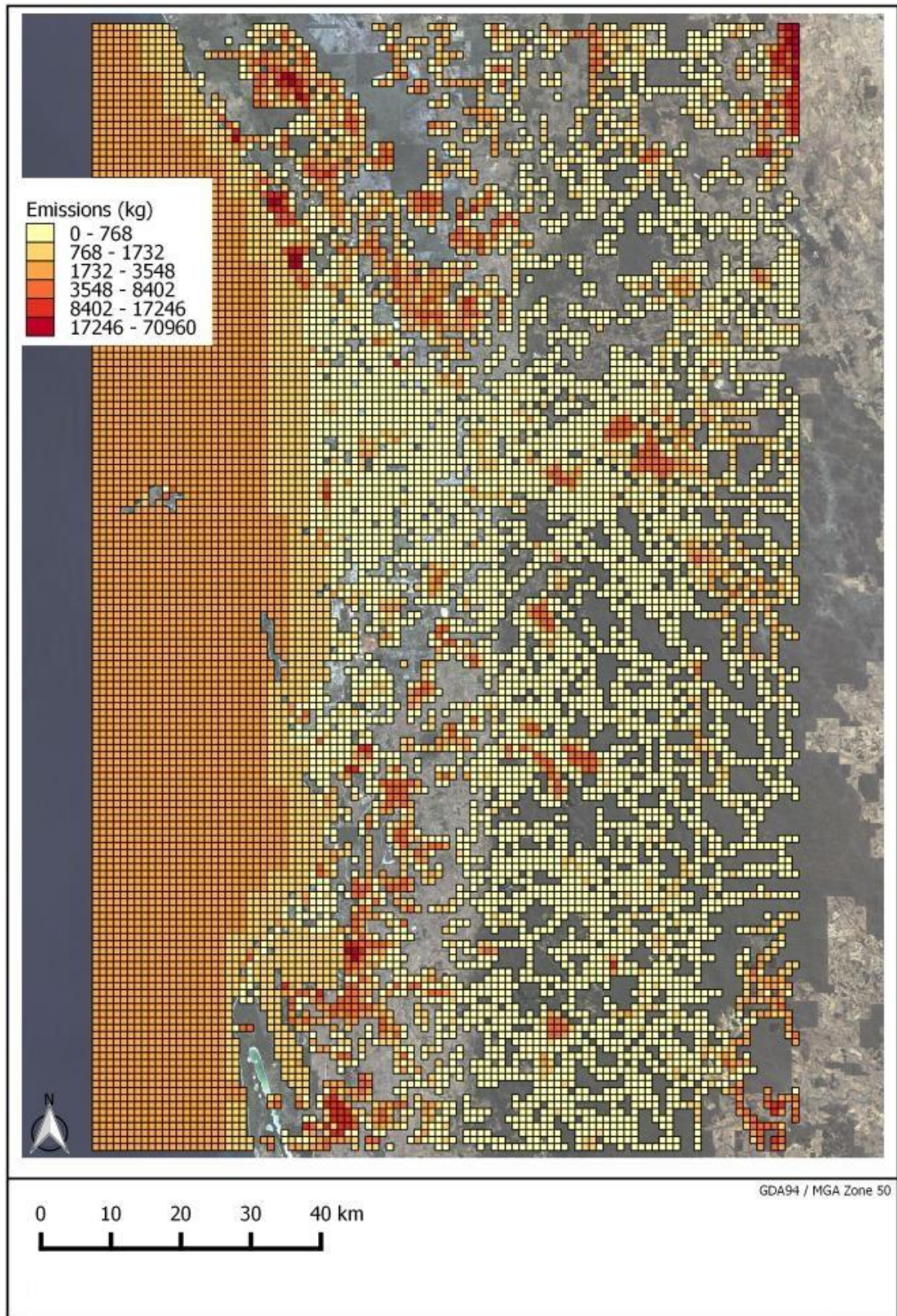


Figure 32 – Spatial allocation of biogenic and geogenic PM_{10} emissions

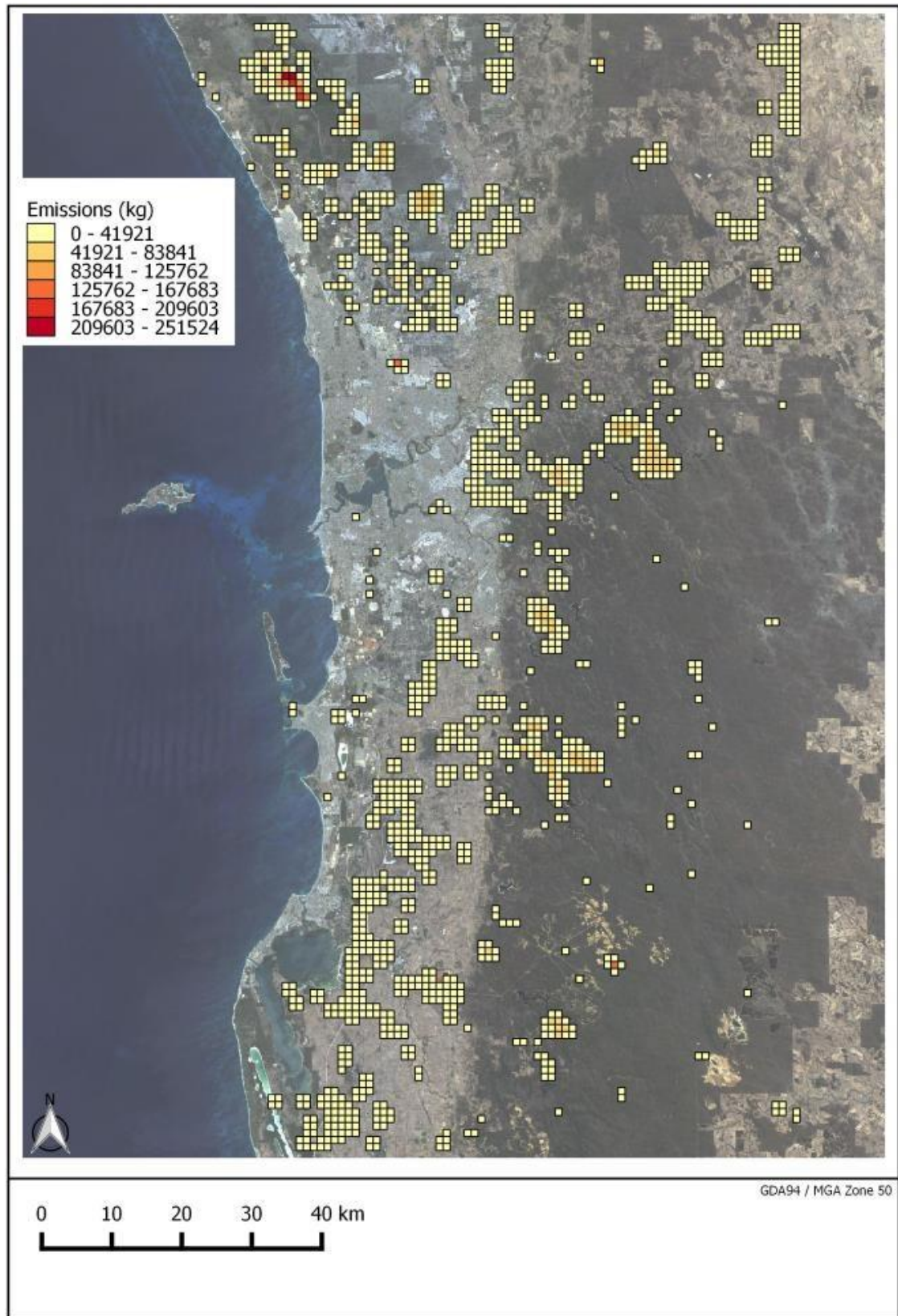


Figure 33 – Spatial allocation of biogenic and geogenic CO emissions

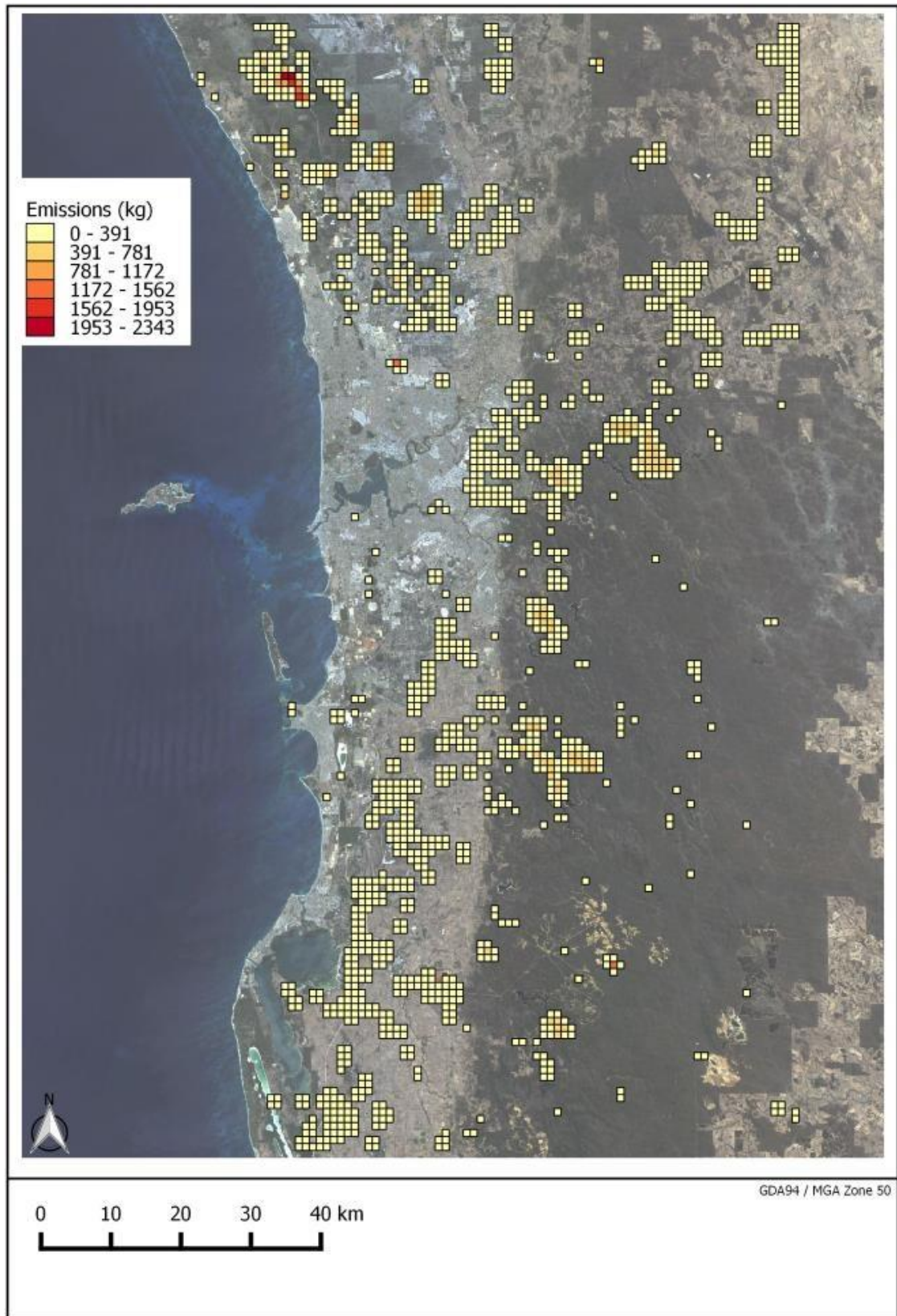


Figure 34 – Spatial allocation of biogenic and geogenic SO₂ emissions

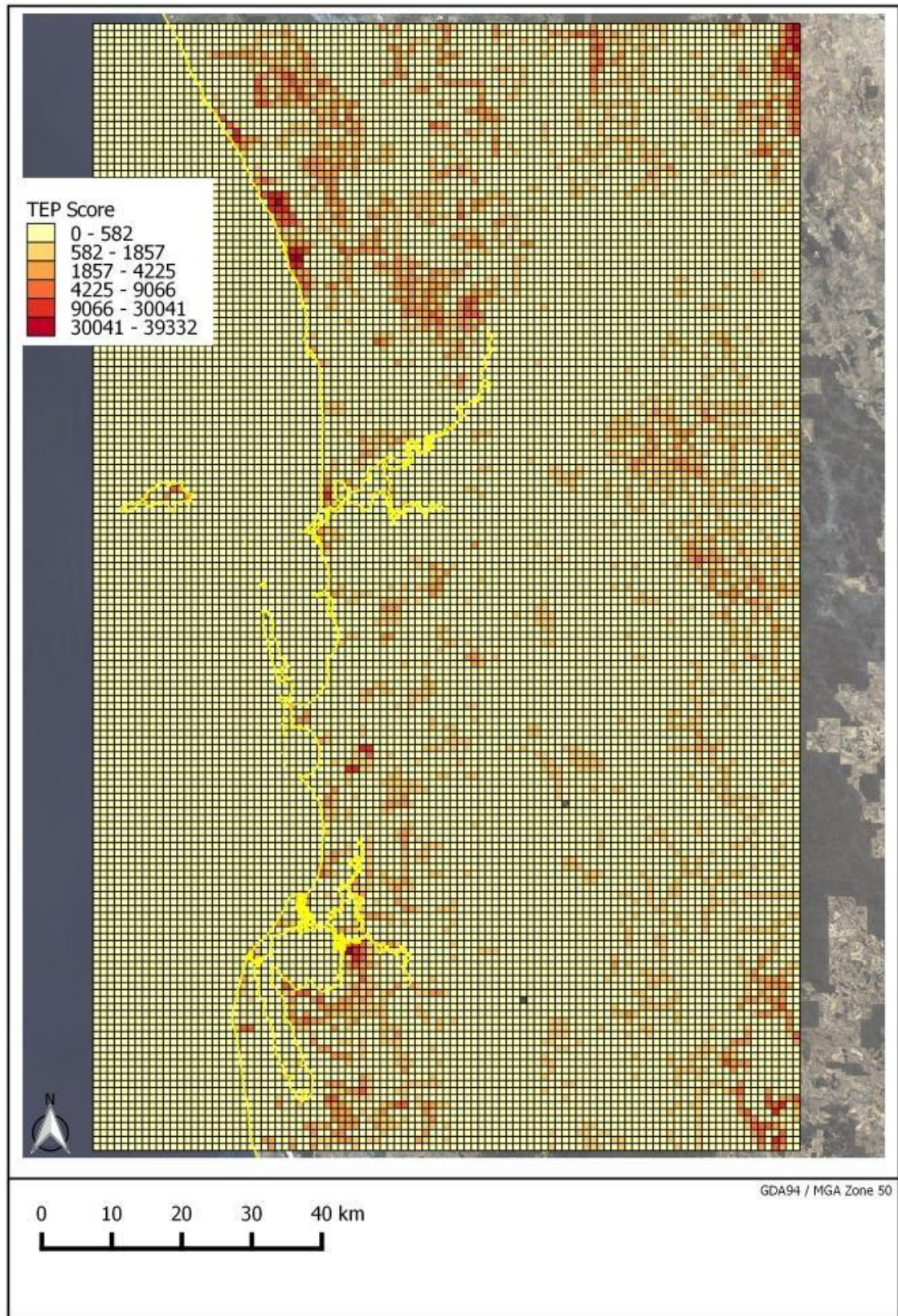


Figure 35 – Spatial allocation of biogenic and geogenic TEP score

4 Key considerations

This study has found that:

- Emissions of heavy metals in dust are the most significant emissions risk from biogenic and geogenic sources due to the higher toxicity of these substances. Heavy metal emissions are based on generic activity particulate speciation profiles and thus have greater uncertainty than the more specific estimation methods used for key pollutants. A localised dust speciation profile specifically for wind erosion sources would reduce this uncertainty.
- The spatial distribution of emission risk was focused in areas with the highest levels of wind erosion: along the coast (from land development and site preparation) and inland areas (unpaved roads and agricultural lands).
- Biogenic and geogenic emissions, by mass, were dominated by VOCs, with the primary source being tree canopies. The emission estimation technique used to estimate tree canopy emissions was conservative, which is likely to have resulted in an overestimate of emissions from this source. Further work is needed to refine the emission estimation technique used and reduce uncertainty in estimates.
- The spatial allocation of emissions was as significant as the volume of emissions from biogenic and geogenic sources:
 - Unpaved roads produced significantly higher net emissions than other wind erosion sources in the study area, but were spread out over most of the study area. Wind erosion emissions from land development and site preparation and agricultural lands dominated the areas in which they occurred. Net particulate emissions from fire sources were lower still, but were even more concentrated in the areas where they occur.
 - Emissions from backyard and small-scale domestic burning would likely be lower than other fire sources, but were closer to populated areas. A domestic survey is required to collect the data required for estimates.

This study's outcomes should be viewed in the wider context of other major emission sources (domestic, commercial and industrial, on-road vehicles, off-road mobile) that were also part of the Perth Air Emissions Study 2011–2012.

Appendices

Appendix A – Toxic equivalency potential score

Table 34 – NPI substance TEP rating

Substance	Non-cancer risk score (TEP) ¹
Acetaldehyde	9.3
Acetic acid (ethanoic acid)	N/A
Acetone	0.05
Acetonitrile	30
Acrolein	1,600
Acrylamide	2,000
Acrylic acid	62
Acrylonitrile (2-propenenitrile)	38
Ammonia (total)	3.8
Aniline (benzenamine)	91
Antimony and compounds	8,100
Arsenic and compounds	84,000
Benzene	8.1
Benzene hexachloro- (HCB)	21,000
Beryllium and compounds	24,000
Biphenyl (1,1-biphenyl)	0.98
Boron and compounds	N/A
Butadiene (vinyl ethylene)	2.2
Cadmium and compounds	1,900,000
Carbon disulfide	1.2
Carbon monoxide	0.14
Chlorine and compounds	N/A
Chlorine dioxide	N/A
Chloroethane (ethyl chloride)	0.02
Chloroform (trichloromethane)	14
Chlorophenols (di, tri, tetra)	51
Chromium (III) compounds	N/A
Chromium (VI) compounds	3,100

Substance	Non-cancer risk score (TEP) ¹
Cobalt and compounds	31,000
Copper and compounds	13,000
Cumene (1-methylethylbenzene)	0.41
Cyanide (inorganic) compounds	580
Cyclohexane	0.02
Dibromoethane	1,500
Dibutyl phthalate	11
Dichloroethane	4.2
Dichloromethane	7
Ethanol	N/A
Ethoxyethanol	N/A
Ethoxyethanol acetate	N/A
Ethyl acetate	0.09
Ethyl butyl ketone	N/A
Ethylbenzene	0.14
Ethylene glycol (1,2-ethanediol)	0.25
Ethylene oxide	56
Di-(2-Ethylhexyl) phthalate (DEHP)	33
Fluoride compounds	3.6
Formaldehyde (methyl aldehyde)	16
Glutaraldehyde	N/A
Hexane	N/A
Hydrochloric acid	12
Hydrogen sulfide	34
Lead and compounds	580,000
Magnesium oxide fume	N/A
Manganese and compounds	780
Mercury and compounds	5,000,000
Methanol	0.09
Methoxyethanol	N/A
Methoxyethanol acetate	N/A
Methyl ethyl ketone	0.05
Methyl isobutyl ketone	0.03

Substance	Non-cancer risk score (TEP) ¹
Methyl methacrylate	0.53
Methylene-bis(2-chloroaniline) (MOCA)	N/A
Methylene bis (phenylisocyanate)	N/A
Nickel and compounds	3,200
Nickel carbonyl	N/A
Nickel subsulfide	N/A
Nitric acid	2.1
Organo-tin compounds	N/A
Oxides of nitrogen	2.2
Particulate matter 2.5 µm	17
Particulate matter 10 µm	1.5
Phenol	0.38
Phosphoric acid	16
Polychlorinated biphenyls	2,000,000
Polychlorinated dioxins and furans (TEQ)	880,000,000,000
Polycyclic aromatic hydrocarbons (B[a]P _{eq})	N/A
Selenium and compounds	2,400
Styrene (ethenylbenzene)	0.08
Sulfur dioxide	3.1
Sulfuric acid	N/A
Tetrachloroethane	56
Tetrachloroethylene	65
Toluene (methylbenzene)	1
Toluene-2,4-diisocyanate	N/A
Total nitrogen	N/A
Total phosphorus	N/A
Total volatile organic compounds	1
Trichloroethane	4.9
Trichloroethylene	0.63
Vinyl chloride monomer	69
Xylenes (individual or mixed isomers)	0.27
Zinc and compounds	190

¹ based on toluene equivalent

References

- ABARES, 2012. *Cropping calendars for natural resource management regions of Australia 2010 – August 2012*. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.
- ABS, 2011. *Census of Population and Housing: Mesh Block Counts, 2011*. Data cube: Excel spreadsheet, cat. no. 2074.0.
<http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/2074.0Main+Features12011?OpenDocument>
- ABS, 2012. *Greater Capital City Statistical Areas*. Statistical Geography Fact Sheet. Commonwealth of Australia 2012.
[http://www.abs.gov.au/websitedbs/D3310114.nsf/4a256353001af3ed4b2562bb00121564/6b6e07234c98365aca25792d0010d730/\\$FILE/Greater%20Capital%20City%20Statistical%20Area%20-%20Fact%20Sheet.pdf](http://www.abs.gov.au/websitedbs/D3310114.nsf/4a256353001af3ed4b2562bb00121564/6b6e07234c98365aca25792d0010d730/$FILE/Greater%20Capital%20City%20Statistical%20Area%20-%20Fact%20Sheet.pdf)
- ABS, 2013. *Agricultural Commodities, Australia 2011–12*. cat. no. 7121.0. Commonwealth of Australia 2013.
<http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7121.02011-12?OpenDocument>
- Battye, W. & Barrows, R., 2004. *Review of Ammonia Emission Modeling Techniques for Natural Landscapes and Fertilized Soils*. EPA Contract No. 68-D-02-064, Work Assignment No. 2-09, EC/R Project No. PRD-209, EC/R Incorporated, 6330 Quadrangle Drive, Suite 325, Chapel Hill, NC 27517, USA.
https://www.epa.gov/sites/production/files/2015-08/documents/nh3_report_0504.pdf
- Beard, J.S., Beeston, G.R., Harvey, J.M. Hopkins, A.J.M. & Shepherd D.P., 2013. *The vegetation of Western Australia at the 1:3 000 000 scale Explanatory Memoir Second Edition* In: Conservation Science Western Australia, Vol 9.
- Boer, M.M., Macfarlane, C., Norris, J., Sadler, R.J., Wallance, J. & Grierson, P.F., 2008. *Mapping burned areas and burn severity patterns in SW Australian eucalypt forest using remotely-sensed changes in leaf area index*. Remote Sensing of Environment 112 (2008) 4358–4369.
- BRS, 1991. *Digital Atlas of Australian Soils*, Bureau of Rural Sciences, GPO Box 858, Canberra, ACT 2601, Australia. <http://www.asris.csiro.au/themes/Atlas.html>
- BRS, 2010. *2005–06 Land Use of Australia, Version 4*, Bureau of Rural Sciences, GPO Box 858, Canberra, ACT 2601, Australia.
<http://www.agriculture.gov.au/abares/aclump/land-use/data-download>
- CARB, 1996. *Atmospheric Pollutant Emissions Factors from Open Burning of Agricultural and Forest Biomass by Wind Tunnel Simulations Volume 2*. Prepared by: B.M. Jenkins, I.M. Kennedy, D.P.Y. Chang, O.G. Raabe, S.Q. Turn, E.B. Williams, S.G. Hall and S. Teague, Californian Air Resources Board, 1001 "I" Street P.O. Box 2815 Sacramento, CA 95812, USA.
- CARB, 1997a. *Area-Wide Source Methodologies, Section 7.12 Windblown Dust – Agricultural Lands*. Californian Air Resources Board, 1001 "I" Street P.O. Box 2815 Sacramento, CA 95812, USA. <http://www.arb.ca.gov/ei/areasrc/fullpdf/full7-12.pdf>
http://www.arb.ca.gov/ei/areasrc/wbagdust_supp.pdf

CARB, 1997b. *Area-Wide Source Methodologies, Section 7.13 Windblown Dust – Unpaved Roads*. Californian Air Resources Board, 1001 "I" Street P.O. Box 2815 Sacramento, CA 95812, USA. <http://www.arb.ca.gov/ei/areasrc/fullpdf/full7-13.pdf>

CARB, 2003. *Development of a biogenic hydrocarbon emission inventory for the Central California Ozone Study domain (draft)*. Report prepared by Scott, K.I. for California Air Resources Board, 1001 I Street, Sacramento, California 9581. <http://www.arb.ca.gov/ei/ccosbeigis2.pdf>

CARB, 2004. *Area-Wide Source Methodologies, Section 9.3 Wildfires*. Californian Air Resources Board, 1001 "I" Street P.O. Box 2815 Sacramento, CA 95812, USA. www.arb.ca.gov/ei/areasrc/fullpdf/full9-3.pdf

CARB, 2005. *Area-Wide Source Methodologies, Section 7.17 Agricultural Burning and Other Burning Methodology*. Californian Air Resources Board, 1001 "I" Street P.O. Box 2815 Sacramento, CA 95812, USA. www.arb.ca.gov/ei/areasrc/fullpdf/full7-17.pdf

CARB, 2006. *Area-Wide Source Methodologies, Section 7.15 Wild Fire Use (WFU)*. Californian Air Resources Board, 1001 "I" Street P.O. Box 2815 Sacramento, CA 95812, USA. www.arb.ca.gov/ei/areasrc/fullpdf/full7-15.pdf

CARB, 2014a. *PM Speciation Profiles (PMPROF)*. Californian Air Resources Board, 1001 "I" Street P.O. Box 2815 Sacramento, CA 95812, USA. <http://www.arb.ca.gov/ei/speciate/pmchemprofile20aug14.zip>

CARB, 2014b. *PM Size Fractions (PMSIZE)*. Californian Air Resources Board, 1001 "I" Street P.O. Box 2815 Sacramento, CA 95812, USA. <http://www.arb.ca.gov/ei/speciate/pmsizeprofile20aug14.zip>

CARB, 2015. *Organic Chemical Profiles (ORGPROF)*. Californian Air Resources Board, 1001 "I" Street P.O. Box 2815 Sacramento, CA 95812, USA. <http://www.arb.ca.gov/ei/speciate/orgprofile11feb15.zip>

CAWCR, 2009. *Chemical Transport Model – Technical Description*. CAWCR Technical Report No. 015 October 2009. The Centre for Australian Weather and Climate Research. http://www.cawcr.gov.au/technical-reports/CTR_015.pdf

CSIRO, 2000. *Estimation of Soil Properties Using the Atlas of Australian Soils*. CSIRO Land and Water, Canberra ACT. Technical Report 11/00, February 2000. www.clw.csiro.au/aclep/documents/tr11-00.pdf

DotE, 2014. *National Inventory Report 2012 Volume 1*. Commonwealth of Australia 2014. Department of the Environment. <http://www.environment.gov.au/climate-change/greenhouse-gas-measurement/publications/national-inventory-report-2012>

DEH, 2004. *Technical Report No. 3 Inventory of Dioxin Emissions in Australia, 2004*. Prepared by Kelsey Bawden, Pacific Air & Environment. Commonwealth of Australia May 2004.

Guenther, A. B., Zimmerman, P. R., Harley, P. C., Monson, R. K. & Fall, R., 1993. *Isoprene and monoterpene emission rate variability: model evaluations and sensitivity analyses*. J. Geophys. Res. 98, 12609-12617.

- Hurley, P.J., 2008. *TAPM V4. User Manual*. CSIRO Marine and Atmospheric Research Internal Report No. 5. October 2008.
<https://publications.csiro.au/rpr/download?pid=procite:7f1f5a42-69e4-4711-ad81-a21befc593b9&dsid=DS1>.
- IFA, 2015. *IFADATA, Consumption of Nitrogen Fertilizers in Australia 2011 and 2012*. International Fertilizer Industry Association, 28 Rue Marbeuf, 75008 Paris, France. <http://ifadata.fertilizer.org/ucSearch.aspx>
- Kirstine, W., Gallbally, I., Ye, Y. & Hooper, M., 1998. *Emissions of Volatile Organic Compounds (Primarily Oxygenated Species) from Pasture*. Journal of Geophysical Research, Volume 103, Number D9, pp 10,615–10,619.
- NASA, 2011. *Shuttle Radar Topography Mission Version 2.1 STRM3 Australia*. U.S. National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology. http://dds.cr.usgs.gov/srtm/version2_1/SRTM3/Australia/
- NOAA, 2010. *Solar Calculation Details*. National Oceanic & Atmospheric Administration, U.S. Department of Commerce.
<http://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html>
- NPI, 2012. *National Pollutant Inventory Emission Estimation Technique Manual for Mining Version 3.1*. January 2012. Commonwealth of Australia 2012.
- NPI, 2014. *National Pollutant Inventory Guide Version 6.0*. December 2014. Commonwealth of Australia 2014.
- NSW EPA, 2012. *Air Emissions Inventory for the Greater Metropolitan Region in New South Wales, 2008 Calendar Year, Biogenic and Geogenic Emissions: Results*. Technical Report No. 2. August 2012.
<http://www.epa.nsw.gov.au/resources/air/120046AEITR2Biogenic.pdf>.
- Radian, 1996. *Biogenic Sources Preferred Methods*. EIIP Technical Report Series Volume V, Emission Inventory Improvement Program. Radian Corporation, Post Office Box 13000, Research Triangle Park, NC 27709, USA.
<http://nepis.epa.gov/Adobe/PDF/2000CY9B.pdf>
- Scorecard, 2015. *Using a Screening Level Risk Assessment to Assign Risk Scores*.
http://scorecard.goodguide.com/env-releases/def/tep_caltox.html.
- USEPA, 1974. *Development of Emission Factors for Fugitive Dust Sources*, EPA-450/3-74-37, United States Environment Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC 27711, USA.
<http://nepis.epa.gov/Adobe/PDF/2000MC6B.PDF>
- WAPC, 2009. *Liveable Neighbourhoods, a Western Australian Government sustainable cities initiative*. January 2009, Update 02. Western Australian Planning Commission, Department for Planning and Infrastructure.
http://www.planning.wa.gov.au/dop_pub_pdf/LN_Text_update_02.pdf
- Weiss, A., & Norman, J.M., 1985. *Partitioning Solar Radiation into Direct and Diffuse, Visible and Near-Infrared Components*. Agricultural and Forest Meteorology, 34 (1985) 205–213.

Zhang, L., Moran, M.D. & Brook, J.R., 2001. *A comparison of models to estimate in-canopy photosynthetically active radiation and their influence on canopy stomatal resistance*. Atmospheric Environment 35 (2001) 4463–4470.