Potential of vegetation to mitigate road-generated air pollution

Part I – Review of background information

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Landcare Research Contract Report: LC0506/00xx

PREPARED FOR:

DATE: August 2006

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Contents

Foreword

- The original intention of this report was to use the available literature to provide an indication of design options for roadside vegetation that would maximise air pollution mitigation potential. However, during review of the literature it became apparent that insufficient information was available to enable design options to be suggested, and that some experimental data was needed to critically assess different design options. As such, it is intended that part II of the report provides the results of experimental work, and the combined information will provide a basis for design options.

1. Introduction

Vehicle emissions are a key contributor to air pollution in a number of New Zealand cities, and it is estimated that particulate matter <10 µm (PM_{10}) associated with these emissions is responsible for the premature deaths of approximately 400 people per annum. Trees have a demonstrated potential to improve air quality in urban areas through increasing deposition rates of particulates and/or absorption of gaseous pollutants. For example, preliminary estimates for Auckland indicate that 1320 t of particulates and 2740 t NO_2 are removed annually by urban trees (Cavanagh & Clemons 2003). Roadside vegetation has the potential to mitigate vehicle-generated air pollution although this beneficial role is currently not well recognised in NZ. A previous report (Cavanagh & Clemons 2003) provided an overview of the influence of urban vegetation on urban air quality. The current report extends the original report and focuses on the potential of roadside vegetation to mitigate road-generated air pollution, and to assess critical design factors to enhance mitigation.

Further, recognition needs to be given to the multiple purposes for which roadside vegetation may be used, for example, aesthetics, road run-off control/remediation, increasing biodiversity as well as the need for practical considerations regarding road-user safety, and location (e.g. how much space for plantings there is adjacent to a given road) considerations. It is intended that the information yielded in the proposed work can be integrated with these other 'uses' and constraints to yield designs that maximise the benefits of roadside vegetation. In order to achieve this it is important to understand how these other factors influence current roadside landscaping (and any potential restrictions this may place on vegetation design).

2. Background

There are a number of mechanisms by which urban vegetation can improve air quality. Trees can intercept atmospheric particles and absorb various gaseous pollutants. Various tree configurations can alter wind profiles or create local inversions to trap pollutants such that the localised removal of pollutants is enhanced (McCurdy 1978 cited in Nowak 1994; Khan & Abbasi 2001). Trees can lower air temperatures through transpiration, which affects the photochemistry of ozone and reduces ozone production (Cardelino & Charmeides 1990). Further, trees can reduce building energy use by shading buildings and altering air flows, thereby indirectly reducing pollution emission from power plants (Nowak 1994).

Recently, there has been renewed interest in the role in which trees can play in improving urban air quality (e.g. Powe and Willis 2004, Stewart et al. 2002, Beckett et al. 1998). For example, Powe & Willis (2004) estimate that for Britain as a whole, the economic value of health benefit of woodlands is £900,000 per year, in terms of savings from deaths brought forward, and reduced hospital emissions. Stewart et al. (2002) estimated that doubling the number of trees in the West Midlands of the UK could result in saving 140 lives from the effects of air pollution; Nowak (1994) estimated that trees in Chicago resulted in an average air quality improvement of 0.3% with the greatest overall removal effects for particulates <

10 µm (PM_{10}) removing 234 tons; Nowak et al. (1998) estimated that trees in Philadelphia improved air quality by 0.72%.

There are demonstrated health impacts in people living close to roads. For example, Kunzli et al. (2003) found that lung function growth was approximately 10% slower in children living in communities with higher levels of traffic-related pollution. Hoek et al. (2002) found that cardiopulmonary mortality was found to be associated with living near a major roads, and less consistently with the estimated ambient background. While there is a demonstrated potential of urban vegetation to enhance air quality, there are been few studies on the influence of roadside vegetation in improving air quality.

3. Objectives

The objectives of the current report are :
- review the existing literature to assess different design strategies (eg. spacing, width, plant types, etc.) of vegetation buffers to improve air quality (forthcoming)

4. Review

4.1 Pollutant removal by vegetation

The influence of vegetation in the removal of atmospheric pollutants is mainly seen in dry depositional processes, which are dependent on the nature of the surface. For example, as a consequence of the aerodynamically rough surface of forests and woodlands, transfer of pollutants is greater over forests than over short vegetation such as grass. The rates of dry deposition are dependent on both transfer to surfaces and the processes at the surface that determine uptake of gases and capture of particles. The first stage of the deposition process involves transport of the particles and gases to the forest canopy (Figure 1). Once inside the forest canopy, gases and particles must penetrate the leaf boundary layer. Gases and small particles (<1 µm) diffuse through this layer, while larger particles have to penetrate this layer by impaction or sedimentation. Impaction occurs when streamlines of airflow bend around obstacles but the particles continue in a straight line and impact the obstacle. Capture of particles that pass near to the leaf surface but without impacting it (interception) also occurs and is enhanced by the presence of fine hairs, surface roughness (e.g. bark vs leaf), leaf area, or stickiness (e.g. resins). Sedimentation is driven by gravity and will depend on particle density and diameter; typically it is more important for larger particles (>5 µm).

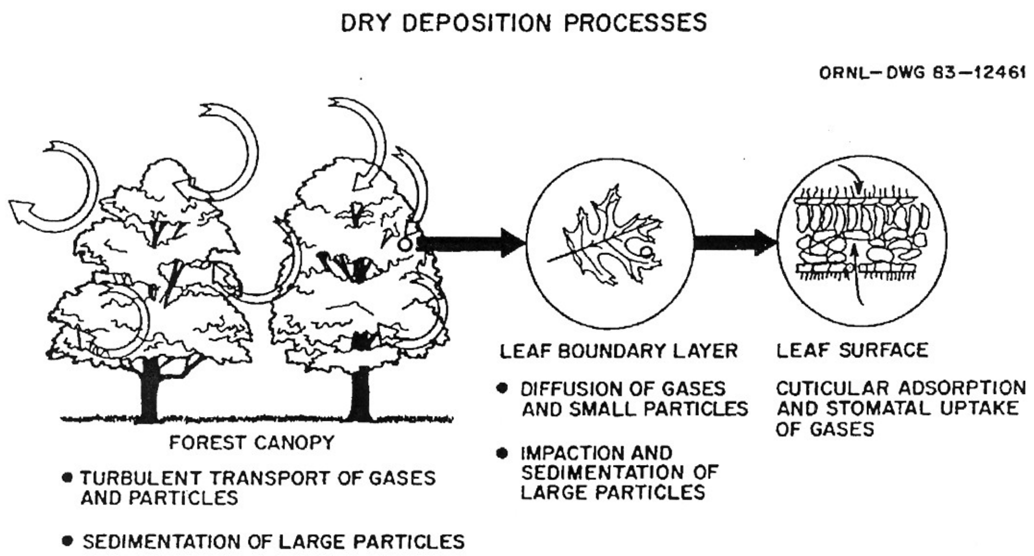

Figure 1 Dry deposition processes (Source: Lovett 1984).

Gaseous pollutants may either adsorb to the leaf surface or enter the interior of the leaf through the stomata (stomata are openings on the underside of the leaf and control the exchange of water vapour and CO_2 between a leaf and the atmosphere). Small particulates may similarly enter the leaf interior as the opening of the stomata is generally between 8-10 μm (Farmer 2002). Particles of this size are likely to become lodged in stomatal openings, while larger particles will be excluded from the leaf interior.

Deposition rates of pollutants onto vegetative surfaces are typically determined using a flux equation:

Flux (g/cm^2/s) = deposition velocity (cm/s) × concentration (g/cm^3).

Concentration and deposition velocity are defined for a specified height in the boundary layer. Deposition velocity or flux is then measured and used to calculate flux or deposition velocity respectively for the measured concentration at a given height. Deposition velocity is typically measured or determined using resistance analogy, where deposition velocity is given by the inverse of the sum of the atmospheric resistances and canopy resistances (e.g. Erisman et al. 1994; Nowak 1994). Alternatively, deposition flux can be determined by micrometeorological techniques (e.g. Nicholson 1988; Hanson & Lindberg 1991; Fowler et al. 2001) or direct measurement (e.g. Lindberg & Lovett 1985; Dasch 1987; Lovett & Lindberg 1984). Flux may be expressed on the basis of leaf surface area, or ground area using leaf area index (LAI), where leaf area index is the ratio of leaf surface area to ground area. Once flux has been determined, the above equation can be used to estimate deposition velocity for an individual pollutant (e.g. Freer-Smith et al. 2005).

Studies on the regional influence of trees on air quality have typically estimated deposition across a given region by multiplying the deposition flux of individual pollutants by the leaf surface area. The leaf surface area has been determined on the basis of the composition of tree species in that area and the leaf area of those tree species (e.g Nowak 1994; Simonich & Hites 1994b; Nowak et al. 1998; McPherson et al. 1998; Stewart et al. 2002). Nowak (1994), Nowak et al. (1998) and McPherson et al. (1998) estimated deposition flux, by determining the deposition velocity and measuring the air concentration of pollutants. These authors calculated the deposition velocity for individual pollutants using resistance analogy (see earlier). Meteorological data were used to calculate atmospheric resistances for the given geographical area, while the canopy resistance was averaged from literature estimates for gaseous pollutants

4.2 Deposition of particulates

Particulates are typically the primary factor driving health impacts of air pollution (e.g. Pope & Dockey), and significant health benefits may be gained by reducing particulate pollution. For example, El'Fadel & Massoud (2000) estimated that a 10-$\mu g/m^3$ reduction in PM_{10} in Lebanon could save 11–617 lives and US$0.27–12.6 million in the costs of illness. Removal of particulates by urban trees has received particular attention (e.g. Freer-Smith et al. 2005, Beckett et al. 2000).

Particles exhibit markedly different deposition velocities depending on their size – although a single deposition velocity for particulates is typically used in regional estimates of removal of particulates by urban vegetation (e.g. Nowak 1994, Nowak et al. 1998 and McPherson et al. 1998). A typical profile of the deposition velocity of particulates is shown in Figure 2. The different regions of the curve demonstrate the relative importance of different mechanisms of transport. For large particles (>5 µm) sedimentation effects predominate while for fine particles, Brownian diffusion predominates and increases with decreasing particle size. Particles in the size range of 0.1–2 µm are suggested to have limited means to move through the leaf boundary layer (Sehmel 1980; Lovett 1984; Fowler 2002).

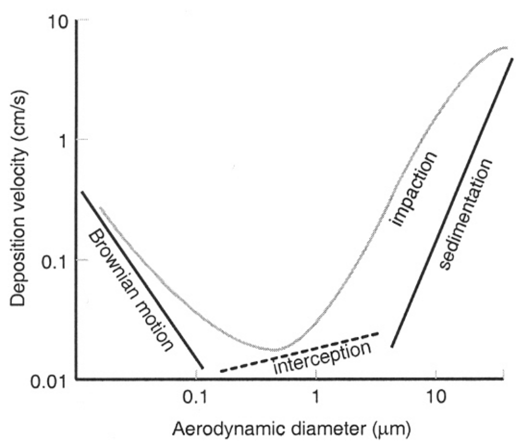

Figure 2. Deposition velocity profile for particulates of different sizes, and predominant depositon mechanisms (Source: QUARG 1996).

Larger particulates will be deposited closer to the source of pollution while smaller particles will be transported longer distances and behave more similarly to a gas. For example, Everett (1980 cited in Farmer 2002) found that most particulates larger than 50 µm were deposited within 8 m of the road, and at 30 m from road few particles less than 20 µm were found. In contrast Little & Wiffen (1978) estimated that less than 10% of lead, which is primarily associated with particles <0.1 µm, was deposited within 100 m of busy motorways.

Species-specific factors influencing mitigation potential

Tree type and leaf shape may influence the rate of removal of pollutants. Theoretically, greater deposition can occur over coniferous forests compared to broadleaf forests due to the larger leaf surface area of pines per ground area. Pine forests have 479 g of foliage per square metre of ground area, while oak has 106 g/m^2 (Whitherspoon & Taylor 1969). However, some studies show greater deposition of PAHs and PCDDs/PCDFs to deciduous forests than coniferous forests (Horstmann & McLachlan 1998). They attribute this difference to seasonal weather differences and partly to differences in canopy turbulence/leaf surface properties (and the subsequent influence on diffusive deposition to the canopy). In contrast, Matzner (1984) estimated that PAH deposition to soil was greater under spruce forests than beech forests.

More recently, Freer-Smith et al. (2005) calculated deposition velocities of different size particulates to 5 tree species (Table 2). Markedly higher deposition velocities were found for ultra-fine particulate fraction (aerodynamic diameter (Dp) <0.1 μm) than for the fine (<0.1 μm Dp <2.5 μm) and coarse (<02.5 μm Dp <10 μm) particles. This suggests that vegetation would be effective in removing these particulates that could be expected to have the greatest dispersion capacity. The lowest deposition velocities were found for the fine fraction, which corresponds to the typical deposition velocity profile.

Table 1. Particulate deposition velocity of particulates to different tree species.

Location Particulate size	**Deposition velocity (cm/s)**				
	Pine	**Cypress**	**Maple**	**Poplar**	**Whitebeam**
Sussex					
Coarse	2.79	3.43	3.64	0.57	5.35
Fine	1.75	4.58	9.22	0.81	11.04
Ultra-fine	36.24	33.72	31.72	25.43	27.2
Withdean					
Coarse	4.65	6.15	1.75	0.44	3.25
Fine	6.09	3.71	2.52	0.75	4.54
Ultra-fine	29.88	19.49	11.6	12.3	16.94

Species specific differences in efficacy of particulate capture (eg. Table 2), may in part be due to their size and available leaf area plants but also leaf surface. For example, plants with hairy or sticky leaves will result in greater deposition and retention of deposited particles. Absorption of particle-bound pollutants into the leaf epicuticular wax, particularly of conifers, appears to be an important factor in the deposition of semi-volatile contaminants to soil from conifers (Horstmann et al 1997).

However, trees can also contribute to air pollution through the emission of volatile organic compounds (VOCs), which can react in the atmosphere to form ozone in the presence of nitrogen oxides (NO and NO_2, collectively NO_x). The significance of the contribution of VOCs produced by trees to ozone production has only been recently recognised and the production of plant-sourced VOCs was suggested to be a reason for the failure of ozone abatement strategies in the US (Chameides *et al*. 1988; Cardelino & Chameides 1990).

Different plant species produce different types and amounts of VOCs (Corchnoy *et al.* 1992; Benjamin & Winer 1998). This information has been used to select species for planting in urban areas (e.g. Corchnoy *et al.* 1992; Benjamin *et al.* 1996) or to factor in the pollution potential of trees in the urban environment (e.g. Stewart *et al.* 2002; Taha 1996; McPherson *et al.* 1998).

Fate of captured particulates

Vegetation is considered a temporary repository for particles and particle-bound contaminants, as particles may be removed by rain or wind from the vegetative surface ('blow-off'). Indeed, some estimates of particulate dry deposition are based on measuring what is removed during rain events. Further, while the increased turbulence created by vegetation may result in the removal of particulates from the upper atmosphere, these particulates may not be deposited on the vegetation as they may 'bounce-off' the vegetative surface and be resuspended. Ultimately, a consequence of particulate capture by vegetation is that contaminant concentrations are elevated in soils under the vegetation.

Surface interactions may also influence retention of the particles. For example, sticky or wet leaves will result in greater retention of deposited particles. Particle surface characteristics, including particle charge, will also influence particulate retention. For example, lipophilic particles, such as those found in wood smoke, will adhere more strongly to waxy surfaces.

4.3 Particulate dispersion from roadways

Understanding the dispersion of particulates from roadways could assist in developing design options for roadside vegetation. These studies can be broadly grouped into three categories; a) particle profiles b) contaminant profiles and c) dispersion modelling. The latter category are mainly those that relate to regional modelling of air pollution and were not relevant for the current work, so are not discussed further.

Only a limited number of studies on the profiles (size-distribution) of road-generated particles were found. Of these, the majority were related to numbers of ultrafine (<1 μm) particles, (e.g. Weijers et al. 2004, Zhang et al. 2004a, 2004b, Gromotnev & Ristovski 2004), and did not consider the changes with vertical or horizontal distance from the road. An exception was Morowska et al (1999) who found that with the exception of close proximity to the freeway (15 m) there was no difference in particle number concentration of particles in the size range of 16-626 nm up to 200 m away from a road. Similarly there was no correlation with height of particle number concentration. However, studies on particle number are difficult to relate to the mass of particulates, which are the common measure for regulatory agencies, as these ultra-fine particles are typically only a small fraction of the total mass of PM_{10}.

One study on the vertical and horizontal profiles of particulates from roads, expressed on a mass basis, was found. This study found that concentrations of PM_{10}, $PM_{2.5}$ and PM_1 decreased as the height above ground increased from 2 m to 79 m, with the concentrations declining to 60%, 62% and 80% respectively, of the concentrations present at 2 m. The maximum decrease in concentration along a horizontal transect perpendicular to the road showed a maximum decrease in PM_{10}, $PM_{2.5}$ and PM_1 of 10% 9% and 7% respectively up to 228m from roadway. It would be expected that the presence of roadside vegetation would result in greater decreases of particulate mass along this transect.

Contaminant profile studies are those based on examining the concentrations of particulate-bound contaminants present in soils collected along transects perpendicular to the road. These studies typically find that the majority of contaminants are deposited within a narrow margin (e.g. 20-40 m) from the roadway. For example, Harrison & Johnstone (1985) found that fluxes of polycyclic aromatic hydrocarbons (PAHs), cadmium and copper were highly elevated close to the road and decreased to background concentrations within 20-40m. An exception to this is lead, which is typically associated with fine particles (see above). Whilst lead showed considerable roadside enhancement, deposition continued to decline over the full 220 m transect. Similarly, Little & Wiffen (1978) estimated that less than 10% of lead, which is primarily associated with particles <0.1 µm, was deposited within 100 m of busy motorways

A few studies have examined the influence of vegetation on deposition of particles or particle-bound contaminants. For example, Freer-Smith et al (1997) found that more dust accumulated on leaves of trees near to the M6 motorway. Novoderzhkina et al. (1966, cited in Dochinger (1980) found that dust concentrations in regions where widely spaced building planted with greenery, and separated from traffic by an 8-m wide greenbelt, did not exceed 0.5 $\mu g/m^3$ and was 2 to 3 times less than in areas where little greenery was present. Heichel & Hankin (1976, cited in Little & Wiffen 1978) found that the accumulation of lead in soil under a coniferous windbreak was twice that of open ground. Similarly, Little and Martin (1972, cited in Little & Wiffen 1978) found enhanced concentration of zinc, lead and cadmium under hedgerows and woodland in the vicinty of a smelter. Heath et al. (1999) examined the deposition of lead, copper and cadmium in transects located both in shelterbelts and open fields and found that the soil metal concentrations in a predominantly Scots Pine shelterbelt were highest at highway/shelterbelt interfaces, decreasing rapidly thereafter. In a birch shelterbelt it was found that influence of shelterbelt overrode the influence of prevailing wind, and resulted in similar soil metal concentrations being present in the transects on both sides of the road. Other studies have found an increase in the concentration of contaminants in the leaves of trees in close proximity to roads. For example, Kim & Fergusson (1994) found that lead concentrations on the leaves of horse chestnuts in Christchurch increased over a growing season, indicating capture of aerosol lead arising from the combustion of leaded petrol.

However, while these studies demonstrate the capture and potential for capture, of road-generated particulates by vegetation, they provide no information as to any critical design features (e.g. tree height, density of planting) that would enhance mitigation. Similarly, the available studies on particulate dispersion from roadways were also not useful in assisting the development of appropriate design options for roadside vegetation to enhance air quality benefits.

5. Design options for roadside vegetation

The available literature indicates that roadside vegetation has the potential to capture road-generated air pollution but provides no basis as to how different designs might influence the efficacy of capture. Further most of the existing literature is focussed on estimating the influence of vegetation in removing pollutants from ambient air; one purpose of roadside vegetation should be to capture road-generated pollution before it is able to be widely dispersed. Preliminary work is required to quantitatively establish the influence of roadside vegetation on road-generated air pollution, and in particular the relative efficacy of different designs.

There are a number of features that may impact on mitigation efficacy of roadside vegetation, the initial key features are anticipated to be proximity to road, vegetation height, and vegetation structure. Proximity to road and vegetation height will be influenced by a number of factors including road type (e.g. motorway vs road in the central business district), safety considerations (e.g. visibility at intersections, vehicle speed) and aesthetics. The Transit New Zealand *Guidelines for Highway Landscaping* (Tranist New Zealand 2003) provide some indication of the considerations that should be taken into account when undertaking planting of roadside vegetation. Vegetation structure is considered to be the overall shape of the vegetation. For example, in Christchurch some of the predominant roadside vegetation structures are; overhanging tree structure, hedge structure, landscape structure (which have largely been developed for noise reduction purposes) (Figure 3). Vegetation present in median strips and intersections can encompass a wide array of structures, although is typified by low shrubs and grasses (Figure 4). Within each of these generic structures there will be variations in the height, width and density of planting that will potentially influence mitigation efficacy. Species-specific differences will also influence mitigation potential, although it is initially anticipated that this will play a secondary role to the 'structural' features of roadside vegetation.

Two approaches will be adopted to ascertain the mitigation potential of roadside vegetation; an empirical approach, and a modelling approach. The empirical approach is based on direct measurement of particulate capture by roadside vegetation – this will be undertaken by measuring the deposition of particulates along transects perpendicular to the road in vegetated and non-vegetated areas. Leaf washing to ascertain the deposition of particulates on leaves may also be required for some vegetation structures (eg overhanging trees, median strip vegetation. The modelling approach is focussed on gaining better understanding the dispersion of particulates from roadways, primarily by gaining a better understanding of changes in particle-size distribution in relation to distance and height from the road. This would enable predictions to be made about the likely efficacy of roadside vegetation on particulate capture. For example, if the bulk of road-generated particulates are dispersed from the roadway at a height greater than 3-4 m, then overhanging trees are likely to be most effective. Conversely, if the bulk of road-generated particulates are dispersed from the roadway at a height less than 3-4 m then hedge or landscaped structure are likely to be most effective. Meteorological conditions will influence dispersion and needs to be taken into account, as does the influence of vegetation on dispersion. The modelling approach could also be used to estimate the relative significance of the capture of road-generated pollution by roadside vegetation in relation to the total road-generated emissions for a given road corridor, and potentially on a regional scale.

The initial work to be undertaken will be monitoring of particulate deposition along transects perpendicular to the road where a hedge structure and a landscape structure are present. Particulate deposition along these transects will be compared with that along transect(s) where no roadside vegetation is present. A different approach will be required to assess the overhanging tree structure, largely because overhanging trees are primarily located in residential or commercial areas which do not allow for appropriate transects to be established. Further in Christchurch there is a predominance of deciduous species as street trees, and there is a need to establish the relative influence of the overhanging trees during in-leaf and out-of-leaf seasons. To do this, the use of deposition plates, in combination with leaf-washing techniques (in-leaf season only) will be investigated. Finally, particle-size monitoring will be undertaken in locations close to the road, and at different heights. Monitoring of meteorological conditions and road traffic is also required.

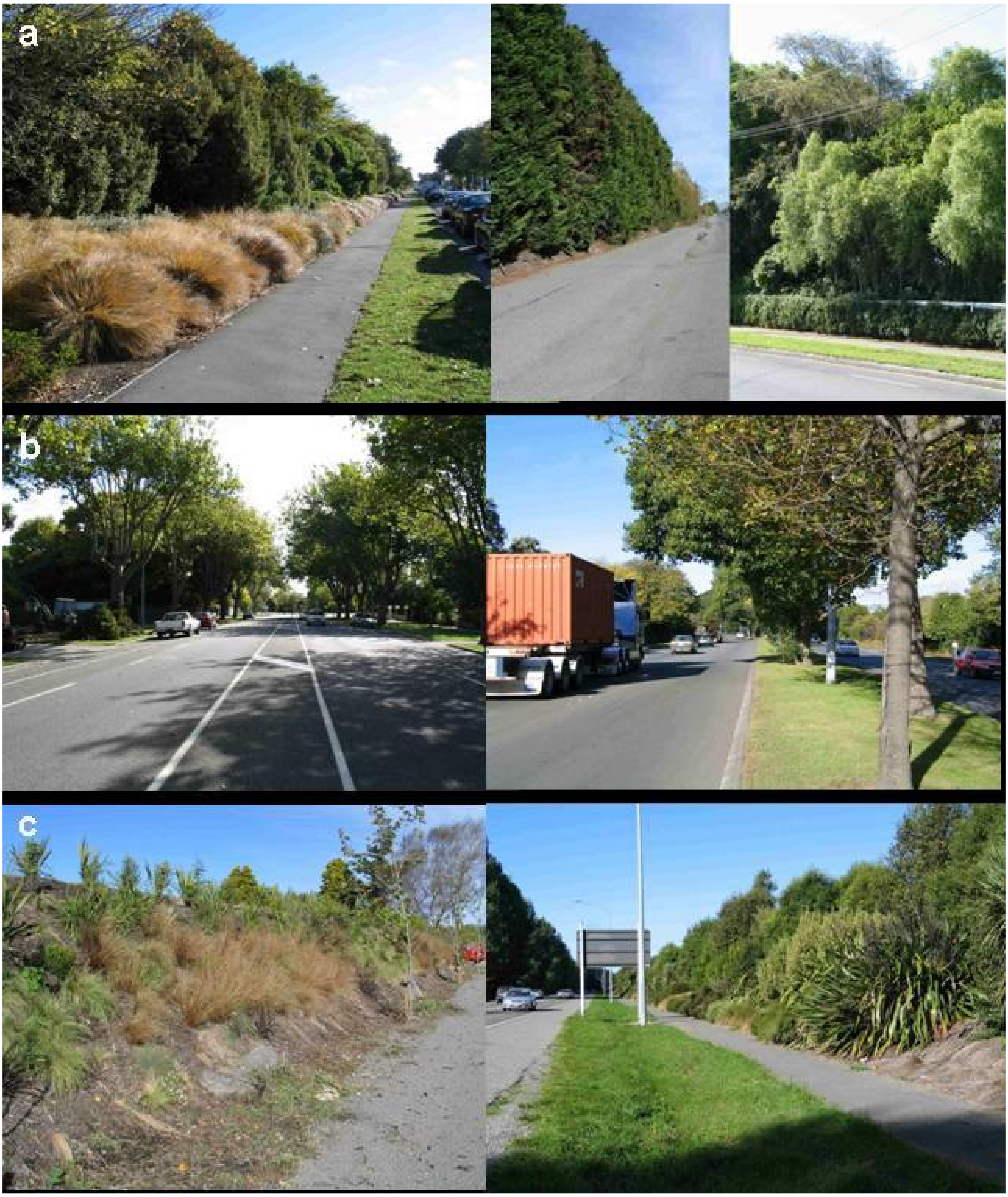

Figure 3 Examples of different roadside vegetation structures; a – 'hedge'; b – 'overhanging tree structure'; c – 'landscaped structure'.

Figure 4 Examples of vegetation present in median strips

6. Conclusions

While numerous studies have demonstrated the potential of roadside vegetation to mitigate road-generated particulates, they provide no information on design features (e.g. tree height, density of planting) that would enhance mitigation. Similarly, the available studies on particulate dispersion from roadways were also not useful in assisting the development of appropriate design options for roadside vegetation to enhance air quality benefits.

It is anticipated that forthcoming experimental work will enable design options for the enhancement of the mitigation potential of roadside vegetation to be developed.

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