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Black Carbon Monitoring Feasibility Report

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Mote Limited Consultancy Report 2024/002

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Executive Summary

This report details the feasibility of monitoring Black Carbon (BC) in New Zealand. BC is an atmospheric aerosol derived from the incomplete combustion of carbonaceous fuels (primarily fossil fuel and biomass). There is a growing body of evidence regarding the negative impacts of BC on human health and the Earth's climate. A number of global organisations (The World Health Organization (WHO), The Intergovernmental Panel on Climate Change (IPCC) and The International Agency for Research on Cancer (IARC) have issued and continued their warnings to reduce emissions of BC due to these impacts. As part of its updated 2021 Air Quality Guidelines and Good Practice Statements the WHO recommends to: *Make systematic measurements of black carbon and/or elemental carbon. Such measurements should not replace or reduce the existing monitoring of pollutants for which guidelines currently exist.*

The motivation for Councils and Unitary Authorities to monitor BC are threefold: a) to quantify and track changes in BC emissions (from a State of the Environment (SoE) perspective) and its impact on human health, for both national and international evaluation; b) to better understand the drivers of peak particulate matter (PM) concentrations and emission sources (i.e. source apportionment and the impact of policy interventions on BC emissions; c) to gauge the importance of BC emissions on any present or future climate obligations, particularly through current energy transitions.

Across New Zealand, historical BC monitoring data and source apportionment from receptor modelling highlight two key sources of BC: diesel vehicle emissions and domestic home heating emissions. BC concentrations vary (by time and location), with defined peaks and patterns through hour-of-the-day and season. Within urban centres, BC is dominated by diesel vehicle emission adjacent to busy roads and intersections whilst in smaller towns and residential areas, BC is dominated by domestic home heating due to the prevalence of solid-fuel burners. Due to New Zealand's geography, there is a north-south increase in domestic home heating use. Concentrations remain elevated due to unfavourable topography and associated meteorological conditions, especially in the cooler months. Given these differences in BC emissions, a range of monitoring strategies are likely to be appropriate, given the various population sizes of regulatory authorities, funding and variations in emissions sources.

Internationally, the extent of BC impact is not fully understood due to limited continuous monitoring data and inconsistencies in monitoring methodologies. BC measurement is defined by optical methods consisting of light transmission or reflectance techniques. Optical methods can include online instruments such as aethalometers or offline instruments like reflectance or multi-wavelength transmissometers which can take measurements from filters. However, variability in instrument algorithms can lead to varying results. Care must be taken to understand instrument variability, with co-location seen as an important step.

One large benefit of aethalometers is their ability to differentiate between sources in real-time. This enables regulatory authorities to resolve and evaluate the impact of various emission sources (e.g. diesel vs domestic home heating emissions) at different locations, times of the day and seasons. This information can be crucial for understanding PM emission sources and tracking the effectiveness of targeted policy and mitigation practices pertaining to specific activities.

The size of the jurisdiction and current understanding of emissions sources will determine the approach to monitoring. For small regions, there are two options: a) an online, seasonal survey with a multi-wavelength aethalometer or b) an offline seasonal survey using a filter sampler and offline BC assessment methods. For larger cities, it is recommended that continuous measurement of BC is undertaken with a multiwavelength aethalometer at peak PM sites. For regions unable to perform dedicated BC monitoring, sampling being undertaken for regulatory PM monitoring can be sent to a lab for offline, post-sampling analysis.

Feedback from regulatory authorities highlighted that a number are already performing BC monitoring as part of their ongoing regulatory monitoring or have performed screening surveys during peak PM concentrations. A number of authorities are planning to commence or expand monitoring in the coming years although note key barriers being a lack of a standard, guidance on how to monitor and process their data, funding and limited skills and knowledge sets within their current teams. They also highlighted the lack of a $PM_{2.5}$ standard and would like to see more traction in this area before progressing BC monitoring.

As the literature continues to grow, defining the impact of BC on human health and the environment, there is motivation for Councils and Unitary Authorities to monitor BC. Across New Zealand, the sources of BC are understood but continuous, online monitoring is limited. This is further highlighted by the lack of local emissions factors and inventories for BC.

1. Introduction

Black carbon (BC) is a measurement property of atmospheric aerosols derived from combustion associated activities (primarily fossil fuel and biomass burning) due to incomplete combustion, synonyms include 'soot' or light absorbing carbon (LAC). BC has a negative impact on human health with links to increased hospital admissions, reduction in healthy life years and increased mortality (Luben et al., 2017). It also has impacts on the Earth's climate system acting as a short-lived climate forcer.

Within New Zealand the extent of the impact of BC is not fully understood due to limited data and inconsistences in monitoring methodology. There is a need to understand what monitoring methodology is most widely accepted and would be appropriate for the regulatory monitoring of BC.

This report details the feasibility of monitoring BC for Regional Councils and Unitary Authorities. The scope of work, methodology and report structure are detailed below. This includes engagement with regional Councils and Unitary Authorities as well as international experts.

1.1. Scope of Work

Mote Limited was contracted to deliver a report on monitoring BC in New Zealand. The following questions were posed and will be addressed in the following chapters.

1. How BC should be defined for monitoring purposes?
2. How practical is it (for Regional Councils) to monitor BC?
3. What are the estimated costs of monitoring BC?
4. How should BC monitoring be linked in with existing monitoring?
5. What will BC monitoring provide that existing council air quality monitoring doesn't (e.g. value/benefit of BC monitoring)?
6. A summary of BC emissions factors applicable to New Zealand and identification of gaps/further work needed.
7. What are the recommended next steps for monitoring BC in New Zealand?

1.2. Report Structure

The report is comprised of eight chapters and can be broken down as follows:

1. Chapter 2 defines BC, detailing its sources, properties and impacts on human health and climate. This chapter builds a case for measuring BC in a systematic manner.
2. Chapter 3 describes the various ways in which BC can be measured and recommends appropriate techniques for regulatory measurement. It also highlights various instrumental techniques and the significant benefit of real-time source apportionment offered by multi-wavelength aethalometers.
3. Chapter 4 investigates implementing BC monitoring in New Zealand. It describes the local sources of BC, the current locations of measurement and presents historical data. This chapter also details which regulatory authorities are planning to monitor BC and the associated costs to measure BC using various instruments.
4. Chapter 5 presents the benefits of monitoring and what other pollutants should be measured alongside BC.
5. Chapter 6 presents emissions factors and inventories for BC whilst comparing them with long-term trends from monitoring data.
6. Chapter 7 provides a summary and synthesis of the report.
7. Chapter 8 details knowledge gaps and recommendations.

The appendices provide more detailed information on relevant sections.

1.3. Engagement with Councils, Unitary Authorities and International Experts

As this work is reporting on the feasibility of monitoring a new pollutant in airsheds across New Zealand, an integral part of this report was to engage with New Zealand Regional Councils, Unitary Authorities and international experts. For Council engagement, this process involved circulating a questionnaire (Appendix 1) which was then followed up with short interviews. Responses from the questionnaire are included throughout the report. We achieved a high response rate from respective regulatory authorities. From the initial survey, 12 out of 16 Councils responded. For the follow up short interview, we had engagement from 15 Councils. Engagement with international experts was conducted via virtual interviews to gather relevant information pertaining to industry standards, guidelines and monitoring methodology.

2. Why Measure Black Carbon?

This chapter introduces how BC is defined, describes its sources and the physio-chemical properties of BC, its effects of human health and the environment. This chapter also highlights the lack of guidelines in New Zealand and the need for systematic measurement.

2.1. How is Black Carbon defined?

Black carbon is a term given to soot-like atmospheric aerosols that consist of (almost) pure carbon in several linked forms, and which is formed through the incomplete combustion of carbonaceous fuels. BC is a common constituent of airborne particulate matter (PM) and is a global environmental problem that has impacts on human health and the environment (Janssen et al., 2012). BC is not to be confused with other carbonaceous aerosols. Total carbon (TC) aerosol mass is comprised of three parts: organic carbon (OC), inorganic carbonates (IC) and the third fraction is referred to elemental carbon (also: BC, soot, refractory carbon) (Petzold et al., 2013). There is ambiguity around a strict definition of BC depending on specific disciplines and the measurement techniques employed (Savadkoohi et al., 2023; Shu et al., 2023).

Bond et al. (2013), defined BC as being characterised by carbonaceous material that:

1. Strongly absorbs visible light with a mass absorption coefficient of 5 $m^2 g^{-1}$ at a wavelength of 550 nm.
2. Is refractory and retains its basic form at high temperatures, with a vaporization temperature near 4000 K.
3. Is insoluble in water, in organic solvents and other atmospheric aerosols.
4. Exists as aggregates of small carbonaceous spherules.

For the purposes of this report, BC refers to the light and heat absorbing component of atmospheric aerosols, and is resistant to chemical transformation (Petzold et al., 2013; Savadkoohi et al., 2023). BC can have different physical and chemical properties depending on combustion source and combustion temperature, giving rise to differing optical light-absorbing properties (Janssen et al., 2012; Manohar et al., 2021). BC measurement can be accomplished through a variety of methods and technologies that measure its concentration in the air, though the most commonly used approaches employ either thermal/optical methods or absorption photometry. The measurement of BC is further explained in Chapter 3.

2.2. Sources of BC

Globally, there are a variety of BC sources. These include: the combustion of fossil fuels (especially diesel engines), domestic home heating due to the burning of wood and coal, power generation using fossil fuels (coal, heavy oil), agricultural field burning, forest wildfires as well as aviation (Janssen et al., 2012; Helin et al., 2018; Correa-Ochoa et al., 2023).

The primary sources can vary from region to region, but across New Zealand, the primary sources of BC include those emitted from the combustion of fossil fuels and domestic home heating (Ancelet et al., 2013; Crimmins et al., 2019; Patel et al., 2020). The sources of BC in New Zealand are further explored in Section 4.1.

2.3. Physio-Chemical Properties of Black Carbon

The size range of BC particles has been well characterised across a variety of emission sources both in New Zealand (Davy et al., 2007; Ancelet et al., 2011a, 2011b; Davy et al., 2012; Salako et al., 2012; Ancelet et al., 2013; Trompetter et al., 2013) and internationally (Ke et al., 2007; Schneider et al., 2008; Lack et al., 2009; Hays et al., 2011; Lopez-Reyes et al.,

2016). Due to the formation process, fresh BC is usually comprised of individual carbonaceous spheres in the ultrafine range (between 10-30 nm in diameter). They can agglomerate to form larger particles between 300-500 nm in diameter. BC is formed due to the incomplete combustion of fossil fuels and biomass, in anoxic environments and under high temperature conditions (Shrestha et al., 2010; Marina-Montes et al., 2022).

The characteristics of the combustion source have an important bearing on particle size and carbonaceous composition. High temperature combustion conditions (diesel engines, power stations) produce smaller, graphitic carbon particle entities (Allen et al., 2001; Huang et al., 2006; Ancelet et al., 2011a; Hung et al., 2014). Lower temperature biomass combustion (wood fires for home heating, wildfire, forest fires) produce a mixture of carbon agglomerations and larger particles (500 – 900 nm) composed of a soot core and coated in organic 'tar' from incomplete combustion (Pósfai et al., 2003, 2004; Davy, et al, 2007).

The physio-chemical properties of particles, (particle shape, size, refractive index and aerosol mixing state within the sample) is dependent on source and location of the source and plays an important role in determining the methods employed to measure BC.

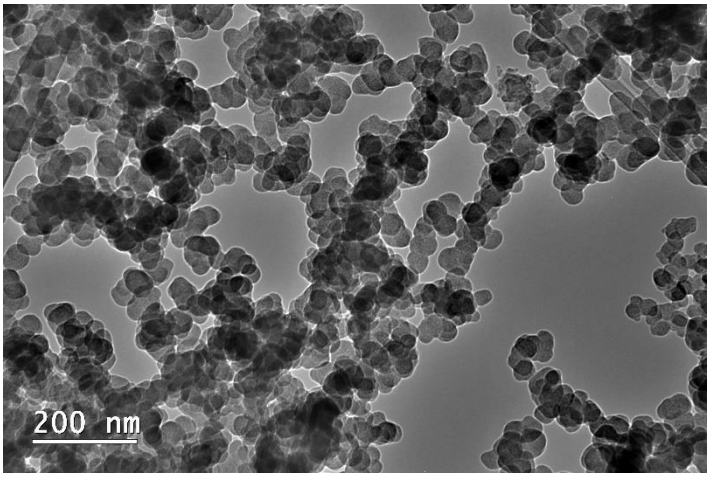

Figure 1: Transmission electron microscopy image of carbonaceous particle agglomerations from biomass combustion (the white scale bar at the bottom left spans 200 nm) (Source: (Davy and Ancelet 2015).

2.4. Health Effects

There is an expanding body of evidence associating negative health impacts with exposure to BC. Due to the small size of BC (usually emitted in the ultrafine fraction with agglomerations in the sub-micron range BC can be inhaled deep into the lungs providing direct access to the blood stream and be transported around the body. BC exposure has been associated with increased respiratory and cardiovascular disease, with increased rates of hospitalization and mortality, along with a significant decrease in healthy-life years (Janssen et al., 2011, 2012; Sharma and Kumar, 2018). Janssen et al. (2011) also concluded in their review that a 1 μg m^{-3} mass increase in BC led to an eight-fold increase in all-cause mortality.

There is increasing evidence for adverse health impacts that are stronger for exposure to BC than for $PM_{2.5}$ (Janssen et al., 2011; Grahame et al., 2014). Studies investigating the toxicological impacts of BC suggest BC may function as a carrier for other toxic chemicals around the body (Janssen et al., 2012; Ezani et al., 2021). Multiple epidemiological studies highlight the positive association between exposure to BC and increased blood pressure, changes in heart-rate variability, oxidative stress and cognitive disfunction (Louwies et al., 2015; Laeremans et al., 2018; Bista et al., 2023). The national burden of BC related health

effects in the United States has been estimated at approximately 14,000 deaths per year (2010 BC levels), and hundreds of thousands of illness cases, ranging from hospitalizations and emergency department visits to minor respiratory symptoms (Lie et al., 2016).

Although New Zealand has no published health related statistics linked to BC, a recent study found that health impacts associated with $PM_{2.5}$ (of which BC is a significant proportion (~40% in Auckland)) is responsible for 1,292 premature deaths and 1.7 million restricted activity days across New Zealand (Kuschel et al., 2022; Boamponsem et al, 2024).

2.5. World Health Organization 2021 Air Quality Guidelines Update

In 2021, WHO released an update of their air quality guidelines (AQG), the first major update in 15 years. Although there were updates to the other criteria air pollutants, a guideline for BC was not introduced due to insufficient evidence to propose an AQG level. To address concerns about the impacts of BC/EC on environmental and human health, three good practice statements were formulated:

1. *Make systematic measurements of black carbon and/or elemental carbon. Such measurements should not replace or reduce the existing monitoring of pollutants for which guidelines currently exist.*
2. *Undertake the production of emission inventories, exposure assessments and source apportionment for BC/EC.*
3. *Take measures to reduce BC/EC emissions from within the relevant jurisdiction and, where considered appropriate, develop standards (or targets) for ambient BC/EC concentrations.*

2.6. Environmental Impacts and Atmospheric Lifetime

Due to its physio-chemical form, BC plays an important role in the Earth's climate system. While most aerosols in the atmosphere scatter incoming solar radiation, resulting in a net cooling effect on the atmosphere, BC absorbs significantly more light than it reflects, resulting in a net warming effect. The magnitude of the positive radiative forcing from BC is reported to be third only to CO_2 and CH_4 (IPCC, 2023). It is noted that there remains significant uncertainty in quantifying the radiative forcing of BC aerosols due to uncertainty in scattering coefficients of the aerosol (Wu et al., 2018, 2019; Sun et al., 2019).

When BC is deposited on, or precipitated with snow, it lowers the albedo (reflective properties) and the absorbed light heats the snow causing it to melt. This has important implications for permanent snowpack such as the Himalayan, Arctic and Antarctic regions (Bond et al., 2013; Santos et al., 2014; Spohn et al., 2022; Cuesta-Mosquera et al., 2024).

Reduced visibility is common in cities due to haze formation from air pollutants. The primary cause of haze is fine particles ($PM_{2.5}$) (Lei et al., 2021; Marley et al., 2021), of which, BC is a core constituent. Particles within the atmosphere reduce visibility by scattering and absorbing incoming solar radiation (Kirchstetter et al., 2004). The scattering and absorption of visible light from BC particles is further enhanced due to its physical size and colour (i.e. BC particle size is comparable to the wavelength of visible light and dark in colour). Many of New Zealand's cities and towns experience reduced visibility due to haze. Smaller towns experience reduced visibility due to high BC emissions (from domestic home heating) whilst Auckland experiences episodic 'brown haze' events associated with high concentrations of $PM_{2.5}$ (of which ~40% is BC) and nitrogen dioxide (NO_2) from motor vehicle emissions (Marley et al., 2021; Boamponsem et al, 2024).

Due to BC's small size, and its ability to be transported and dispersed over long distances, it has wide-ranging effects on visibility and climate. The atmospheric lifetime of BC is estimated

to be in the order of days to weeks. A number of parameters influence the atmospheric lifetime of BC including the emission source (which also dictates composition and internal chemical mixing), the emission height, local meteorology and atmospheric circulation patterns. An important removal mechanism of BC from the atmosphere is wet deposition (Park et al., 2005; Cape et al., 2012). Due to its relatively 'short' atmospheric lifetime, the management of BC emissions is seen to be a prime candidate for near-term reduction in positive climatic forcing (Park et al., 2005; Jacobson, 2010; Sasser and Chappell, 2011; Cape et al., 2012; Smith and Mizrahi, 2013).

2.7. Current Standards and Guidelines

As stated in Section 2.6, the WHO has not formally introduced an air quality guideline (AQG) for BC. This is mirrored around the world with no current guidelines or target values for ambient BC in any jurisdiction. The absence of guidelines is largely due to a historical lack of consistent methodologies and long-term modelling (Tobías et al., 2018; Crimmins et al., 2019; Nie et al., 2022; Savadkoohi et al., 2024). The exception is occupational workplace exposure limits which are outside the scope of this report.

In 2017, the European Committee for Standardisation (CEN) released a standard for a coherent approach in the analysis of carbonaceous aerosols. *EN16909:2017 - Ambient air - Measurement of elemental carbon (EC) and organic carbon (OC) collected on filters*. Although the standard does provide a detailed methodology for the analysis of EC and OC from quartz filters, the standard does not provide a guideline or target concentration for regulatory air shed management.

In 2024, the European Parliament tightened its regulations to align with the updated 2021 WHO AQG (Directive 2022/0347/COD). It suggests monitoring of BC and ultrafine particles to support understanding of their impacts on the environment and health. It also suggests the use of monitoring supersites to gather continuous long-term data for criteria pollutants, and unregulated emerging contaminants, such as BC and ultrafine particles.

3. Measuring Black Carbon and Recommended Techniques

This chapter describes the different methods for measuring BC and how the light absorbing properties of BC are used (by the instrumentation) to infer BC mass. Different types of instrumentation are discussed with real-time source apportionment being a key benefit of aethalometers measuring BC.

3.1. Measurement Techniques

There are three quantitative methods for characterising combustion particles based on the physio-chemical properties described in Section 2.3. The three methods include Thermal Optical Analysis (TOA), Optical Methods (OM) and Light-Induced Incandescence (LII). Appendix 2 provides an in-depth description of the three methods with advantages and disadvantages. However, a synopsis of the three methods is below:

- Thermal optical analysis (TOA) is ideally suited for differentiating between elemental carbon and organic carbon by heating the sample in different atmospheres (oxidising/non-oxidising) and analysing the gases released at different temperatures. This method is best for in-depth analysis of the different types of carbon collected on a sample but requires complex lab analysis of samples.
- Optical methods are ideally suited for measuring the amount of BC on a filter. This method can be employed in offline or online continuous measurement. It works by measuring the attenuation of light (of different wavelengths) through a filter. The light attenuation is indirectly converted to a mass of BC using a mass absorption coefficient (MAC); discussion on MAC is detailed in Section 3.2.
- Laser induced incandescence takes a sample on a filter where it is heated rapidly to achieve gasification. A mass of BC is determined by the intensity of the signal measured by instrumentation. Like the TOA method, this method requires complex lab analysis techniques.

Selection of the most appropriate method will depend upon the purpose of the BC monitoring programme. Whilst TOA and LII are used globally to measure carbonaceous species (measuring OC/EC), they are not be suitable for the real-time measurement of BC within regulatory applications due to their complex and expensive setups, high uncertainties at low concentrations, as well as their inability to measure BC (Zhang et al., 2023). TOA and LII are most appropriately included in a list of techniques that are classified as ‘research’ or ‘forensic’ techniques. Other techniques in this list include Raman Spectroscopy, Scanning Electron Microscopy and Aerosol Mass Spectrometry, Transmission Electron Microscopy and are not commonly used for the long-term determination of BC for regulatory applications. These techniques are outside the scope of report, and we will focus on optical methods moving forward.

Optical methods utilising light absorption are an internationally recognised and accepted method of measuring BC for both offline and continuous online measurement. Due to the physio-chemical properties, BC absorbs strongly in the visible light spectrum, with much less absorption from other primary aerosols such as soil, sea salt and secondary aerosols (sulphates, nitrates and organics).

Various subsets of BC sources, such as biomass burning, and fossil fuels (among others) may be distinguished by light absorption ratios at different wavelengths, thereby allowing the contribution from different combustion sources to be assessed from monitoring data. In this way, the instrument can infer the source of the BC emissions; this is further examined in Section 3.4.

3.2. Mass Absorption Coefficient (MAC)

Optical methods utilise a MAC to indirectly infer BC mass from light attenuation measured from a sample (Bond and Bergstrom, 2006; Bond et al., 2013; Grange et al., 2020; Zhang et al., 2023). MAC is dependent on the physio-chemical properties of the particles which varies due to source and location. Throughout the literature, MAC values have been known to vary significantly due to particle age, location, sources and time of year (Grange et al., 2020; Savadkoohi et al., 2023). This is important to understand as most OM instruments employ a fixed MAC; this is understood to be a significant source of uncertainty in the determination of BC concentrations. This assumption only holds for BC particle sizes less than λ/π where, λ is the wavelength of the absorbing light and π represents a constant of ~3.142 (Horvath, 1997; Manohar et al., 2021).

The UK Department for Environment, Food & Rural Affairs (DEFRA) have noted that different instruments and changing algorithms have impacted their data and are currently working to find a solution to make their data comparable (Ciupek et al., 2022). Some Councils and international experts also highlighted this discrepancy which is further validated in the literature.

3.3. Filter Artifacts

Filter artifacts are an important consideration with filter-based absorption measurements (both online and offline). There are three main artifacts to consider. These are 1) multiple scattering; 2) aerosol backscattering; 3) the loading effect (Table 1) (Bond et al., 2013; Ferrero et al., 2021).

Table 1: The three main filter artifacts associated with filter-based optical measurements.

Artifact	Description
Multiple Scattering	Enhanced light attenuation and optical path scattering by filter fibres.
Aerosol Backscattering	Light attenuation due to scattering by aerosols embedded in the filter.
The Loading Effect	The non-linear optical path reduction induced by absorbing particles accumulated in the filter.

Most instruments deal with these artifacts internally (through instrument algorithms). Therefore, it is important to understand how your instrument applies its correction (especially when comparing data from different instruments or changing instrument types (make/model/firmware) at a site.

3.4. Instruments for the Measurement of Black Carbon

There are a number of commercially available BC optical instruments. These include offline measurements that can make reflectance or transmission measurements using filters collected from a separate PM measurement system or online (continuous) measurements from in-situ devices such as aethalometers. These are described in further detail in this section.

3.4.1. Offline Measurements

Offline measurements are made from pre-collected ambient air samples which have been collected using a separate PM sampling system (such as a Thermo Partisol or MetOne E-SEQ Sampler). The filter is then returned to the lab where post-sampling analysis takes place. The mass of BC is determined using an instrument such as the Smoke Stain Reflectometer (SSR) or the Multi-wavelength Absorption Photometer (MABI). The SSR (white light, average wavelength of 550 nm) is still widely used for determining BC mass, however, has several limitations in that it cannot be used to assess sources of BC. The MABI is a relatively new instrument, operates at 7 different wavelengths, and provides the ability to perform source apportionment. As the instrument utilises light transmission, it is important that pre-sampling measurements are made prior to sampling. Most co-location data is linearly correlated, with changes in slope or intercept largely a result of variations in the MAC. For offline measurements care should be taken when handling filters.

3.4.2. Online Measurements

Online measurements are made using an automated instrument which provides data in near real-time. In this instance, an instrument (such as an aethalometer) samples PM onto a filter tape. The instrument measures the attenuation of light at either single or multiple wavelengths through the tape. The instrument then calculates the mass of BC using a predefined MAC set in the instrument software. Online instruments include the Aethalometer (AE) – (single and multi-wavelength), the Multi-Angle Absorption Photometer (MAAP) and the Particle Soot Absorption Photometer (PSAP). The Magee AE33 is the most commonly cited instrument throughout the literature and commonly used for instrument intercomparisons. AE are produced by several other manufacturers including, MetOne, Aethlabs and ThermoFisher. Table 2 highlights some of the advantages and disadvantages of various optical measurement methods for determining BC.

Table 2: Advantages and disadvantages of various optical measurement methods for determining BC.

	Filter-based	Multi Wavelength Aethalometer	Dual Wavelength Aethalometer	Single Wavelength Aethalometer	Low-cost /Portable /Handheld
Number of wavelengths measured	Varies	3 – 8	2	1	Varies (between 1-5)
Wavelengths measured (nm) (can vary)	Broadband,405, 465, 525, 639, 870, 940, 1050,	370, 470, 520, 590, 660, 880, 950	370, 880	870	370, 470, 520, 625, 880
Capital Expenditure	$$	$$$$	$$$	$$	$
Operating cost (consumables)	$	$$$	$$	$$	$$
Operating cost (labour)	$$$$	$	$	$	$$$
Minimum useable time resolution	Depends on PM sampling system (hourly possible)	Sub-hour	Sub-hour	Sub-hour	Sub-hour
Enclosure needed?	No	Yes	Varies	Varies	Yes
Ease of data telemetry	N/A	Good	Good	Good	Moderate
Size selective inlet option	Yes	Yes	Yes	Yes	Yes
Operator skill level required	Low	Moderate	Moderate	Low	Low
Source Apportionment	Yes	Yes	Yes	No	Sometimes

3.5. Source Apportionment

Source apportionment is a process which identifies sources of various air pollutants at a particular location providing useful information for policymakers to formulate and implement BC emission mitigation strategies.

As outlined by Kirchstetter et al. (2004) BC from biomass burning has a different spectral dependency than that produced from motor vehicle tail-pipe emissions. Low temperature combustion processes (such as biomass burning) produce aerosols that exhibit much stronger spectral dependence than those produced by high temperature (diesel tail-pipe emissions). This has been further confirmed throughout the literature (Sandradewi et al., 2008; Grange et al., 2020). BC from fossil fuel sources, such as diesel exhaust emissions absorb over the whole visible and near-infrared (nIR) wavelengths (~600 nm – 950 nm) whilst emissions from biomass burning, which contain other LAC, absorb more strongly at the ultraviolet (UV) and low visible wavelengths (~300 nm – 500 nm) (Kirchstetter et al, 2004; Grange et al., 2020).

This spectral dependence is useful for real-time source apportionment of biomass and vehicle traffic combustion sources utilised by multi-wavelength instrumentation. Attenuation of nIR and UV light can be used to apportion BC mass to either biomass or fossil fuel combustion using pre-defined MAC's. This is often referred to as the 'aethalometer model' and been used widely (Sandradewi et al., 2008; Healy et al., 2017; Mousavi et al., 2019; Nie et al., 2022).

Figure 2 presents data from the aethalometer at the Henderson, Auckland air quality monitoring station. The aethalometer model for apportioning BC to biomass or fossil fuel combustion clearly distinguishes between traffic and domestic home heating emissions at this location. During summer, when domestic home heating emissions are low/negligible, there is no deviation between the 370 nm and 880 nm channels. As time progresses through autumn and winter, the impact of domestic home heating in the morning and evening is observed being greatest in the winter, when domestic home heating emissions peak, evidenced by much larger deviation between the two channels in winter are limited.

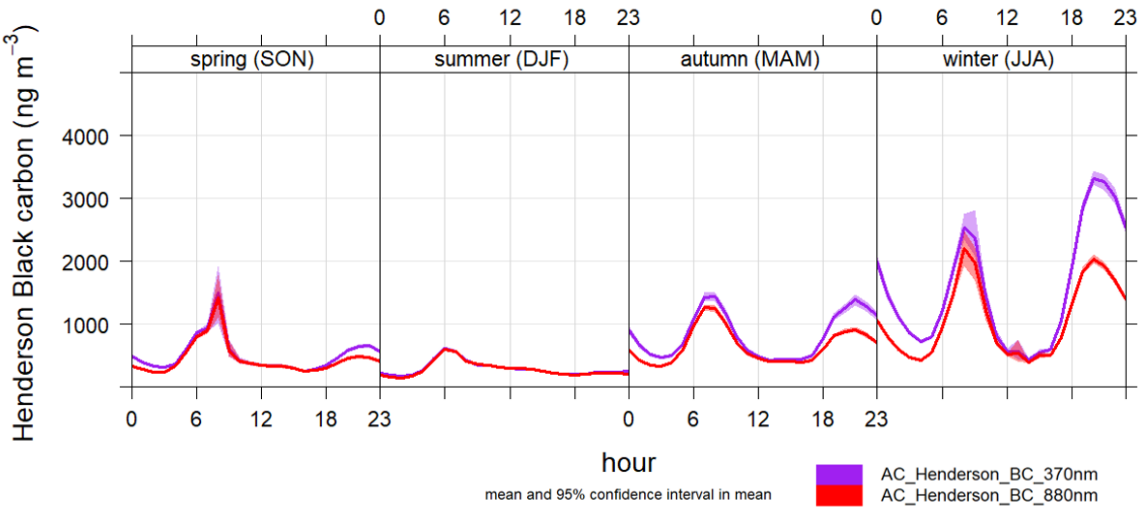

Figure 2: Data from the aethalometer at the Henderson air quality monitoring station presented over hour-of-day and month-of-year. The purple line represents the ultraviolet channel, whilst the red line represents infrared channel.

While offline measurement techniques offered by reflectometry can quantify mass of BC, they are unable to apportion sources. Instruments like the MABI do offer a solution to offline measurement source apportionment, however online instrumentation like multi-wavelength photometers offer superior time resolution of BC as well as source apportionment (Helin et al., 2018); this is one significant advantage of the aethalometer. During stakeholder engagement for this review, source identification was highlighted as one of the primary objectives of current monitoring programmes from regulatory authorities currently monitoring BC.

A benefit of offline measurements is their ability to be archived and analysed at a later date. They can also be analysed via gravimetry to determine the amount of PM in the air and further analysis may be undertaken using techniques such as ion beam analysis, x-ray fluorescence spectroscopy, scanning electron microscopy and Raman spectroscopy for the determination of particle sources using source apportionment.

3.6. Sample Stability and Size Fraction Dependence

Black carbon concentrations in PM samples collected on filters have been determined by the same methodology across all sample sets held by GNS Science since 1996. Full descriptions of the light absorbance measurement methodology and derivation of BC concentrations are provided in Appendix 3. A remarkable feature of BC is the stability of measured concentrations even after years of storage. Figure 3 presents a plot of BC concentrations on filters from several Auckland sites and Hastings that were measured in 2007 and then again in 2016 and 2023 respectively after being stored in the meantime (individual petri dishes in cardboard boxes at room temperature). The Auckland sites are dominated by BC from motor vehicle combustion emissions (Davy and Trompetter, 2019) whereas the Hastings site is dominated by BC emissions from solid fuel fires for domestic home heating in the winter (Davy and Trompetter, 2023).

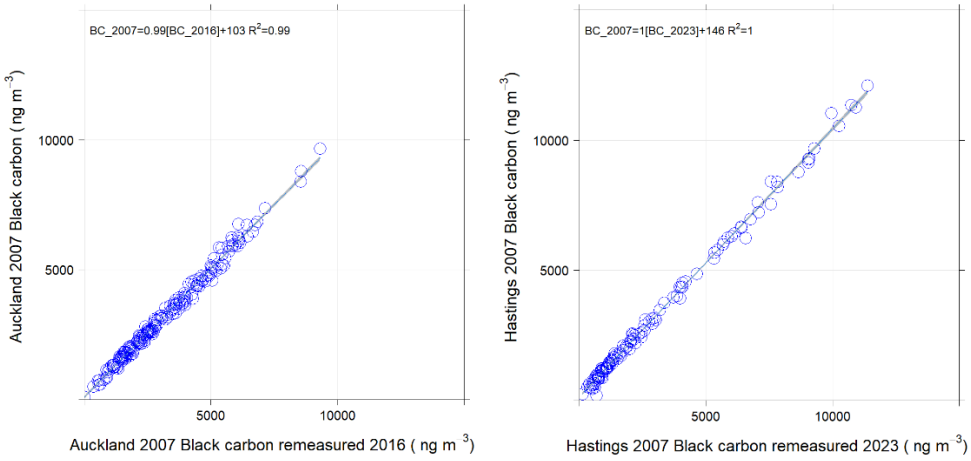

Figure 3: Comparison of BC measurements on the same filters after 10 years in storage.

The simultaneous monitoring of the two size fractions at several locations has provided the opportunity to directly compare component species for coincident samples. For BC, concentrations in both $PM_{2.5}$ and PM_{10} were found to be essentially the same (slight differences are due to measurement uncertainty), as presented in Figure 4. This is expected since BC particles are smaller than 2.5 microns and are entirely contained in the $PM_{2.5}$ fraction (a subset of PM_{10}). Therefore, when discussing BC concentrations from different sampling campaigns we can reasonably intercompare results for PM_{10} and $PM_{2.5}$ sampling.

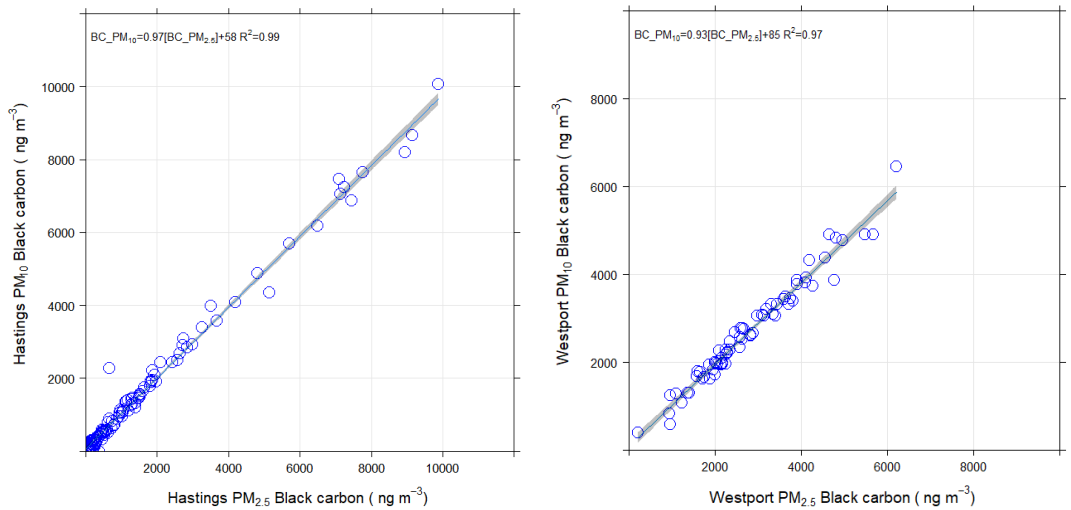

Figure 4: Black carbon concentrations in $PM_{2.5}$ versus PM_{10} samples from (Left) Hastings during 2022 and (Right) Westport during winter 2023. (Source: Davy and Trompetter 2023, 2024).

4. Implementing Black Carbon Monitoring in New Zealand

This chapter investigates implementing BC monitoring in New Zealand. It describes the local sources of BC, the current and historical locations and measurements. This chapter also details which regulatory authorities are planning to monitor and the associated costs to monitor using various methods.

The flow chart below (Figure 5) describes under what circumstances different techniques could be applied and the justification for this. It is noted that a basic, off-line BC analysis can already be implemented using existing PM monitoring equipment, such that for populations of < 30,000 the motivation for additional, dedicated BC monitoring may be of limited benefit.

The population thresholds selected are defined by Statistics New Zealand *Functional Urban Area (FUA)* classifications (Stats NZ, 2021). FUA's with more than 100,000 residents are classified as metropolitan areas whilst FUA with less than 30,000 residents are grouped into regional centres (small, medium and large) (Stats NZ, 2021). The three sizes of regional centres are not referred to in this report.

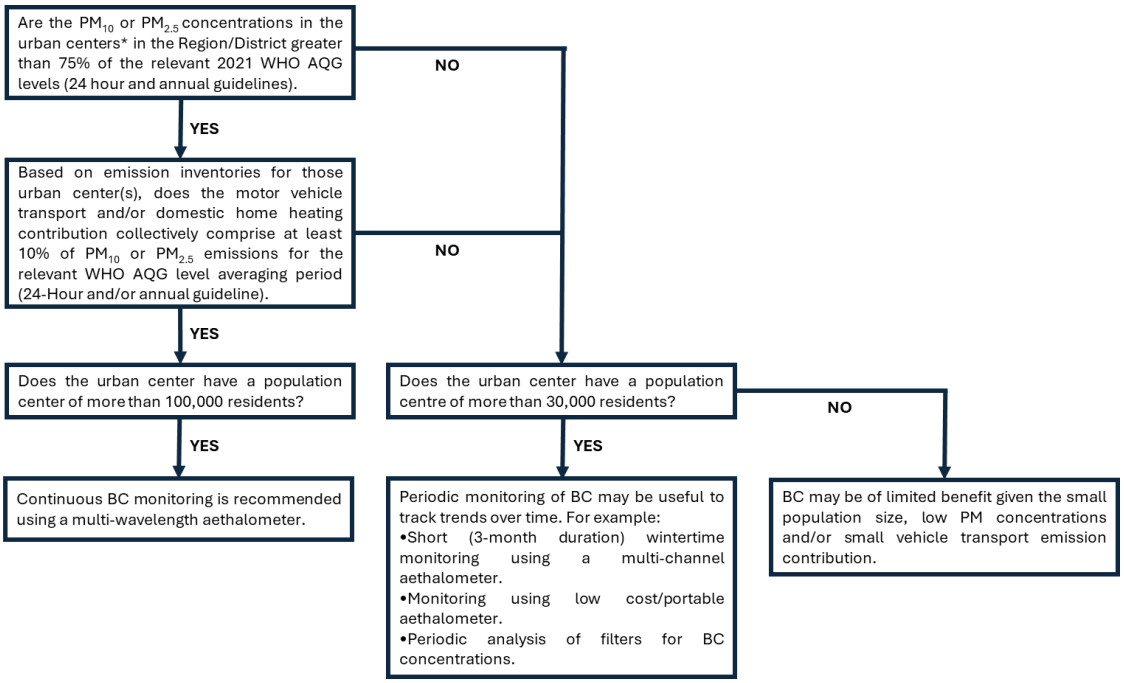

Figure 5: A flow chart describes under what circumstances different techniques could be applied and the justification for this.

4.1. Sources of Black Carbon in New Zealand

Most of the global sources outlined in Section 2.3 are also present in New Zealand, however, agricultural waste burning (stubble or scrub and tree burn offs) are intermittent and more seasonally based. Historically, thermal power stations burning fossil fuels were generally only brought into the network if necessary to cover peak power usage and this is most likely during winter or when hydro-lake storage levels are low, however emissions from thermal power stations have become more common over the past 12 months due to increased use (Ministry of Business, Innovation and Employment, 2024). While forest and vegetation wildfires can release significant quantities of BC and other pollutants to atmosphere, such (accidental) fires are relatively rare and are generally aggressively managed and extinguished to prevent loss of life, property damage and to protect the forestry estate. Occasionally, New Zealand does experience the downwind effects due to emissions from Australia bushfires (Davy and Trompetter, 2020). Another category of combustion sources emitting BC are those stationary industrial heat generation plant used for manufacturing or processing and localised emergency power generation (primarily diesel powered) used to support essential facilities and services during interruptions to normal electricity supply networks.

4.2. Existing Black Carbon Monitoring in New Zealand

BC is currently being measured using a variety of different techniques around New Zealand using various online, in-situ measurements as well as offline, filter-based techniques.

4.2.1. Online Measurements

Online continuous measurement of BC is currently being undertaken at 6 sites across New Zealand. Four permanent instruments are located in major urban centres (two in Auckland) and are identified in Figure 6 (in blue). The fifth and sixth locations are temporary instruments located in Ashburton and Arrowtown respectively. All locations utilise the Magee AE33 except for Auckland's Customs Street which utilises the MetOne 1060.

4.2.2. Offline Measurements

Black carbon samples have been collected and analysed at approximately 40 sites across New Zealand, with some urban areas including multiple sites. For example, Auckland BC data includes sites at Takapuna, Henderson, Kingsland, Newmarket (Khyber Pass Road), Auckland CBD (Queen Street), Penrose and Patumahoe (40 km southwest of the CBD) as well as a sampling campaign in the Johnstone Hills tunnel north of Orewa (Davy et al., 2011a, 2014, 2017; Davy and Trompetter, 2019; Boamponsem et al, 2024).

Sites where PM has been collected for BC analysis also included PM elemental speciation with the accompanying receptor modelling and reporting. Figure 6 presents the BC sampling locations in New Zealand to date. Appendix 4 identifies the specific locations, sampling period and reporting details. Several of the PM compositional monitoring campaigns have been only during winter months in order to understand source contributions to peak winter PM concentrations for air quality management purposes.

Figure 6: Black carbon sampling locations in New Zealand. Sites in BLUE indicate continuous permanent monitoring locations, while sites in RED are collecting continuous BC data from temporary locations. Sites in BLACK and BLUE indicate the locations where offline (filter-based) measurements have been collected.

In addition to the urban monitoring locations, several studies have targeted source specific BC, these include motor vehicle tunnels (Ancelet et al., 2011a; Davy et al., 2011a) and wood burner emissions (Davy et al., 2009; Ancelet et al., 2011b) to better understand emission source characteristics including BC emissions. Most of the BC sampling and analysis campaigns have been targeted studies collecting 24-hour time integrated samples that ran for 1-2 years in order to better understand the local drivers of air pollution for air quality management purposes. The exception to this is the Auckland multi-site air particulate matter speciation database that has been running since mid-2004 and, using archived filters, the BC measurements have been extended back to 1998 at some sites providing a 25-year BC dataset. A 10-year dataset has also been compiled for Nelson monitoring sites (Nelson South and Tahunanui).

For several locations, high-resolution sampling (hourly) and analysis was undertaken as part of a research programme to better understand the observed diurnal variation in particulate matter concentrations at New Zealand urban centres (Trompetter et al., 2010; Ancelet et al., 2012, 2014a, 2014b).

4.2.3. Monitoring results from New Zealand

As discussed in Section 4.2.2, most of the BC datasets extend only for 1-2 years except for the Auckland, Wellington and Nelson sites where up to 20 years of continuous BC data is available. Figure 7 presents the BC concentration data from monitoring sites across New Zealand where at least one year of sampling was undertaken to cover concentration variations across the seasons.

High concentrations of BC are located in areas with high vehicle use (major urban centres like Auckland) and regions reliant on domestic home heating (evident in the North - South increasing gradient. Historical exceedances of the WHO $PM_{2.5}$ AAQG in Takapuna, Penrose, Christchurch and Timaru can wholly be attributable to BC. For further detailed analysis please refer to *Heavy metals, black carbon and natural sources of particulate matter in New Zealand* (Davy and Trompetter, 2018).

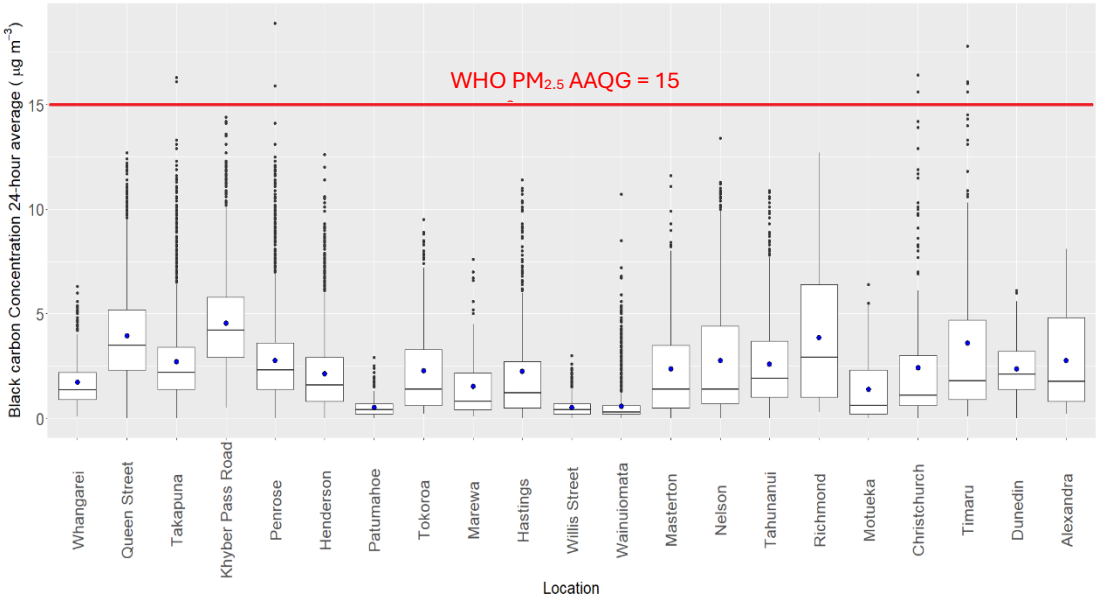

Figure 7: Filter-based offline BC concentrations measured at NZ monitoring locations. The red line represents the WHO $PM_{2.5}$ AAQG of 15 µg m^{-3}.

4.2.4. Future Black Carbon Monitoring

As part of this report, a questionnaire was sent to all regional Councils and Unitary Authorities in New Zealand. A summary of responses is attached as Appendix 5 and is summarised below:

- Of the 16 Councils who responded, 10 are not considering permanent BC monitoring in the future.
- Auckland Council is planning to extend their current programme, adding a multi-wavelength aethalometer at Mount Victoria, Devonport in late 2025.
- The Hawkes Bay Regional Council air quality team intend to implement BC monitoring when they can secure the necessary funding and resourcing but that won't be until at least 2027/2028
- Waikato Regional Council is committed to continuous BC monitoring as part of the council's long term monitoring plan but have been waiting for more guidance around its use and recommendations on instruments, servicing and calibration.
- Otago Regional Council staff believe it would be beneficial to monitor at 3 or 4 of their air quality monitoring stations but due to cost and lack of guidelines and standards is unlikely to be a priority compared to other air quality monitoring projects.
- Environment Canterbury will consider monitoring BC in more areas if existing data show it is useful for tracking change in combustion emissions and for differentiating between sources.

4.3. Cost to Monitor Black Carbon

This section describes the costs associated with monitoring BC with online and offline measurements. Costs have been broken down into capital expenditure (CAPEX), and annual operating expenditure (OPEX) (consumables and labour) for implementing a monitoring programme within a jurisdictional area. The associated costs are estimates as of May 2024 and will be subject to change due to inflation, currency fluctuations, changes in the price of goods, and in costs associated with time attributed to tasks (e.g. filter changes, maintenance). Travel expenses are not included. Labour costs associated with tape replacement and servicing and operation of the instrument have been estimated at one day per quarter.

These costs assume an existing air-conditioned monitoring location with mains power available to house the instrument and that the digital output can be coupled to an existing data logger at the site. Costs do not take into consideration the time already allocated to perform maintenance on other equipment at existing stations. Low-cost/portable/handheld devices, which can sometimes be used for screening purposes have been considered in Section 4.3.3.

4.3.1. Online Instrumentation

Table 3 considers the costs of purchasing new instruments (multi or dual wavelength aethalometers along with ongoing OPEX costs which includes estimates for filter tapes, quarterly and annual servicing. Three detailed examples for multiwavelength aethalometers are also provide in Table 4. Areas with very high winter BC concentrations may require a tape change every 3 weeks. However, for most sites in New Zealand monthly changes are adequate during the winter and tapes may last up to three months during summer periods.

Table 3: Costs to purchase and operate (for one year) multi-wavelength aethalometers.

Instrument	Multiwavelength Aethalometer	Dual wavelength Aethalometer
CAPEX*	~$50,000 - $70,000	~$20,000 - $40,000
Shipping	$2,000	$1,000
OPEX (consumables)	~$4,800 - $10,000	$3,600 - $6,000
OPEX (labour, data processing, maintenance – 3 quarterly services, 1 annual service)	$5,000	$5,000

*does not include GST

These costs can be further broken down in detail for specific instruments below:

Table 4: Detailed costs to purchase and operate various common brands of multi-wavelength aethalometers.

CAPEX COST	Magee AE33 (multi-wavelength)	MetOne BC1054 (multi-wavelength)	MetOne BC1060 (dual wavelength)
Instrument	$60,000	$56,000	$30,000
Shipping	$2,000	$2,000	$1,000
GST	$9,000	$8,400	$4,500
CAPEX TOTAL	**$71,000**	**$66,400**	**$35,500**
OPEX COST	**Magee AE33 (multi-wavelength)**	**MetOne BC1054 (multi-wavelength)**	**MetOne BC1060 (dual wavelength)**
Replacement tape*	$1250 per tape, 8 per year $10,000	$600 per tape, 8 per year $4,800	$400 per tape, 8 per year $3,600
Replacement screen/filters and silicon	$200	$200	$200
Pump service kit	$350	$350	$350
OPEX (labour, data processing, maintenance – 3 quarterly, 1 annual)	$5,000	$5,000	$5,000
ANNUAL OPEX TOTAL	**$15,550**	**$10,350**	**$9,150**

4.3.2. Offline Instrumentation

Table 5 below considers the costs of purchasing offline instrumentation to perform analysis. It is assumed that an existing PM sampling instrument is available. Commonly used PM sample instruments include Thermo Partisol and the Met One E-SEQ which can collect 16 samples unattended. The primary costs associated with offline analysis include filter purchase, labour associated with filter replacement and the BC filter analysis costs. Costs include ongoing OPEX costs such as estimates for filter changes but do not include the maintenance of equipment. To implement PM sampling equipment, and for ongoing maintenance, estimates would be similar to *Multiwavelength*

Aethalometer prices in Table 3. Pre-sampled filters using could also be sent to a lab for BC analysis with cost estimates between $20-30 per filter (depending on frequency and volume). Various filter media may be used (polycarbonate, PTFE, glass fibre, quartz), however, the choice of filter will impact or determine what further analyses may be performed.

Table 5: Detailed costs to run a filter-based monitoring programme for the analysis of BC using existing PM monitoring instruments.

Sample Routine	1 day in 3 (122 filters)	1 day in 6 (61 filters)
CAPEX (MABI/SSR)	~ $10,000 - 20,000	
OPEX (filter changes (labour) – excludes travel)	$2,000 (eight site visits)	$1,000 (four site visits)
OPEX (filters) a) PTFE b) polycarbonate	 a) $2,860 b) $600	 a) $1,430 b) $300
OPEX (BC filter analysis)	$2,600 - $3,900	$1,250 - $1,950

4.3.3. Low-cost/portable/handheld

a variety of low-cost portable aethalometers are now available in the market. These range in price from $10,000 - $25,000 depending on the model. Portable instruments usually have smaller filter rolls which require extra site visits to replace them. Portable instruments may not have a weatherproof enclosure or telemetry which will add to the set-up costs. An advantage of some of these smaller portable devices is the ability to locate them on lampposts for screening assessments such as the one completed by Greater Wellington Regional Council investigating emissions from the changing bus fleet (Mitchell, 2021). However, be mindful of the added costs for traffic management and associated health and safety when installing smaller portable instruments up lampposts/near roadways due to the proximity to vehicle traffic. As these devices aren't always housed in a conditioned environment, artifacts associated with temperature and humidity may increase measurement uncertainty.

4.3.4. Project Based Scenarios

Although outright costs for new instrumentation are outlined above, in most cases it may not be realistic for regulatory authorities to implement BC monitoring due to budgetary constraints. In addition, the management of their airshed may might not require permanent, long-term instrumentation to be installed.

Therefore, we have estimated the costs for three different monitoring programmes, based on specific problems, to provide a 'real-world' estimate. Estimated costs are based on monitoring at one site with the costs of additional sites calculated by multiplying the number of sites by the estimated rental charges.

4.3.4.1. Scenario 1

A coastal regional town with a population of 35,000 which continues to exceed the NES-AQ for PM_{10} (in the winter) would like to track emissions from domestic home heating.

In this situation, a short (3-month) winter monitoring programme could be implemented to monitor BC. Monitoring could comprise renting an aethalometer or via filter sampling (sampling 1 day in 3).

1. Aethalometer monthly instrument rental at one site would range from $2,500 (dual channel aethalometer) to $5,000 (multi-channel aethalometer). Total costs of the 3-month monitoring programme would be between $7,500 and $15,000.

2. Monthly instrument rental of a multi-filter sampler (Partisol or similar) at one site would start at $2,000. Approximately 51 filters would be collected with 1 filter cartridge change per month. The estimated cost would be $1,000 for filter changes, $1,100 for analysis and $6,000 for instrument rental, totalling $8,100 for a winter monitoring campaign.

It is important to remember the differences in data that each approach will provide. The Aethalometer will produce high time-resolution data could be used to differentiate diurnal patterns and imply source contributions. The filter-based approach will give you some information about BC which is likely to be aggregated over the same period as your PM sampling system (in most cases 24-hours). Note that 51 samples is not enough samples for a multi-elemental analysis for receptor modelling. The samples could be analysed with the MABI instrument to imply source contributions. Gravimetry or other analysis could be undertaken on archived filters.

4.3.4.2. Scenario 2

A major urban centre would like to track emissions from motor vehicles and contributions from domestic home heating in the winter.

In this situation, site selection would be driven by existing data from existing PM monitoring, traffic data or modelling results. The recommendation would be to implement a permanent instrument as part of an ongoing monitoring campaign at either one or multiple sites.

The costs associated with this would be similar to Table 3, with an estimated CAPEX cost of ~$50,000 - $70,000 for a multi-wavelength aethalometer or ~$20,000 - $40,000 for a dual wavelength aethalometer. Consumables and maintenance are estimated to be between $9,000 - $16,000 per annum. The costs of ongoing maintenance may be less if combined with the service and maintenance program of the existing instruments at the monitoring station.

4.3.4.3. Scenario 3

A regulatory authority already performing 1 day in 3 filter sampling for gravimetric analysis, using a $PM_{2.5}$ low-volume sampler (Partisol or similar) would like to understand BC contributions in their airshed.

In this scenario, existing filters could be sent to a lab on an ongoing basis for $20 - 30 per filter. Based on a 1 day in 3 sample with 122 filters per year, analysis costs could range from $2,440 - $3,660 per year. Based on a 1 day in 6 sample with 61 filters per year, analysis costs could range from $1,300 - $1,900 per year.

5. Benefits of Introducing Monitoring to Jurisdictional Programme

This chapter details the links to existing pollutants and monitoring programmes and what the additional benefits of monitoring are for jurisdictions.

5.1. Links to Other Pollutants

In most regulatory long-term applications, the Magee AE33 is the instrument of choice. All criteria pollutants (O_3, CO, PM_{10}, $PM_{2.5}$, NO_2, SO_2) were commonly measured alongside a co-located BC instrument (Patel et al., 2020; Kertész et al., 2024). In a New Zealand context, this is not necessarily feasible due to budgetary constraints.

However, in most cases, BC should be monitored at peak sites with other pollutants associated with combustion activity (i.e. NO_2, $PM_{2.5}$, CO and SO_2). For example: a) at peak traffic sites, BC should be monitored with NO_2; b) at peak domestic home heating sites, BC should be monitored with PM_{10}, but preferably $PM_{2.5}$. If emissions from ports, coal-fired power stations or fertiliser works are an issue, BC should be monitored alongside SO_2. Figure 8 below presents results from Councils and Unitary Authorities on their preferences for co-located pollutant monitoringNO_2, PM_{10} and $PM_{2.5}$ are the most common response for pollutants that the survey participants consider should be monitored alongside BC monitoring.

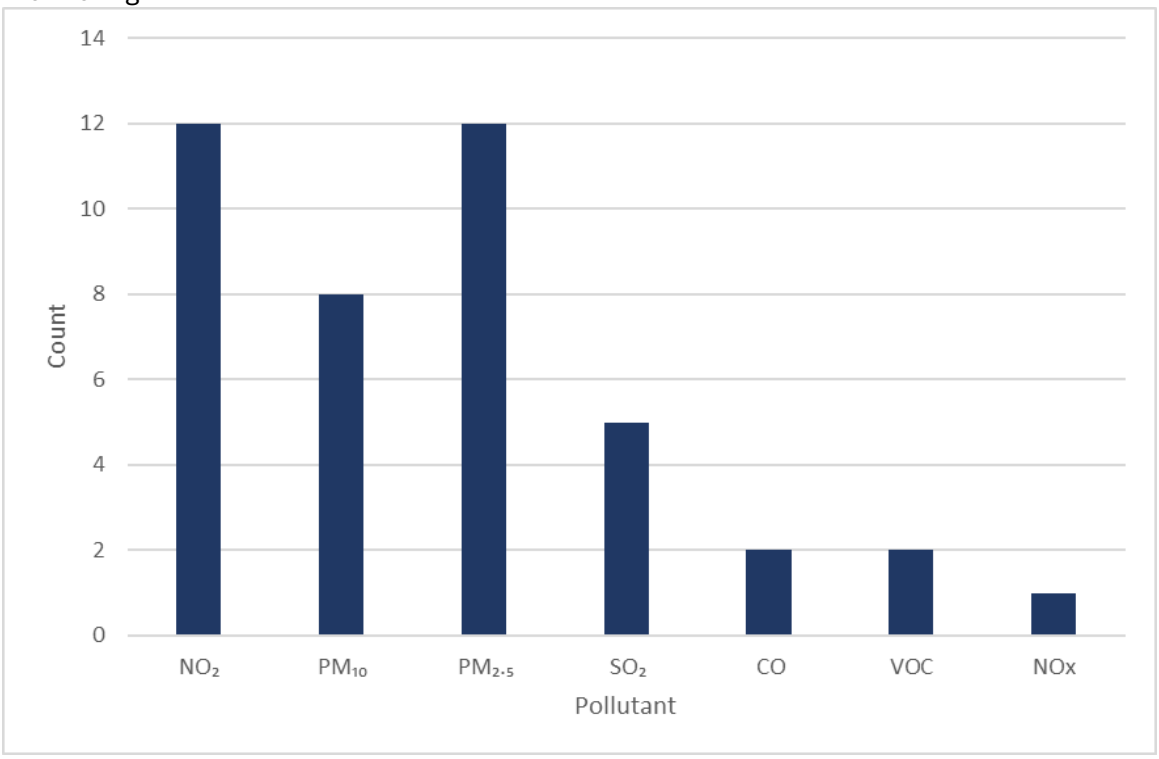

Figure 8: Results from Councils and Unitary Authorities on their preferences for co-located pollutant monitoring.

Black carbon tracks well with other pollutants like $PM_{2.5}$ The ratio of in the BC to $PM_{2.5}$ ratio in the long-term Auckland dataset (Figure 9), has remained constant at approximately 40% for the 2006 – 2016 period and indicates that combustion sources are a key driver of $PM_{2.5}$ concentrations in Auckland (Boamponsem et al., 2024). The ratio of BC to $PM_{2.5}$ at other locations in New Zealand ranges from 15 to 45% and contrasts European and North American cities where ratios of BC to $PM_{2.5}$ (annual averages) ranged from 5-10% (Li et al., 2016).

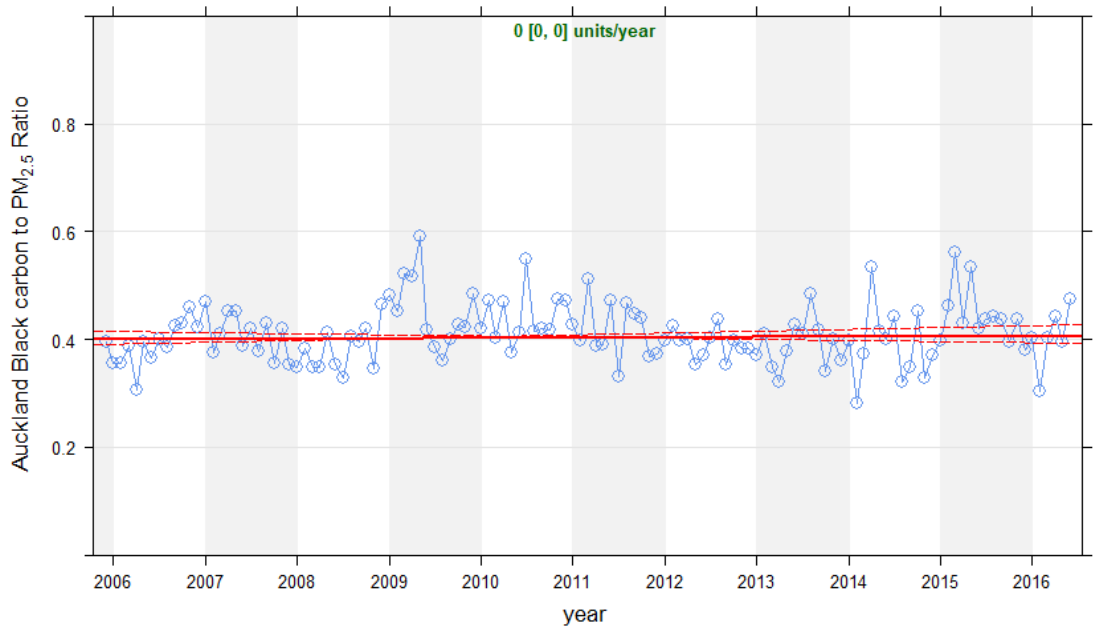

Figure 9: TheilSen trend showing the ratio of BC to $PM_{2.5}$ from the Auckland. Statistically significant to 99.9% confidence interval.

5.2. Benefits of Monitoring

There are a number of benefits of monitoring BC in your jurisdiction. The most significant across the literature includes tracking BC sources in real-time to track the effectiveness of policy interventions targeting domestic home heating and traffic. As BC is a tracer of urban combustion sources, it also represents the atmospheric burden of ultrafine PM emitted from such combustion sources along with its consequent health burdens (Li et al., 2016; Luben et al., 2017).

Along with BC analysis from filter samples, additional elemental analysis and receptor modelling can be performed. A direct result of using this technique is that the sources of BC (or any other variable) can be derived and the mass contribution of each BC emission source to atmospheric BC concentrations determined (Appendix 6). The most substantive and informative activity is the multi-site, multi-year speciation network in Auckland where PM samples for BC and elemental analysis have been collected continuously since 2004 (Davy et al., 2014, 2017; Davy and Trompetter, 2019; Boamponsem et al., 2024The Auckland data shows that motor vehicles (diesel engines) are the primary emission source of black carbon with solid fuel fire emissions a significant source during winter months (Boamponsem et al., 2024).

Offline methods provide an in-depth understanding of the PM load within respective airsheds and can provide clear evidence if a peak PM value was likely to be associated with an anthropogenic emission source (and therefore manageable); was primarily in the $PM_{2.5}$ size fraction (with greater health impacts); or was more likely to be associated with a natural PM

event. Identification of the source(s) contributing to a peak PM event is important if the PM_{10} NESAQ was exceeded. An exemption for exceptional events may be granted if the source of the exceedance was outside the control of the regulatory authority (Reg 16A, NES-AQ, 2004).

The average BC source contribution data from New Zealand monitoring sites reflects the dichotomy of motor vehicle BC emissions dominating at locations with higher traffic volumes while the influence of winter combustion emissions from residential heating drives BC concentrations in smaller urban centres and cities in the South Island as presented in Figure 10. The ability to discern sources from the two most dominant contributors of PM/BC provides air quality managers with better information that can be used to reduce and mitigate emissions from these sources.

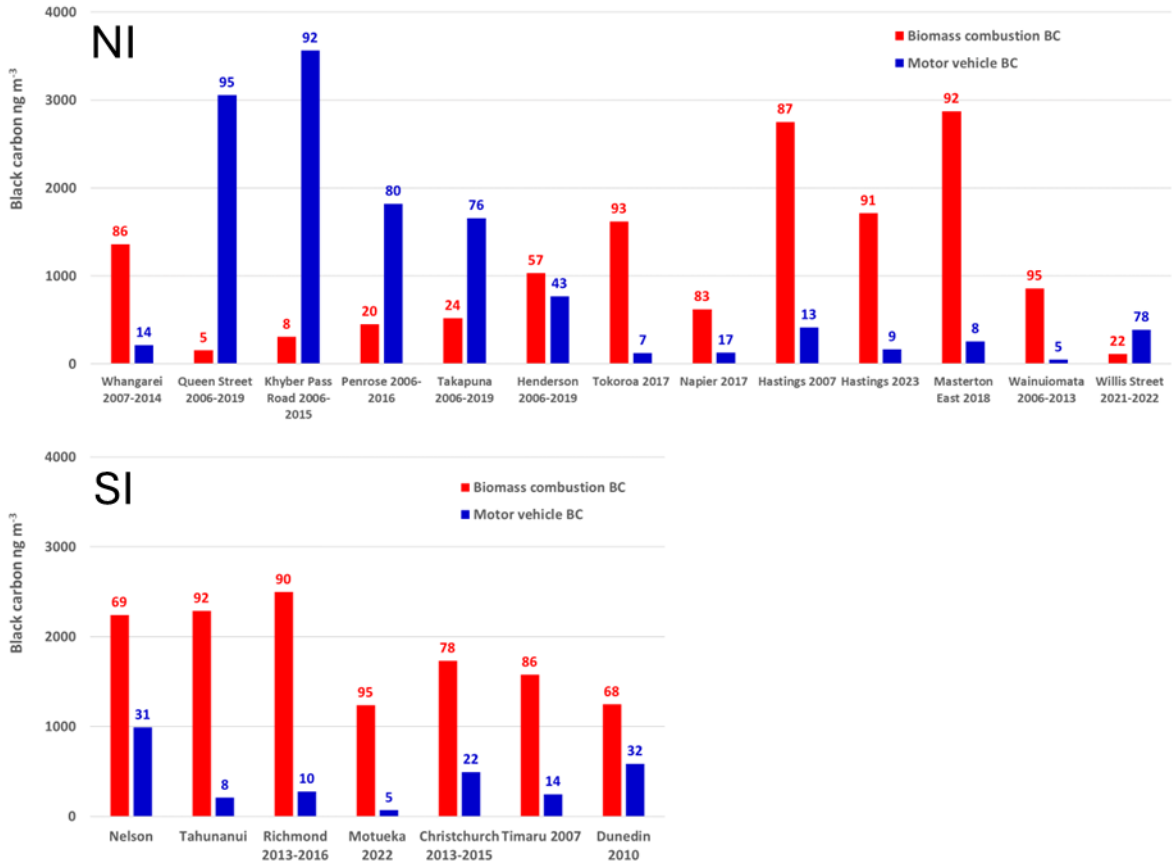

Figure 10: Average source contributions to BC concentrations at New Zealand monitoring sites in the North Island (top) and South Island (bottom).

5.3. Practicality of Measurement

There are a number of barriers when it comes to practical measurement of BC monitoring in New Zealand jurisdiction. We had responses from all 16 Councils; the following is a summary of the key barriers as seen from a Council perspective:

Councils were asked about barriers to carrying out BC monitoring in New Zealand jurisdiction as part of the survey described in Section 1.3. The survey response from all 16 Councils are summarised below:

- The first and most crucial point was funding. Councils were unable to ascertain how they would fund monitoring when they already struggle to fund their current air quality monitoring programmes.
- It was suggested that if BC monitoring was introduced by the Ministry, it should be funded by Central Government. Public health and research grants were also suggested as sources of funding.
- There is currently a lack of standards and guidelines, therefore it is seen as a 'no need' to monitor BC.
- The fact that New Zealand still doesn't have a $PM_{2.5}$ standard which most OECD nations had in place for over a decade was also concerning.
- It wasn't only the cost of CAPEX and ongoing OPEX that was of concern. It was voiced that most Councils lack the staff and expertise to process, analyse, and report BC data, especially the source apportionment data analysis. There would need to be significant upskilling on the Councils behalf.
- Reporting of data was also raised, with questions about the comparability of data from different instruments due to different algorithms, the changing algorithms in firmware updates and the changes in mass absorption coefficients within air sheds.

6. Emissions Inventories & Long-Term Trends

This chapter provides comments on emissions inventories and how they are calculated from emissions factors. The latter part of chapter investigates emissions inventories from New Zealand (from an international study) and links it with observed measurement trends over the same period in Auckland.

6.1. Emissions Inventories

Emissions inventories are an essential tool when it comes to managing and regulating air pollution. They enhance our understanding of the ways in which sources of air pollution contribute to an airshed and their potential impact on people and the environment. Sources within inventories can be categorised into point source, area sources, mobile sources. They are generally a 'bottom up' approach (Crimmins et al., 2019). They provide an estimate of the total amount of air pollution, usually for specific pollutants generated from all sources and provide pertinent information relevant for policy development to mitigate air pollution. Emissions inventories do not take into account how the atmospheric chemistry might change the pollutant loading with time.

Bottom-up emission inventories are calculated by using emission factors for the categories mentioned above multiplied by specific activity data (e.g. tonnes of raw material processed; units manufactured by an industrial source; or vehicle kilometres travelled (VKT) by motor vehicles). Throughout the literature it is well known that emissions inventories are subject to high uncertainty due to the associated uncertainty in data that feeds approximations and models. Inventories also do not consider the effect of varying topography or meteorology may act to reduce or enhance dispersion. These uncertainties and averaging of both emissions factors and activity data across a source category may reduce the utility of emissions inventories for air quality management purposes. Quite often, output from an emissions inventory is on a tonnes of pollutant/year basis. Temporal resolution may be improved to a tonnes/pollutant/typical winter or summer day, or alternatively, a weekday/weekend difference. However, as the estimations and temporal resolution of emissions inventories are improved there is a consequent increase in the cost of compiling the inventory.

Inventories have been calculated internationally at different scales (global, regional, national) and consistency across findings identifies major BC emissions are attributable to combustion activities. These include the combustion of fossil fuels (diesel, petrol, coal) as well as biomass and open burning (including wildfires) as well as aviation (Xu et al., 2021).

6.2. New Zealand Emissions Inventories

Although inventories have been collated for other criteria air pollutants across New Zealand, there are no specific and robust inventories for BC specifically for New Zealand (Crimmins et al., 2019; Ministry for the Environment & Stats NZ, 2020; Patel et al., 2020). However, Xu et al., (2021) estimated global emissions from 1960-2017 using updated activities and emissions factors for 73 sources across a 0.1 x 0.1 spatial resolution. They estimated global anthropogenic emissions in 2017 to be 6.2 Tg with a 50% uncertainty level (4.8 - 8.3 Tg). The 50% uncertainty was also apportioned to emissions inventories compiled for Auckland (Crimmins et al., 2019). Although Xu et al., (2021) did not specifically comment on New Zealand, they did provide their data in the supplementary information, across 5 key sources (energy sector, industrial, residential, on-road motor vehicles, other anthropogenic and wildfires). Emissions inventory data used in this chapter is from Xu et al., (2021). A detailed breakdown of emissions from the various sources can be found in Table 6.

Table 6: New Zealand's BC emissions (estimate from emissions inventories) across five anthropogenic sectors as well as wildfires in 2017.

Sector	Emissions in 2017 (Gg)
Energy Sector	0.002
Industrial	1.520
Residential	0.614
On-road motor vehicles	2.750
Other anthropogenic	0.020
Without Wildfires	**4.907**
Wildfires	0.234
With Wildfires	**5.141**

Wildfire emissions were estimated to be the fourth largest contribution to BC in New Zealand in 2017 with 0.23 Gg. However, forest and vegetation wildfires are relatively rare. Occasionally, New Zealand does experience the downwind effects due to emissions from Australia bushfires (Davy and Trompetter, 2020). It is an important finding which has important implications for New Zealand, especially as climatic extremes make the prevalence of wildfires more likely (Langer et al., 2021; IPCC, 2023).

Figure 11 demonstrates totals emissions over from 2002 – 2017. Overall emissions of BC have been decreasing until 2008 after which they increase slightly and then plateau. Looking at sector specific emissions, although motor emissions vehicles have been decreasing, this is being offset by increasing industrial emissions from 2009 onwards. Prior to this they were relatively stable. Residential emissions have been relatively stable over the period apart from a decrease in 2008 after which they then plateaued.

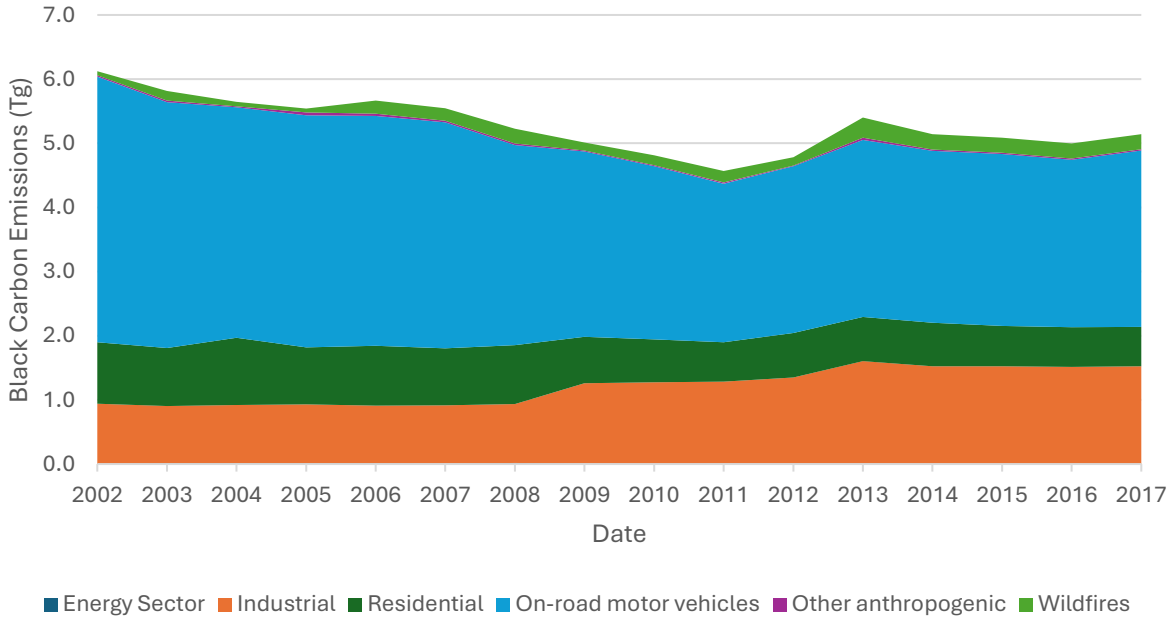

Figure 11: Emissions factors for BC from five main sectors (energy, industrial, residential, on-road motor vehicles, other anthropogenic and wildfires between 2002 and 2017.

6.3. Anthropogenic Emissions

Figure 12a demonstrates estimated anthropogenic emissions for New Zealand from Xu et al., (2021). Emissions have steadily declined from 6 Gg in 2002 to a minimum of 4.3 Gg in 2011. Emissions stopped decreasing and have been increasing slowly between 2011 and 2017 to 4.91 Gg. Emissions have been decreasing at a rate of 0.07 Gg yr^{-1}. BC concentrations measured across Auckland (Figure 12b), at multiple sites, have been steadily decreasing from 5 ng m^{-3} to their 2017 concentration of 2 ng m^{-3}. The plateau observed in total emissions from the inventories is not reflected in atmospheric monitoring data.

More detailed analysis of on-road transport, domestic, home heating and industrial components are investigated Sections 6.3.1, 6.3.2 and 6.3.3 respectively.

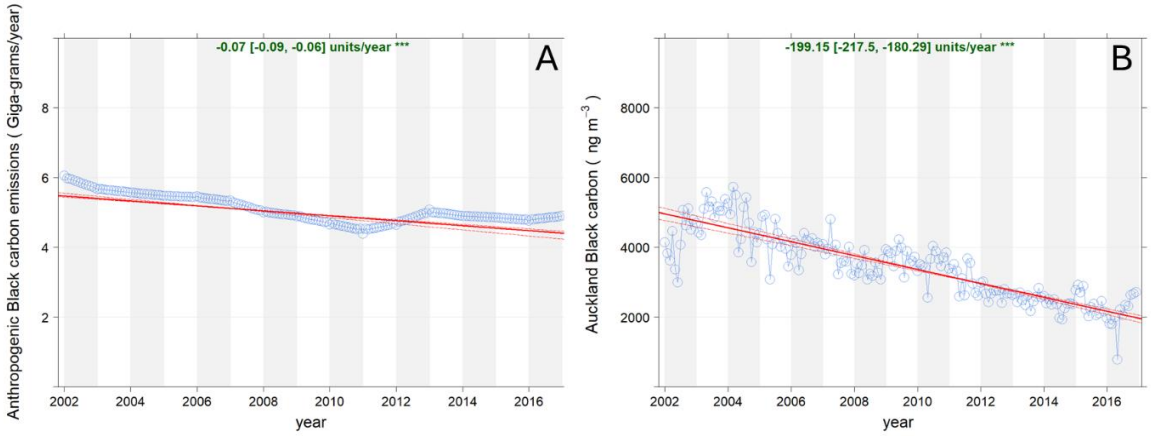

Figure 12: TheilSen trend showing decreasing anthropogenic BC emissions from New Zealand (a) and decreasing BC measured concentrations across the Auckland region (b) from 2002 - 2017. Statistically significant to 99.9% confidence interval.

6.3.1. On-road Transport

The following section includes the analysis of BC emissions inventories from on-road motor vehicles (across New Zealand) and measured concentrations from Auckland from Xu et al., (2021). Motor vehicles are the most dominant source of BC emissions, estimated to contribute 2.8 Gg in 2017. Emissions have been falling by 0.5 Gg yr^{-1} (Figure 13a). A similar trend is observed in atmospheric BC concentrations across Auckland (Figure 13b), with concentrations falling from 3.8 to 2.8 ng m^{-3}. A slowing or plateau of concentrations between the 2014-2017 period is evident in both the emissions inventories and measured concentrations in Auckland. Concentrations over the 2006 – 2017 period have been decreasing at approximately 140 ng yr^{-1}. The key driver of the decrease in BC at Auckland sites has been improvements in motor vehicle tailpipe emissions (primarily diesel fuelled vehicles) (Boamponsem et al, 2024).

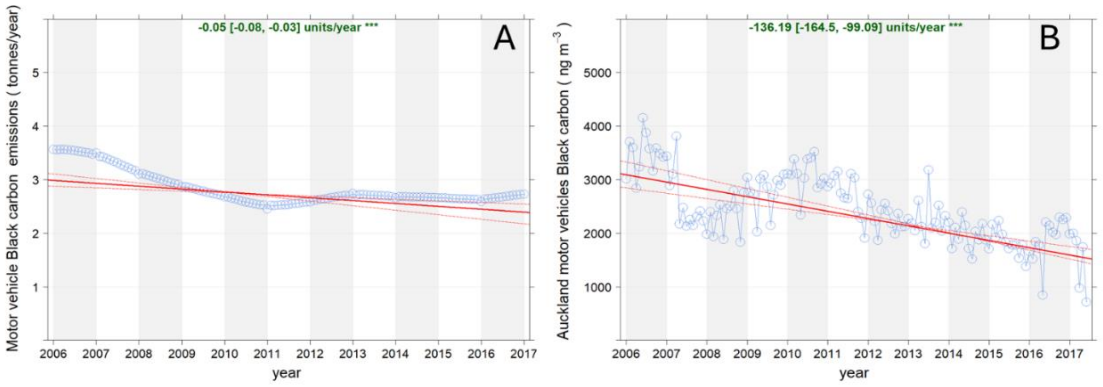

Figure 13: TheilSen trend showing decreasing motor vehicle BC emissions from New Zealand (a) and decreasing motor vehicle associated BC concentrations measured across the Auckland region (b) from 2002 - 2017. Statistically significant to 99.9% confidence interval.

In New Zealand, emissions from motor vehicles are estimated by the vehicle emissions prediction model (VEPM). This model predicts emissions using average speed under typical road, traffic and operating conditions. VEPM estimates tailpipe emissions factors for CO, HC, NO_X, CO_2 and PM, as well as non-tailpipe emissions. BC emissions themselves are still not covered by VEPM but as seen above, BC emissions from vehicle exhaust are the most dominant component of BC emissions in the Xu et al., (2021) inventory for NZ. The composition of the vehicle fleet is the most important factor driving emissions. New Zealand has one of the oldest fleets in the OECD, with the average age of vehicles double the age of those in comparable cities (Environmental Health Intelligence New Zealand, 2024). Although vehicle emissions standards have been improving, the benefit to air quality has been outweighed by the increasing number of vehicles in use in NZ. The Auckland ambient BC source apportionment dataset supports this, with diesel vehicle $PM_{2.5}$ BC/PM ratios ranging from 0.6 to 0.9 on a mass basis depending on monitoring site location. Approximately 40% of all $PM_{2.5}$ in Auckland is composed of BC, this ratio has been relatively stable over the last 20 years, highlighting that improvement in vehicle emissions standards is not being reflected in BC contribution to $PM_{2.5}$,

One of the largest uncertainties in vehicle emissions factors information used in the VEPM is that while tests are usually performed in the lab on dynamometers, real-world emissions can vary significantly due to changes in road gradients and vehicle loads.

6.3.2. Domestic Home Heating (Biomass & Coal)

The following section includes analysis of residential BC emissions from Xu et al., (2021) and domestic home heating BC concentrations measured across Auckland. Residential emissions are the third largest contributor out of the five sectors. BC emissions are estimated to contribute 0.61 Gg in 2017 and have been falling by 0.3 Gg yr^{-1}. After falling to a minimum in 2011, emissions rose slightly, then fell again to their 2011 level (Figure 14a). Unlike on-road motor vehicles, the trend is not realised in BC monitoring data from Auckland (Figure 14b). BC concentrations from Domestic home heating have been rising slowly by 4.3 ng yr^{-1} over the same period. Measured concentrations have roughly doubled over that time, increasing from 60 ng m^{-3} to 100 ng m^{-3}. The reason for this is unknown, but a surprising result.

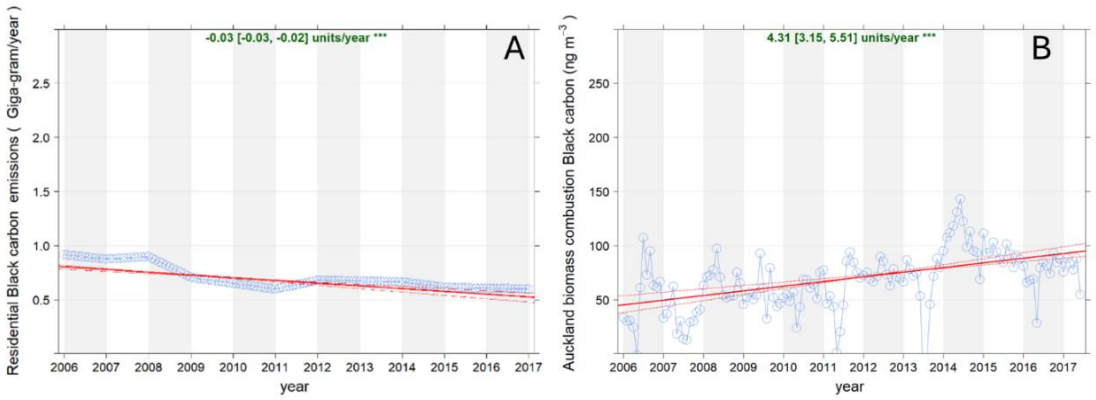

Figure 14: TheilSen trend showing decreasing residential BC emissions across New Zealand (a) an increasing biomass combustion associated BC concentrations measured across the Auckland region (b) from 2002 - 2017. Statistically significant to 99.9% confidence interval.

6.3.3. Industry

Industrial emissions can be a significant source of BC in New Zealand especially in relation to power generation, industrial combustion for heating and other commercial activities such as construction and ports. Emissions from industry were relatively stable from 2002 - 2008 (around 0.9 Gg). After 2000, concentrations were estimated to be steadily increasing from 0.9 to 1.5 Gg in 2017. Estimates of BC emissions from dedicated industrial combustion plant used for generating heat can be relatively straightforward for classes of facility (gas, coal, diesel, residual oil, biomass) or individual units as these can be stack-tested under operating conditions or may already have the data as part of plant design or resource consent conditions. In most cases combustion conditions will be maximised for efficiency to minimise fuel costs, but facilities such as gas flaring (mainly associated with gas and oil extraction, refining facilities or landfills) form a different category.

The open-flame nature of gas flaring distinguishes it from industrial point- sources; the high temperature, flame control, and spatial compactness distinguishes gas flaring from both biomass burning and domestic fuel-use (Fawole et al. 2016). Therefore, emission inventories for the soot yield from gas flaring should consider the variation of fuel gas composition and combustion characteristics. The high-temperature nature of industrial combustion facilities coupled with the height of the stack enables some of the BC to escape further into the free troposphere aiding long-range transport, atmospheric residence times and therefore enhance the potential for climate impacts (Fawole et al. 2016).

Other industrial sources include those construction, shipping and aviation. Some of these sources have significant impact on local BC concentrations with reported exceedances of the NES-AQ from unregulated construction equipment and shipping in Auckland and Tauranga (Boamponsem et al, 2024). Most of these activities are likely to involve combustion of diesel fuels and fuel usage statistics indicate that off-road activities account for around 40% of diesel consumption in New Zealand.

A US study found that, as on-road engine emissions have been controlled, the relative importance of off-road sources has grown (McDonald et al. 2015). For example, in 1970 approximately 90% of BC emissions were from on-road sources; by 2010, off-road engines were estimated to account for 37 ± 20% of total mobile source contributions to BC in the Los Angeles area (McDonald et al. 2015). The US study highlights both the success of efforts to control on-road emission sources, and the importance of considering off-road engine and other source contributions when assessing future BC emissions and ambient air quality trends. A study by Patel et al. (2023) also highlighted the impact of unregulated construction activities and building ventilation system emissions impacting Auckland's air quality.

7. Summary

This report details the feasibility of BC monitoring in New Zealand. BC is a term given to soot-like atmospheric aerosols and a constituent of PM. Internationally, the impact of BC on the environment and human health is not well understood. In New Zealand BC is derived primarily from the combustion of fossil fuels and domestic home heating. In-line with WHO recommendations, systematic measurement should be undertaken. Optical methods using aethalometers are international best practice however, measurement using offline reflectometers and transmissometers are a commonly accepted method.

The size of a jurisdiction will ultimately define the appropriate method for BC analysis. Feedback from regulatory authorities highlighted: the lack of a standard, limited funds and limited skill within existing teams with more guidance and support required to upskill.

It was suggested that BC be monitored alongside other pollutants associated with combustion activity (i.e. NO_2, $PM_{2.5}$, CO and SO_2). BC should be monitored with PM_{10}, although more preferably with $PM_{2.5}$. For example: a) at peak traffic sites, BC should be monitored with NO_2; b) at peak domestic home heating sites, BC should be monitored with PM_{10}, but preferably $PM_{2.5}$. If shipping emissions are an issue BC should be monitored alongside SO_2.

Online multi-wavelength aethalometers can be purchased and operated (for one year) for approximately $45,000 - $86,000 (depending on instrumentation and ancillary infrastructure). Consumables cost $10,000 - $15,000 p.a. (from year two onwards). Offline measurement devices such as the MABI or SSR can be purchased for approximately $10,000 - $20,000. Samples collected using in-situ PM monitoring instruments can then be processed for an extra $5,000 - $10,000 depending on sampling regime (1 day in 3) or (1 day in 6). A BC specific seasonal monitoring programme could be performed with rental instruments for between $7,500 and $15,000, otherwise added to an ongoing PM monitoring programme for an additional $2,000 - $4,000.

A large benefit of aethalometers is their ability to deliver high time-resolution data and perform in-situ source apportionment to enable air quality managers to evaluate sources within their airsheds and develop more effective and targeted mitigation strategies. Offline methods can provide source information but at much lower time resolution.

Black carbon emissions inventories highlighted on-road motor vehicles as being the largest source, with industry and residential sources the second and third largest contributors respectively. Total BC emissions were trending down until 2008, after which, they have increased slightly, and then plateaued. These trends have been ascribed to decreases in motor vehicle emissions that have subsequently been offset by increasing industrial emissions from 2009 onwards.

Recommended next steps for monitoring BC in New Zealand are outlined in Section 8.

8. Recommendations

This feasibility report has outlined the need for systematic measurement of BC with various techniques and methods suited for different situations. In line with WHO recommendations, presented here are a number of feasible monitoring options, for jurisdictions of different sizes, that can be implemented to support WHO Good Practice objectives. Recommendations are as follows:

a) The recommended technique for quantifying BC concentrations within a regulatory setting is based on optical methods that include. aethalometers, reflectometers or transmissometers. For larger jurisdictions (population ~100,000) it is recommended that continuous monitoring be performed at peak sites using continuous multi-wavelength aethalometers. For smaller jurisdictions (population ~30,000), seasonal surveys using aethalometers may be better suited, during episodic pollution periods (i.e. winter when domestic heating emissions are at their highest). Offline analysis may also be performed on PM samples (collected with a separate PM sampling system) in-line with a screening assessment or as part of a wider monitoring programme.
b) The report highlighted variability in instrument algorithms and data output. It is recommended that systematic testing is undertaken to understand algorithms and differences in MAC used by various instrument manufacturers in New Zealand. This also includes testing in various climatic conditions and under variable source contributions to understand the variability of instrument responses.
c) It is recommended that supporting guidance is provided to regulatory authorities to undertake monitoring. Guidance should be developed to assist with data QA/QC, data interpretation (i.e. source apportionment) and reporting of data to provide national consistency.
d) Emissions factors for BC are not well understood within a New Zealand context therefore it is recommended that future research focusses on determining the applicability of overseas emissions factors for New Zealand and/or develop local emissions factors for New Zealand scenarios where there is insufficient data from existing emissions factors. Industrial and off-road emissions inventories should be further investigated and developed.
e) Vehicle Emissions Prediction Model (VEPM) should be updated to include BC including with non-tail pipe emissions (from road and tyre wear).

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Appendices

A1.0 Draft Questionnaire for Councils

Monitoring of Black Carbon in New Zealand – Questionnaire for Councils

1. How should 'black carbon' be defined for monitoring purposes?

2. Is black carbon currently monitored within your region?

NO / YES

If NO – please proceed to **Q7**. If YES, please proceed to **Q3**

3. What instrument(s)/method(s) do you use?

4. What are the primary objectives of your black carbon monitoring programme?

5. How do you interpret/analyse the black carbon data you collect.

6. Have you encountered any issues with current technology/instruments/devices?

7. Do you plan on commencing or expanding black carbon monitoring in your region?

8. What other pollutants (if any) do you think black carbon should be monitored with?
Please circle: NO_2 PM_{10} $PM_{2.5}$ O_3 SO_2 CO

Other (please specify):_____

9. Do you foresee any barriers to monitoring black carbon in your region?

10. How do you envisage monitoring to be funded?

11. Is there anything else you think the Ministry should consider when implementing black carbon monitoring for State of the Environment reporting?

12. Would you be open to a short 10–15-minute zoom/phone call to discuss anything further?

NO / YES

A2.0 Description of Methods

Table A1: Description of the various methods used for the determination of BC with advantages and disadvantages of each

Method	Description	Advantages	Disadvantages
Thermal Optical Analysis (TOA)	This method makes use of the thermal resistivity of 'elemental' carbon (EC) and the diverging thermal properties of organic carbon (OC). The filter is first heated in inert gas and the OC volatilized at different temperatures and detected as CO_2 or CH_4 (depending on the measurement setup). The filter is then cooled and re-heated in the presence of oxygen to combust the EC; gases are detected in the same way. The different heating phases shed light on the specific content of OC/EC in the sample.	Analysis of OC and EC (and other species), ability to perform source apportionment,	Expensive, time consuming and complex lab set-up, cannot provide real-time data, sample loss (charring and pyrolysis), filter membrane effects, high uncertainty at low concentration.
Optical Method	The optical method light of different wavelengths is used to illuminate a sample collected filter media. Due to the different light absorbing properties of BC, BC is indirectly converted to a mass using a mass absorption coefficient (MAC).	Simplicity, cost-effectiveness, insensitivity to gaseous interferences, ability to perform in-field analysis, ability to perform source apportionment	Interferences from other light absorbing substances, variations in mass absorption coefficients.
Laser-Induced Incandescence (LII)	In the LII method, the sample is heated rapidly by a laser to achieve gasification temperature (~4000k). The mass is determined by the intensity of the incandescent signal.	Useful for studying physio-chemical properties and degree of aging, not impacted by organic coating of particles.	Underestimates the mass of larger sized BC particles, Expensive, time consuming and complex lab set-up, cannot provide real-time data, sample loss (charring and pyrolysis).

A3.0 Black Carbon Measurement

When measuring black carbon by light reflection/transmission, light from a light source is transmitted through a filter onto a photocell. The amount of light absorption is proportional to the amount of black carbon present and provides a value that is a measure of the black carbon on the filter. Conversion of the absorbance value to an atmospheric concentration value of black carbon (BC) requires the use of an empirically derived equation (Cohen et al. 2000):

Equation A1.1 $BC\ (\mu g\ cm^{-2}) = (100/2(F\varepsilon))\ \ln[R_0/R]$

where:

ε is the mass absorbent coefficient for BC ($m^2\ g^{-1}$) at a given wavelength.

F is a correction factor to account for other absorbing factors such as sulphates, nitrates, shadowing and filter loading. These effects are generally assumed to be negligible, and F is set at 1.00.

R_0 and R are the pre- and post-reflection intensity measurements, respectively.

Black carbon was measured at GNS Science using the M43D Digital Smoke Stain Reflectometer. The following equation (from Willy Maenhaut, Institute for Nuclear Sciences, University of Gent, Belgium) was used for obtaining black carbon from reflectance measurements on Nucleopore polycarbonate filters or Pall Life Sciences Teflon filters:

Equation A1.2 $BC\ (\mu g\ cm^{-2}) = [1000\ \acute{}\ LOG(R_{blank}/R_{sample}) + 2.39] / 45.8$

where:

R_{blank} is the average reflectance for a series of blank filters; it is close (but not identical) to 100. GNS Science always uses the same blank filter for adjusting to 100.

R_{sample} is the reflectance for a filter sample (normally lower than 100).

With 2.39 and 45.8 constants derived using a series of 100 Nuclepore polycarbonate filter samples, which served as secondary standards; the black carbon loading (in $\mu g\ cm^{-2}$) for these samples had been determined by Prof. Dr. MO Andreae (Max Planck Institute of Chemistry, Mainz, Germany) relative to standards that were prepared by collecting burning acetylene soot on filters and determining the mass concentration gravimetrically (Trompetter 2004).

A4.0 Site Summary and Metadata

Table A2: New Zealand PM speciation and BC monitoring sites.

Region	Sites	Time Period	Frequency	Size Fraction	Location (Lat; Long)
Northland	Whangārei	2004–2012	1-day-in-6	PM_{10}	-35.7252; 174.3177
Wellington	Masterton	2002–2004	1-day-in-3	$PM_{2.5}$, $PM_{10-2.5}$	-40.9523; 175.6465
	Masterton (two sites)	Winter 2010	Hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-40.9593; 175.6531
	Upper Hutt	2000–2002	Variable	$PM_{2.5}$, $PM_{10-2.5}$	-41.1308; 175.0426
	Wainuiomata	2006–2008, 2011–2014	1-day-in-3	$PM_{2.5}$, $PM_{10-2.5}$	-41.2681; 174.9534
	Wainuiomata	2014–onward	6/12-hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-41.2681; 174.9534
	Seaview	2002–2004, 2005–2007	1-day-in-3	$PM_{2.5}$, $PM_{10-2.5}$	-41.2405; 174.9140
	Wairarapa (Masterton, Carterton, Featherston)	Winter 2009	Daily (screening)	$PM_{2.5}$, $PM_{10-2.5}$	-
	Mt Victoria Tunnel	Summer 2009	Peak traffic	$PM_{2.5}$, $PM_{10-2.5}$	-41.3035; 174.7892
	Baring Head	1996–1998	Weekly	$PM_{2.5}$, $PM_{10-2.5}$	-41.4082; 174.8714
	Raumati	Winter 2010	12-hourly	$PM_{2.5}$, $PM_{10-2.5}$	-40.9321; 174.9799
	Seven indoor/outdoor sites	Winter 2017	2-hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-
	Masterton East	2018	1-day-in-3	$PM_{2.5}$	-40.9593; 175.6531
	Newtown	2016	2-hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-41.3111; 174.7797
	Port Nicholson	Dec 2019 – March 2020	6-hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-41.2772; 174.7857
	Willis Street	Dec 2019 – March 2020; April 2021 – ongoing	12-hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-41.2936; 174.7719
Auckland	Kingsland	2004–2007	1-day-in-3	$PM_{2.5}$, PM_{10}	-36.8732; 174.7471
	Takapuna	2007–2016	1-day-in-3	$PM_{2.5}$	-36.7803; 174.7489
	Takapuna	2006–onward	1-day-in-3	PM_{10}	-36.7803; 174.7489
	Takapuna (three sites)	Winter 2012	Hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-36.7803; 174.7489

Region	Sites	Time Period	Frequency	Size Fraction	Location (Lat; Long)
	Queen Street	2006–2016	1-day-in-3	$PM_{2.5}$	-36.8476;174.7655
	Queen Street	2006–onward	Daily	PM_{10}	-36.8476; 174.7655
	Penrose	2006–2016	1-day-in-3	$PM_{2.5}$, PM_{10}	-36.9045; 174.8156
	Khyber Pass Road	2006–2015	1-day-in-3	$PM_{2.5}$, PM_{10}	-36.8662; 174.7705
	Henderson	2006–onward	1-day-in-3	PM_{10}	-36.8681; 174.6284
	Patumāhoe	2010	Daily	$PM_{2.5}$, $PM_{10-2.5}$	-37.2046; 174.8639
	Johnstone Hills tunnel	June 2010	3-hourly	$PM_{2.5}$, $PM_{10-2.5}$	-36.5353; 174.6800
Nelson	Tāhunanui	2005–2019	1-day-in-3	PM_{10}	-41.2949; 173.2431
	Nelson City	2006–2018	1-day-in-3	$PM_{2.5}$, PM_{10}	-41.2783; 173.2735
	Nelson City (three sites)	Winter 2011	Hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-41.2783; 173.2735
Marlborough	Blenheim	2007	1-day-in-3	$PM_{2.5}$, $PM_{10-2.5}$	-41.5268; 173.9561
Otago	Dunedin	2010	1-day-in-3	$PM_{2.5}$, $PM_{10-2.5}$	-45.8689; 170.5177
	Alexandra (three sites)	Winter 2011	Hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-45.2534; 169.3912
Canterbury	Christchurch	2001–2002	Daily	$PM_{2.5}$	-43.5112; 172.6337
	Timaru	2006–2007	1-day-in-3	$PM_{2.5}$	-44.4046; 171.2496
	Woolston	2013–2014	2-hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-43.5572; 172.6811
	Christchurch, Coles Place	2013–2015	1-day-in-3	$PM_{2.5}$, $PM_{10-2.5}$	-43.5112; 172.6337
	Christchurch: Coles Place, Woolston, Riccarton (high-resolution three-site study)	Winter 2014	2-hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-43.5112; 172.6337
	Lyttelton Port high resolution study	Summer 2021	6-hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-43.6061; 172.7273
Hawke's Bay	Hastings	2006–2007	1-day-in-3	$PM_{2.5}$, PM_{10}	-39.6385; 176.8574
	Meanee Rd	2006 + 2008	1-day-in-2 (screening survey)	$PM_{2.5}$, $PM_{10-2.5}$	-
	Napier	2008–2009	1-day-in-3	$PM_{2.5}$, $PM_{10-2.5}$	-
	Awatoto	2016–2017	1-day-in-3	$PM_{2.5}$, $PM_{10-2.5}$	-39.5459; 176.9192

Region	Sites	Time Period	Frequency	Size Fraction	Location (Lat; Long)
	Marewa Park	2017–2018	1-day-in-3	$PM_{2.5}$, $PM_{10-2.5}$	-39.5002; 176.8971
	Hastings	2022–2023	1-day-in-3	$PM_{2.5}$, PM_{10}	-39.6385; 176.8574
Southland	Invercargill	Winter 2014	Hourly continuous	$PM_{2.5}$, $PM_{10-2.5}$	-46.4305; 168.3711
Waikato	Tokoroa	Winter 2014	Daily	PM_{10}	-38.2216; 175.8589
	Tokoroa	October 2015 – October 2016	Daily	PM_{10}	-38.2216; 175.8589
Bay of Plenty	Rotorua (Whakarewarewa Village)	October 2014 – 2019	1-day-in-3	$PM_{2.5}$, $PM_{10-2.5}$	-38.1625; 176.2571
Tasman	Richmond	2013–2016	1-day-in-3	PM_{10}	-41.3396; 173.1833
	Richmond	2015–2016	Daily	$PM_{2.5}$	-41.3396; 173.1833
	Motueka	2022	Daily	$PM_{2.5}$	-41.3396; 173.1833
West Coast	Westport	Winter 2023	Daily	$PM_{2.5}$, PM_{10}	-41.7511; 171.5998

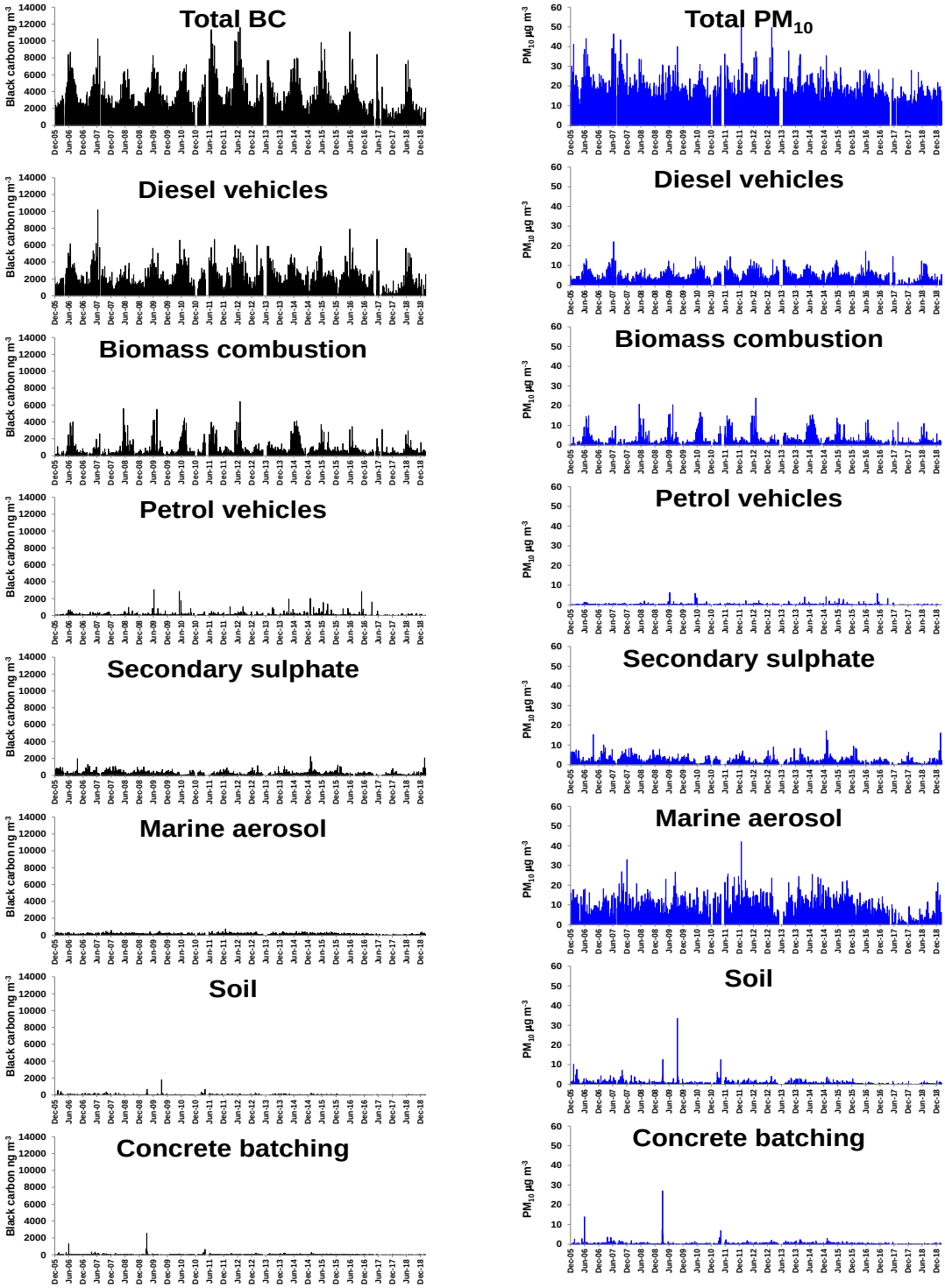
A5.0 Summary of Responses

Table A3: Summary of response from Councils on monitoring of BC

Council	Ever monitored BC?	Continuous	Intermittent/ mobile using continuous	Filter-based analysis	Considering continuous BC monitoring	Instrument Type
Northland Regional Council	YES	NO	NO	YES	NO	
Auckland Council	YES	YES	NO	YES	YES	Magee AE33, MetOne 1060
Environment Waikato	YES	NO	NO	YES	MAYBE	
Bay of Plenty Regional Council	YES	NO	NO	YES	NO	
Gisborne District Council	NO	NO	NO	NO	NO	
Taranaki Regional Council	NO	NO	NO	NO	NO	
Hawkes Bay Regional Council	YES	NO	NO	YES	MAYBE	
Horizons Regional Council	YES	NO	NO	YES	NO	
Greater Wellington Regional Council	YES	YES	YES	YES	YES	Magee AE33, MA350
Marlborough District Council	YES	NO	NO	YES	NO	
Nelson City Council	YES	NO	NO	YES	NO	
Tasman District Council	YES	NO	NO	YES	NO	
West Coast Regional Council	YES	NO	NO	YES	NO	
Environment Canterbury	YES	YES	NO	YES	YES	Magee AE33
Otago Regional Council	YES	YES	NO	YES	YES	Magee AE33
Environment Southland	YES	NO	NO	YES	NO	

A6.0 Source Apportionment

Figure A115: Time-series plot of source contributions to (left) black carbon and (Right) PM_{10} at the Takapuna site, Auckland.



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