Natural England Commissioned Report NECR199

The ecological effects of air pollution from road transport: an updated review

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Background

Biodiversity 2020 identifies air pollution as a direct threat to biodiversity in England. Many habitats of nature conservation importance in the UK are adapted to low nutrient conditions and/or are vulnerable to acidification, and are sensitive to additional airborne nitrogen oxides (NO_x), sulphur dioxide (SO_2) and ammonia (NH_3), as well as to nitrogen deposition and acid deposition.

Pollutants come from a range of different sources, but transport is known to be the single largest source of NO_x emissions. Natural England commissioned a study to assess what risk air pollution from roads poses to the SSSI and Natura 2000 network in England. There are two reports:

- NECR199: A literature review looking at the ecological effects of air pollution from road transport.
- NECR200: A mapping and site analysis report that classifies all designated sites (SSSIs and SACs) in terms of their exposure to NO_x from road traffic, taking into account other background sources of NO_x, and goes on to consider potential risk of impacts of NO_x from road transport in relation to SACs.

The objective of this literature review is to provide an addendum or update to the comprehensive review of ecological effects of diffuse air pollution from road transport on semi-natural habitats that was undertaken by Bignal and others in 2004.

This update:

- summarises the findings of peer-reviewed or grey literature published subsequently;
- incorporates conclusions from research looking at the impacts of, and remedies for, road traffic pollution in relation to Natura 2000 sites, specifically those features of interest that are sensitive to air pollution; and
- updates recommendations on remedies for tackling air pollution.

Natural England Project Manager - Clare Warburton, Senior Environmental Specialist (Transport), Natural England, Mail Hub Block B, Whittington Road, Worcester WR5 2LQ **clare.warburton@naturalengland.org.uk**

Contractor - Ricardo-AEA Ltd

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Further information
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RICARDO-AEA

The ecological effects of air pollution from road transport: an updated review

with supplementary summary of road-traffic measures for reducing emissions

Report for Natural England

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Contact:

Richard Smithers
Ricardo-AEA Ltd
Gemini Building, Harwell, Didcot, OX11 0QR
t: 01235 75 3615
e: Richard.Smithers@ricardo-aea.com
Ricardo-AEA is certificated to ISO9001 and ISO14001

Author:

Richard Smithers, Rachel Harris and Guy Hitchcock

Approved By:

Mark Broomfield

Date:

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Executive summary

A comprehensive review of the ecological effects of diffuse air pollution from road transport on semi-natural habitats (Bignal and others, 2004) concluded that:

- Knowledge of the impacts of road traffic pollution on vegetation was limited and that there were gaps in many aspects of lab-based and field-based research;
- Few studies had looked at differences in impacts along transects away from roads, which are critical to determining a road's 'edge effect' (due to traffic pollutants);
- Although there were many gaps in knowledge, the literature provided evidence that vegetation was being impacted by exposure to motor vehicle pollution at distances of up to 200m from roads and that there was potential for this distance to be greater;
- Although there was some evidence to suggest that wooded shelterbelts act as a physical barrier to nitrogen dioxide transport, buffer zones may be better regarded as providing physical distance between the road and protected sites, rather than an area of vegetation able to remove pollutants from the atmosphere.

The objective of this report, commissioned by Natural England, is to provide an addendum or update to Bignal and others (2004), which:

- Summarises the findings of peer-reviewed or grey literature published subsequently;
- Incorporates conclusions from research looking at the impacts of, and remedies for, road traffic pollution in relation to Natura 2000 sites, specifically those features of interest that are sensitive to air pollution;
- Updates recommendations on remedies for tackling air pollution.

The findings of this literature review are structured in accordance with Bignal and others (2004). Key conclusions from that document are highlighted at the start of each section.

Recent transect studies provide further evidence of the impacts on individual species from exposure to nitrogen oxides (NO_x) and nitrogen dioxide (NO_2) associated with vehicle emissions. These impacts are greatest within the first 50-100m from roads but may be discernible at greater distances. The studies also evidence that traffic emissions are a significant source of metal contamination, although it is unlikely to present a significant immediate toxic risk to plants.

The findings of many studies, undertaken since 2004, of the effect of nitrogen emissions from road traffic on habitats suggest that NO_2, rather than other forms of nitrogen deposition, is the likely driver of changes in roadside plant communities. All of the studies reinforce that differential effects may lead to changes in competitive advantage between species affecting the composition of vegetation, management of roadside sites and nature conservation.

The targeted literature search did not find any recent studies of the impact of road traffic emissions on below-ground biodiversity. However, a number of field studies have sampled and analysed soils, and consistently demonstrate that heavy metal concentrations from vehicle emissions decline within 5–10m and may not be discernible beyond 50m from roads.

The targeted literature search only located one additional study that specifically addressed impacts on plant-insect interactions. While other studies evidence that vehicle emissions are a significant source of metal contamination for roadside vegetation, they do not add weight to concerns about the impact of heavy metals on the wildlife food chain.

Recent fumigation studies using vehicle exhaust highlight that diesel exhaust emissions not only have potential to lead to changes in competitive advantage between plant species due to species-specific responses but also changes in interactions across wildlife food chains, with implications for habitats and communities close to roads.

Regarding the effects of specific road transport pollutants, combined evidence from two fumigation experiments and a transect study suggests that NO_x is the key phytotoxic component of exhaust emissions. The targeted literature search found no new evidence

specific to road emissions from fumigation and filtration studies of VOCs, NH_3, nitrogen deposition, metals or particulates/dust.

A large number of recent studies have focused on the ability of shelterbelts to reduce dispersal of particulate pollution from roads. While the papers' findings happen to interconnect neatly, the evidence, particularly in relation to finer particles, is ultimately more equivocal than suggested by the 2004 review. As with papers cited there, one study suggests that shelterbelts may reduce dispersal of NO_2 by acting as a physical barrier rather than by taking up the pollutant.

While no new papers relating to roadside buffer zones were identified from recent literature, one group of researchers noted that based on their data and the literature, new road building and road expansion should avoid a buffer zone of up to 100–200m from sensitive sites, particularly those where bryophytes are an important component of habitats.

No additional papers were identified on compensatory habitat creation in relation to the impact of air pollution from road transport on semi-natural habitats. However, the concept of 'biodiversity offsetting' may be relevant here, particularly when new roads are proposed. Consideration could be given not only to loss of habitat arising from its construction but also to loss of habitat quality arising from the subsequent impact of air pollution from traffic.

The 2004 review did not address the potential for on-site management to mitigate nitrogen deposition associated with road traffic emissions, but a recent review has identified that the potential varies greatly between habitat and management practice. Further evidence was not secured by the targeted literature search in this regard.

To supplement the results of the literature review, a summary of actions related to reducing emissions through road-traffic measures has been provided.

In relation to the components of the research programme proposed by Bignal and others (2004):

- A geographical analysis of designated sites at potential risk of impacts from road traffic pollution is currently being implemented by Ricardo-AEA, in association with this project, for Natural England;
- Although quite a number of new transect studies have been identified, there remains substantial scope to increase understanding through further such studies in order to address the full range of habitats, traffic flows and meteorological conditions;
- It would be highly beneficial if transect studies could be established for all future major road schemes with potential to affect designated nature conservation sites;
- This review has identified that NO_2 and NO_x are the chemical components of vehicle exhausts of greatest concern and further research in their regard remains a priority;
- There is a need for further research to inform any further refinement, use, and interpretation of Critical Loads for nitrogen deposition and the Critical Level for NO_x. This is of particular importance to consideration of potential impacts from existing and proposed roads on delivery of conservation commitments and biodiversity targets.

Bignal and others (2004) focused the need for future research on the current and future ecological impact of road traffic pollution from the existing road network and new roads. However, this latest review highlights the need for further research into the efficacy of mitigation measures, including:

- Field studies and accurate modelling of relationships between roadside topography, physical barriers (including width and density of shelterbelts) and pollutant dispersal, particularly NO_2 and NO_x;
- Studies to determine impacts of individual management practices on nitrogen across a range of habitats, including novel techniques to remove nitrogen from sites;
- Piloting and monitoring application of road traffic measures in the vicinity of designated nature conservation sites at high risk of impacts from road traffic pollution.

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Appendices

1 Introduction

A comprehensive review of the ecological effects of diffuse air pollution from road transport on semi-natural habitats (Bignal and others, 2004) concluded that:

- Knowledge of the impacts of diffuse pollution from road transport on vegetation was limited and that there were gaps in many aspects of both lab-based and field-based research;
- Few studies had looked at differences in impacts along transects away from roads, which are critical if the ‘edge effect’ of a road (due to motor vehicle pollutants) is to be determined;
- Although there were many gaps in knowledge, the literature provided evidence that vegetation was being impacted by exposure to motor vehicle pollution at distances of up to 200m from roads and that there was potential for this distance to be greater;
- Although there was some evidence to suggest that wooded shelterbelts act as a physical barrier to nitrogen dioxide transport, buffer zones may be better regarded as providing physical distance between the road and protected sites, rather than an area of vegetation able to remove pollutants from the atmosphere.

The objective of this report, commissioned by Natural England, is to provide an addendum or update to Bignal and others (2004), which:

- Summarises the findings of peer-reviewed or grey literature that has been published subsequently;
- Incorporates conclusions from research looking at the impacts of, and remedies for, road traffic air pollution in relation to Natura 2000 sites, specifically those features of interest that are sensitive to air pollution;
- Updates recommendations on remedies for tackling air pollution.

2 Methodology

2.1 Collating all relevant documents

As a starting point for producing an addendum or update to the comprehensive review of the ecological effects of diffuse air pollution from road transport produced by Bignal and others (2004), Natural England provided Ricardo-AEA with a list of relevant literature that it was aware had since been published. Each of the documents highlighted was ‘snowballed’ (i.e. the literature that they cite was also explored). Ricardo-AEA then undertook a targeted search to identify all other relevant documents that have since been published in peer-reviewed journals and ‘grey literature’ from the UK, Europe and internationally. The search engines ScienceDirect and GoogleScholar were used.

The search addressed a wide range of potentially relevant subject areas. These were divided into three themes: ‘Pollutant source’, ‘Ecological receptor’ and ‘Impact’. The themes were sub-divided into lists of keywords designed systematically to identify relevant studies (Table 1).

Table 1 Keywords for targeted literature search

1. Pollutant source	2. Ecological receptor	3. Impact
1a. Road emissions	2a. Habitat	3a. Eutrophication
1b. Road pollution	2b. Woodland	3b. Acidification
1c. Road fumes	2c. Tree	3c. Nitrogen deposition
1d. Traffic emissions	2d. Vegetation	3d. Acid deposition
1e. Traffic pollution	2e. Plants	3e. Mitigation
1f. Traffic fumes	2f. Species	
1g. Vehicle emissions	2g. Soil	
1h. Vehicle pollution	2h. Buffer zone	
1i. Vehicle fumes	2i. Shelterbelt	

Each combination of keywords was entered into the search engines in turn for ‘Pollutant source’ + ‘Ecological receptor’ and then ‘Pollutant source’ + ‘Ecological receptor’+ ‘Impact’. All relevant documents were collated in a summary spread-sheet to facilitate its subsequent evaluation (Section 2.2) and review (Section 2.3). The spread-sheet included the following column headers:

- Author(s);
- Year;
- Title of document;
- Source (including hyperlink where available);
- Location (England, UK, EU, International);
- Data quality (peer-reviewed, Government, third party);
- Strength of data (evidence-based, subjective);
- Data ‘pedigree’ (see Task 2);
- Columns for relevance to each of the sub-headings in Section 3 of this report, which replicate those in the 2004 document;
- Possible case studies;
- Summary of document objectives.

In addition, each of these documents was ‘snowballed’ in an effort to ensure no important sources of information were overlooked.

Finally, a rapid search was undertaken of all government agency and research institution websites to double-check that no documents had been missed.

The search using the term ‘mitigation’ was slightly less thorough, as it identified a large number of documents. As such, only those documents that were consistently identified using the term ‘mitigation’ in combination with the range of other search terms were selected in order to focus in on those that are likely to be of most wide-ranging importance.

2.2 Evaluating evidence and data

The strength of evidence arising from individual studies was assessed having due regard to whether or not they were peer-reviewed and any differences between the conditions under which the data were obtained and the situation in England. Evidence was evaluated following the “data pedigree” approach (van der Sluijs and others 2002). “Pedigree” is a description of the reliability of the information from which data have been derived. It considers the following aspects of the quality of information:

- Proxy: is the value based on a direct measurement of the parameter in question, or on some other measurement that is correlated more or less well with the parameter;
- Empirical basis: is the value based on a large number of field measurements, a smaller number of field measurements, modelled values, estimates or speculation;
- Methodological rigour: is the data obtained using best practice, widely used approaches, laboratory or research tools, or is no information provided on these methods;
- Validation: can the data be cross-checked extensively, to a limited or indirect extent, or not at all?

The pedigree of each of the collated documents was evaluated by scoring key elements of the underlying data between 0 and 4 on the above four aspects, using the framework in Figure 1. Data pedigree was established from the lowest score for any of the key inputs. A score of 0 – 4 was described as poor; 5 – 8 moderate; 9 – 12 good; and 13 – 16 very good. These scores were also recorded in the spread-sheet described in Section 2.1.

		Strength indicators			
		Proxy	**Empirical**	**Method**	**Validation**
Score	**4**	An exact measure of the desired quantity	Controlled experiments and large sample of direct measurements	Best available practice in well-established discipline	Compared with independent measurements of the same variable over long domain
	3	Good fit or measure	Historical/field data, uncontrolled experiments, small sample of direct measurements	Reliable method, common within established discipline, best available practice in immature discipline	Compared with independent measurements of closely related variable over shorter period
	2	Well correlated, but not measuring the same thing	Modelled data, indirect measurements	Acceptable method but limited consensus on reliability	Measurements not independent proxy variable with limited domain
	1	Weak correlation, but commonalities in measure	Educated guesses, indirect approximations, rule of thumb	Preliminary methods with unknown reliability	Weak and very indirect validation
	0	Not correlated and not clearly related	Crude speculation	No discernible rigour	No validation performed

Figure 1 Pedigree-matrix to evaluate data and evidence from the selected literature

2.3 Review and synthesis

All papers identified and evaluated were reviewed and synthesised with reference to the conclusions of the following sections of Bignal and others (2004):

- Section 2.4 Key issues and considerations;
- Section 2.5 Evidence of impacts of road transport pollution;
- Section 2.6 Methods to mitigate the impact;
- Section 3 Case studies;
- Section 4 Summary of current evidence;
- Section 5 Future research.

In addition, conclusions were extracted from a ‘Review of the effectiveness of on-site habitat management to reduce atmospheric nitrogen deposition impacts on terrestrial habitats’ (Stevens and others 2013), as this issue was not addressed by Bignal and others (2004).

To supplement the report, Ricardo-AEA’s experts in reducing emissions through road-traffic measures have also provided a summary of related actions, which were not covered in Bignal and others (2004). Although this summary is based on recent literature, it did not result from the targeted literature review.

3 Results of targeted literature review

3.1 Introduction

The results of the literature review presented here are structured in accordance with Bignal and others (2004), for ease of cross reference, with key quotes from that document highlighted in boxes at the start of each section.

The summary spread-sheet of all relevant documents collated and evaluated following our targeted literature search can be found at Appendix 1. The pedigree of each of the papers identified was evaluated as ‘good’ or ‘very good’ indicating that the information from which the data was derived is reliable.

3.2 Key issues and considerations

Identified in the 2004 review

“When evaluating the impacts of air pollution from roads, it is important to consider a number of key issues (Ashmore 2002):

- *It is important to distinguish the presence of elevated concentrations of a particular substance (contamination) from evidence that these concentrations have an adverse effect (pollution). Thus, many studies have demonstrated that elevated concentrations of lead are found in air, soils, plants and animals close to major roads, but the evidence that these elevated concentrations have significant ecological impacts is more limited;*
- *The effects of pollutants may be cumulative over time. Thus, whereas the impact of opening a new road on wildlife mortality may be immediate, that of air pollution may be much more gradual. Continued emissions, for example, of metals may lead to slow increases in roadside concentrations, while emissions of nitrogen oxides may lead to a gradual increase in the nitrogen content of vegetation and soils close to roads. Biological responses to these gradual chemical changes may be non-linear, only becoming apparent when pollutants have accumulated to specific threshold concentrations. This means that, in terms of air pollution, the full ecological impact of the road building programme which has taken place over the past thirty years may only appear in the decades to come;*
- *The effects of combinations of pollutants, such as those emitted from road traffic, may be quite different from those of the individual pollutants, and this may make it difficult to attribute any effects observed to a particular component of the exhaust emissions. Nevertheless, the potential to link ecological effects to a specific pollutant has important policy implications. For example, emissions of particles and carbon monoxide tend to be high at low speeds, whereas those of nitrogen oxides increase rapidly at high speeds. If nitrogen oxides have greater impacts on a particular ecological community, then measures to reduce local speeds might be beneficial, but if carbon monoxide or particles had a greater impact, then this would not be the case;*
- *There is large interspecific and intraspecific variation in the sensitivity of organisms to air pollution. Thus, the impacts of a particular road scheme may depend critically on the particular communities and organisms found close to it. Evolution of tolerance to both soil metal pollution and atmospheric pollutants has been clearly demonstrated in grasses, and the demonstration that roadside populations have greater pollution tolerance may provide evidence that pollutants are present in ecologically significant concentrations;*
- *The effects of air pollutants may be substantially modified by other local factors, such as climate, soils and management. It is important that these, and other, interactions are considered when evaluating the potential impacts of a particular road scheme. In the case of roadside communities, there may be additional specific stress factors, which may interact with air pollutants, such as salt accumulation in soils or the effects of gusts of wind produced by passing traffic.”*

In addition to the key issues identified by Bignal and others (2004), when evaluating the impacts of air pollution from roads, it is important to take into account that their contribution combines with other sources of pollutants that may already approach or exceed Critical Levels or Critical Loads.

Critical Levels are defined as "*concentrations of pollutants in the atmosphere above which direct adverse effects on receptors, such as human beings, plants, ecosystems or materials, may occur according to present knowledge*"[1]. Critical Loads are defined as "*a quantitative estimate of exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge*"[1].

Critical Loads for nitrogen are set empirically, using evidence from long-term field experiments, field surveys and, to a lesser degree, broad ecological surveillance datasets. Nevertheless, Critical Loads for some habitats rely to a large extent on expert judgment. Furthermore, a recent study (e.g. Emmett and others 2011) has detected that nitrogen deposition below Critical Loads may be associated with changes in some species and ecosystem function indices, indicating that Critical Loads may not protect all species or ecosystem functions, with possible implications for current conservation commitments and biodiversity targets. This study also identified that changes in species and ecosystem function indices continue above Critical Loads.

3.3 Evidence of impacts of road transport pollution

Roadside/field studies

> Conclusions from the 2004 review
>
> ***"Few field studies have been undertaken at different distances from roads*** *and those that have are generally limited to effects on single species rather than communities, habitats or ecosystems.* ***No known studies have looked at a site before and after road construction to assess changes in the vegetation.***
>
> *There are a limited number of field studies that have assessed species response to motor vehicle pollution at either different distances from a road or near roads of different traffic density, and hence different pollution levels. In addition,* ***pollution levels are not measured in many studies, or are recorded only for a limited number of motor vehicle exhaust pollutants making it difficult to assess critical levels for vegetation."***

Introduction

Many of the field studies identified by the targeted literature search look at pollution levels associated with road traffic but not at their impact. Other field studies located look at trends in pollution and changes in vegetation but do not attribute them to roads. There are also still no known studies that have considered sites before and after road construction to assess changes in vegetation. However, described below is a wide range of additional transect studies published since the 2004 review, which have looked at the effects of road traffic emissions on: species; habitats or communities; and plant-insect interactions.

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[1] http://www.unece.org/env/lrtap/WorkingGroups/wge/definitions.htm

Effects on individual species

Conclusions from the 2004 review

"Despite the limited number of field studies on single species and the lack of studies that assess effects on a transect away from the roadside, a number of clear effects of exposure to motor vehicle emissions were observed** that are likely to be applicable to a far wider range of species**. These include effects on surface wax degradation, enzyme activity, physiology, chemistry and senescence. The observed responses have been attributed either solely to exposure to VOCs, particulates, NO$_x$ and ethylene or to a combination of motor vehicle pollutants."

Since the 2004 review, a number of transect studies have looked at the effects of road traffic pollution at a species level. Some have focused on NO$_x$ and nitrogen deposition, others have addressed heavy metals.

NO$_x$ and nitrogen deposition

The sensitivity of epiphytes on ash *Fraxinus excelsior* in London was investigated by comparing roadside sites with high levels of vehicle emissions and background sites where pollutants were present at much lower concentrations (Davies and others 2007). A tentative scale of lichen sensitivity to NO$_x$ (and associated transport pollutants in urban areas) on neutral to eutrophicated bark was deduced from the mean and maximum tolerances exhibited by the species recorded. Lichen diversity declined where NO$_x$ exceeded 70μg/m^3 and NO$_2$ exceeded 40μg/m^3.

Field studies of the local impacts of motor vehicle pollution were undertaken by Bignal and others (2007) at sites adjacent to the M62 in northern England (secondary sessile oak *Quercus petraea* plantation at Bradley Wood and blanket bog at Moss Moor – part of the South Pennine Moors Special Area of Conservation, SAC) and the M40 in SE England (beech, *Fagus sylvatica,* woodland at Aston Rowant National Nature Reserve, NNR). The remoteness of these sites from other point sources of air pollution helped attribution and interpretation of results. Tree health was assessed at Bradley Wood and Aston Rowant, and the vegetation (including bryophytes and lichens) was surveyed at Moss Moor, along transects extending up to 250m from the edge of the motorways. Measurements of NO$_2$ concentrations were also made at all three sites. At Bradley Wood, more than 60% of oak trees adjacent to the road had severely defoliated and discoloured crowns, but 50m along the transect some oak trees had no defoliation and by 150m no trees were severely defoliated. At Aston Rowant there was little difference in beech tree health between 50–200m from the motorway except for leaf discolouration, which affected more than 30% of trees up to 100m from the road. The results at Bradley Wood implied a shorter growing season with potential consequences for the functioning of the woodland. The distribution of individual species along transects from the motorway at Moss Moor showed few patterns with the exception of the moss *Polytrichum commune*, which was more abundant within 50m of the road and declined significantly in frequency with distance from it. The distance from the motorways that effects on the health of sessile oak, beech and the frequency of *P. commune* were recorded was consistent with the measured profile of NO$_2$, which declined from c. 25ppb at roadside to background levels (c. 10-17 ppb) at about 100m at all three sites.

Bignal and others (2008) undertook a transplant study to determine the impact of exposure to road traffic pollution on six bryophyte species: *Dicranum scoparium, Hylocomium splendens, Isothecium myosuroides, Pleurozium schreberi, Racomitrium lanuginosum* and *Rhytidiadelphus loreus*. They assessed whether air pollutants from a motorway had significant effects on the growth and physiology of the bryophytes over a seven-month period from autumn to spring in two different habitats, woodland and moorland. Within 50-100m of the road, all species showed an increase in one or more of the following: growth, membrane leakage, chlorophyll concentration, and nitrogen concentration. Although, it was difficult to attribute the observed effects to specific pollutants, they were consistent with the profile of concentrations of NO_2 and NO_x, which declined from c.25ppb at roadside to background levels (c.15ppb) within 100-125m of the motorway. Other pollutants ruled out were the impact of salt and other spray and particulates (including metals and particle-bound polycyclic aromatic hydrocarbons, PAHs) and gases with a high-deposition velocity (e.g. nitrous acid, HONO, and ammonia, NH_3). The observed effects were also typical of nitrogenous pollution.

Laffrey and others (2010) focused on transplants of purple moor grass *Molinia caeruea* a common species of nitrogen-limited habitats, including acid grassland, heathland and bogs. They sought to assess whether nitrogen emissions from road traffic had significant effects on the growth of plants and their nitrogen content and to estimate distances from roads at which significant effects could be detected. Plants were established adjacent to main roads at two different sites, selected for their remoteness from other major point-sources of nitrogen in southeast France. NO_x levels, measured using passive samplers, followed an exponential relationship with distance from roads declining to a low level beyond 300m. Plant-growth parameters were measured along 500m transects at right angles from roads. Nitrogen content was found to be higher in plants closer to roads with concentrations significantly elevated up to 300m from roads. Increased nitrogen content promoted plant growth, as indicated by differences with distance from the road, although the effects of long-term exposure were not determined.

Bell and others (2011) carried out a transect study in the Natural History Museum's Wildlife Garden in Central London, located alongside one of the capital's busiest arterial roads, in order to complement controlled fumigation experiments with diesel exhaust pollutants, nitric oxide (NO), nitrogen dioxide (NO_2) and their mixture. The study benefited from records from a continuous air pollution monitoring station situated within the garden. The experiment was undertaken over winter along a transect using smooth meadow-grass *Poa pratensis* common sorrel *Rumex acetosa* and white clover *Trifolium repens* as all three species remain green and commence growth in the early spring, and the lack of a tree canopy minimised potentially confounding impacts of shade. The plants were placed at five locations along a 100m transect from the edge of the road. Air pollution data showed significant gradients of pollutants away from the road: NO_2 declined along the entire transect; NO fell to background levels within 35m; while ozone (O_3) increased with distance from the road. The influence of pollutants on leaf surface structure, as measured by the static contact angle of water drops on individual leaves, decreased significantly with the logarithm of distance from the road for both *P. pratensis* and *R. acetosa*.

Lee and Power (2013) undertook transect studies at eight species-rich calcareous grassland sites of high conservation value in Hampshire, Surrey and East Sussex (Aston Rowant NNR, Butser Hill NNR, Lewes Down NNR, Martins Down NNR, Newlands Corner nature reserve, Stockbridge Down Site of Special Scientific Interest – SSSI, St Catherine's Hill SSSI and Seale Chalk Pit SSSI). The sites were all in close proximity to roads with a range of traffic flow rates and had a variety of slopes and aspects. Along 100m transects perpendicular from roadside boundaries: soil samples were analysed for toxic metals, soil pH, salinity and moisture content; and cover estimates of vascular plants in $1m^2$ quadrats were used as a measure of species abundance, while the total number of vascular plants was used to define species richness. Average, frequency-weighted UK Ellenberg values[2] were determined for fertility, salt, reaction (pH) and moisture for each quadrat (Hill and others 1999). NO_2 concentrations were modelled at each site based on a year-long study at three of the sites where NO_2 concentrations were also measured over a two-month period. A positive linear relationship was found between the modelled and measured monthly NO_2 concentrations. Modelled annual mean concentrations at roadside ranged from 13−45$\mu g/m^3$ for NO_2 and

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[2] Ellenberg values have been assigned to all vascular plant species likely to be found in the British Countryside. Values relate to a species realised ecological niche and have been assigned on relative scales of 1-9 with regard to their tolerance to light, fertility, salt and reaction (pH), and on a relative scale of 1-12 for moisture (Hill and others, 1999).

from 2.3−7.3µg/m^3 for NH_3, both declining logarithmically away from the road edge, However, while modelled NH_3 declined to background concentrations within 20m of roadsides, modelled NO_2 deposition rates remained considerably higher than the background along the entire length of the transects and the authors concluded that NO_2 deposition rates are likely to continue to decline over a greater distance. Dropwort *Filipendula vulgaris* and wild thyme *Thymus polytrichus* increased nearer roadsides; species which the authors note experiments have shown respond positively to addition of nitrogen. The abundance of five nitrophilic species was also greater closer to roads: cocksfoot *Dactylis glomerata*, Yorkshire-fog *Holcus lanatus*, dove's-foot crane's-bill *Geranium molle*, red bartsia *Odentites verna*, and wild parsnip *Pastinaca sativa*.

Heavy metals

Viard and others (2004) studied two sites alongside the A31 between Nancy (France) and Luxembourg to assess contamination arising from road traffic (c. 40,000–60,000 vehicles per day). Transects 300m long were surveyed on both sides of the road at the two sites. Along the length of each transect, atmospheric deposition was measured by collecting liquid and solid fallout, and soil samples were collected monthly along with grasses (tall fescue *Festuca arundinacea*, canary-grass *Phalaris sp.* and cocksfoot) and analysed for metals. Ten juvenile garden snails *Helix aspersa aspersa* were introduced in cages along the length of the transect, left in situ for one week, analysed for bioaccumulation of metals and results compared with those for ten snails kept for the same period under controlled conditions. Deposition of zinc and lead exceeded national guidelines with lead still at elevated levels 320m from the road. Metal concentrations in the grasses at different distances differed according to the site and the metal. In decreasing order of magnitude, concentrations of zinc, lead and cadmium in the on-site snails were significantly higher than the reference snails. Those placed in cages at 1–5m from the highways were the most contaminated. Lead was identified as the best indicator of highway contamination but, with the introduction of unleaded fuel, the authors suggest another indicator needs to be found (eg platinum from catalytic silencers or additives of unleaded petrol, such as MTBE (methyltertiobuthylether), ETBE (ethyltertiobuthylether), or TAME (methyltertioamylether).

Transect studies were carried out by Peachey and others (2009) at a rural control site and two parks in Central London, selected as close to roads and recognised as particulate 'hotspots' where air quality objectives are often breached due to the high traffic densities. Measurements indicated that concentrations of particulate matter of 10nm in diameter or less (PM_{10}) in the air were higher within 25m of roads at both urban sites and that metal concentrations in soils declined sharply within 10–12m and more gradually between 12–50m. As a result, plants of downy birch *Betula pubescens L.*, Lawson cypress *Chamaecyparis lawsonia*, field maple *Acer campestre L*. and common nettle *Urtica dioica L.* were placed along 12m transects perpendicular to roads. The species were chosen to represent a wide range of potential particulate uptake rates and because of their prevalence in urban areas. After having been left in situ at the urban sites, leaves of all four species had elevated concentrations of metals (cadmium, chromium, copper, iron, nickel, lead and/or zinc) associated with particulate pollution from road traffic emissions, as compared to plants at the rural control site. There were no major differences between metal concentrations in leaves at the two urban parks despite plants being exposed for 55% longer at one site (114 days as compared to 74 days). The authors draw support from other studies to suggest that adsorption sites on leaves may be quickly filled with metal particles, as explanation for concentrations plateauing in less than 11 weeks. Despite observed declines in PM_{10} concentrations in the air and metal concentrations in the soil with distance from the road, metal concentrations in leaves of the three tree species did not show any consistent pattern except for copper concentrations in birch and maple, which were significantly related to the distance from the road. However, total concentrations of cadmium, chromium, copper, iron, nickel and zinc in nettle leaves were all closely related to distance from the road. The authors note that these differences between species are likely to be due to their differing leaf arrangement, morphology and/or surface properties. By reference to other studies, they highlight that species, such as nettle and birch, with a large number of small, hairy, sticky leaves are more efficient at capturing particulates, while lower metal concentrations found in maple leaves may be due to their larger leaves and waxy cuticles. Although concentrations in Cypress needles were lower than in the other species, the authors note that, as this tree has a larger leaf area index, the total mass of particulates may be greater and compounded by it not being deciduous.

In order to investigate whether leaves of plane trees *Platanus orientalis* are damaged by traffic pollution, Pourkhabbaz and others (2010) measured metal concentrations in soils and air, as well as functional properties of leaves, at a megacity (Mashhad, Iran) and a rural area. The urban soils contained higher concentrations of lead, zinc, chromium, and copper, while lead cobalt and chromium were elevated in the urban air. The authors point to other studies that suggest road traffic contributes up to 75% of such pollution. However, lead was the only metal found at raised levels in urban leaves. The authors note that this is unlikely to be due to uptake from soils, as lead is a heavy metal with low mobility in plants. Urban leaves were smaller, covered in cost and had thinner cuticles and a lower density of stomata, however, the latter were not clogged and their other anatomical properties were unaffected, which the authors suggested indicate that plane trees can cope with road traffic emissions. However, rates of photosynthesis and hence growth may be affected, as may be tolerance to drought.

These field studies of individual species on transects away from roadsides reinforce the conclusions from the 2004 review. They provide further evidence of the impacts on individual species from exposure to NO_x and NO_2 associated with vehicle emissions and that these are greatest within the first 50-100m from roads but may be discernible at greater distances. The studies also evidence that traffic emissions are a significant source of metal contamination for vegetation close to roads, although the leaf concentrations recorded are unlikely to present a significant immediate toxic risk to plants.

Impacts on habitats and communities

> Conclusions from the 2004 review
>
> *"**Few studies have attempted to take into account the effect of emissions from motor vehicles on entire habitats or communities, as opposed to individual species.** This approach is recommended, however, as species do not exist in the environment in isolation, and any effects on a single species may be expected to have knock-on effects on the habitat or community in which it occurs.*
>
> *…**motor vehicle pollution affects the species composition of heathland habitats as well as lichen communities.**"*

Measurement of NO_2 and NH_3 concentrations at Epping Forest (Gadsdon and Power 2009), a 2,500ha Special Area for Conservation Epping Forest located 18 km NE of London, has demonstrated that local road traffic emissions can make a substantial contribution to the exceedance of critical levels and critical loads. Epping Forest is crossed by several major roads, including the M25, and the M11 also runs close by. Critical levels of NO_2 and NH_3 were exceeded at nearly all roadside locations and up to 20m away in some instances. Away from roads, concentrations were higher in the canopy than at ground level but the reverse was true at roadsides where NH_3 dominated nitrogen inputs.

A range of field studies undertaken since 2004 have sought to investigate the effect of nitrogen emissions from road traffic on habitats or communities.

To determine the extent that nitrogen emissions from traffic, disturbance and management affect the vegetation composition of road verges, Truscott and others (2005) surveyed 11m transects at 92 verges in Scotland. Sites were stratified by background nitrogen deposition and road type. Species and cover of vascular plants, mosses and lichens were recorded in 10m x 1m quadrats with the long axis parallel to the road. NO_x and NH_3 concentrations were monitored bimonthly at 15 key sites for a year and were shown to decrease with increasing distance from the road. Although the UK Ellenberg fertility scores (Hill and others 1999) for the vegetation communities also generally decreased further from the road there was no correlation with air concentrations of NO_x and NH_3 at the 15 key sites. Bare ground and ruderal species increased towards the edge of the road indicating that direct and indirect disturbance was an important factor in determining the composition of roadside vegetation, although the increase may also be attributed to a nutrient gradient. As such, the study was unable to determine whether nitrogen levels, disturbance, salt or a combination of these factors influenced the vegetation composition.

A transect study in the Munich-area of Southern Germany (Bernhardt-Römermann and others 2006) considered the effect of motorways on the composition of a 90–120year-old homogeneous Norway spruce *Picea abies* forest, which they dissect. Background levels of nitrogen pollution in the area were 15–20kg/ha. The composition of vegetation, soil parameters and deposition data were sampled along 520m transects. Patterns detected suggested that impacts on the composition of the field layer extended for up to 230m downwind and up to 80m upwind of the motorways. It was concluded that the vegetation was predominantly affected by nitrogen deposition from fuel combustion and the use of road salt.

Davies and others (2007; see Section 3.3 Effects on individual species) also considered the influence of road traffic emissions on diversity of epiphytes on ash *Fraxinus excelsior.* The diversity of epiphytes declined where NO_x exceeded 70μg/m^3 and NO_2 exceeded 40μg/m^3. In stark contrast, Frati and others (2006), studying the impact of road traffic emission in rural Italy, found that the distance from a highway had little influence on lichen diversity or on tree bark properties. This is not surprising, given that NH_3 levels (0.5-1.0μg/m^3) and NO_2 levels (7.3-16.6μg/m^3) were low or very low and only NO_2 concentrations declined with distance from the road.

The transect study of blanket bog at Moss Moor (part of the South Pennine Moors SAC) adjacent to the M62 in northern England (Bignal and others 2007; described in Section 3.3 Effects on individual species) used UK Ellenberg fertility scores for vascular plants (Hill and others, 1999) to calculate a cover-weighted Ellenberg index. This clearly showed that species adapted to higher nitrogen availability had greater ground cover up to about 75m, which was consistent with the measured profile of NO_2, which declined to background levels at about 100m.

The transplant study (described in Section 3.3 Effects on individual species) undertaken by Bignal and others (2008) to determine the impact of exposure to road traffic pollution on six bryophyte species identified that some species grew more rapidly suggesting that they benefited from their proximity to the motorway, however, other species did not respond.

Lee and others (2012) studied three important, species-rich chalk grassland sites alongside roads with different traffic densities in SE England: Aston Rowant NNR adjacent to the M40; Butser Hill NNR next to a moderately busy road; and Martins Down NNR, neighbouring a relatively quiet road. Along transects from the roads extending 300-350m into the sites, they: measured NO_2 concentrations from which NH_3 concentrations were modelled; sampled soils and analysed them for heavy metals, extractable nitrogen and mineralisation and nitrification rates; measured soil pH and soil moisture; recorded cover measurements of vascular plants and bryophytes; and calculated frequency-weighted Ellenberg scores for fertility, salt, pH and moisture using UK Ellenberg indicator values (Hill and others 1999). Mean annual NO_2 concentrations nearest the roadside were 49μg/m^3, 30μg/m^3 and 14μg/m^3 for the three sites respectively and declined logarithmically with distance from the roads. Substantial areas of Aston Rowant and Butser Hill were exposed to mean annual concentrations above the critical level for ecosystems of 30μg/m^3. Mean NH_3 concentrations at roadside were modelled as 7.3μg/m^3, 7.1μg/m^3 and 4.3μg/m^3. NH_3 input by vehicles was expected to decline by 99% within 20m of the roadside at all three sites. Ellenberg fertility scores decreased with distance from the roadside at Butser Hill and Martins Down consistent with the profile of measured NO_2 concentrations but were unrelated to estimated NH_3 concentrations at any of the sites. The authors note that while NH_3 has been found to alter the composition of vegetation in experimental ecosystems, the anticipated rapid decline in NH_3 concentrations with distance from the roads means NO_2 was more likely to be driving such changes at these sites. The lack of a relationship between Ellenberg fertility scores and roadside proximity at Aston Rowant was ascribed to variations in soil moisture across the site.

The transect study undertaken by Lee and Power (2013) at eight chalk grassland sites in Southeast England (see Section 3.3 Effects on individual species) identified that frequency-weighted UK Ellenberg scores (Hill and others, 1999) increased closer to roadsides and declined logarithmically with distance from roads, for fertility, pH and moisture but not for salt. Plant species abundance and richness increased with modelled NO_2 deposition, as did total vegetation cover due to tall, fast-growing edge species not typical of chalk grassland; Ellenberg fertility scores increased logarithmically. An increase in NO_2 deposition from 2–12kgN/ha/yr was associated with mean increases of 70% in species abundance and 2 species/m^2.

The findings of many of these studies (Truscott and others 2005; Bernhardt-Römermann and others 2006; Bignal and others 2007; Lee and others 2012; Lee and Power 2013) suggest that NO_2 from road traffic emissions, rather than other forms of dry or wet nitrogen deposition, are the likely driver of changes in the composition of roadside plant communities. All of the studies reinforce the provisional conclusions of the 2004 review in highlighting that differential effects may lead to changes in competitive advantage between species with resultant implications for the composition of vegetation, management of roadside sites and nature conservation.

Below-ground impacts

Conclusions from the 2004 review

*"…**there is evidence that pollutants arising from motor vehicles have effects on tree fine-roots and soil microbes,** which will affect nutrient cycling and ecosystem function. These affects have been attributed to heavy metals and PAHs. However, **this is based on very limited data."***

The targeted literature search did not unearth any recent studies that provide further evidence of the impact of road traffic emissions on below-ground biodiversity. However, a number of the field studies described in Section 3.3 (Effects on individual species) and Section 3.3 (Impacts on habitats and communities) did sample and analyse soils.

Concentrations of all metals in soil decreased with increasing distances from the A31 between Nancy (France) and Luxembourg at the two sites studied by Viard and others (2004). Close to the road concentrations were highest on the downwind east side. Although deposition of zinc and lead exceeded national guidelines with lead still at elevated levels 320m from the road, its impact on soils was only detected up to 20–40m from roadside.

Transect studies carried out by Peachey and others (2009) at a rural control site and two parks in Central London identified that metal concentrations in soils associated with road traffic emissions declined sharply within 10–12m and more gradually between 12–50m.

Pourkhabbaz and others (2010) compared metal concentrations in soils at a megacity (Mashhad, Iran) with those from a rural areas and found urban soils contained higher concentrations of lead, zinc, chromium, and copper, which they attributed largely to road traffic emissions.

The transect studies at three important, species-rich chalk grassland sites in SE England undertaken by Lee and others (2012) found that copper, lead and zinc concentrations in roadside soil were approximately double that 300-350m away and declined logarithmically with distance from the roads. Zinc declined most rapidly and within 4.5m of the road edge was at levels measured more than 300m from the roadside, while approximately 43% of the decline in mean copper and lead occurred within the first 10m. Traffic volume did not have any effect on the concentration of these heavy metals. The authors noted that past studies have found that run-off from roads transport heavy metals and that copper and zinc are in part derived from petrol and diesel exhaust emissions, as well as from lubricating oil, brake wear and tyre erosion. The presence of lead at the roadside was thought to be a legacy of leaded petrol, deposition from brake wear or diesel exhaust emissions.

Concentrations of zinc and lead at the eight chalk grassland sites in Southeast England studied by Lee and Power (2013) were highest at the roadside and declined logarithmically with distance to background concentrations approximately 20m and 5m from road edges, respectively.

These studies are consistent in demonstrating that concentrations of heavy metals from vehicle emissions decline rapidly within the first 5–10m and may not be discernible beyond 50m from roadsides. In contrast, analysis of soils samples from 520m transects perpendicular to motorways dissecting a coniferous forest in Southern Germany (Bernhardt-Römermann and others 2006) found that the concentration of nitrate (NO_{3-}) and ammonium (NH_{4+}) in soils decreased with distance to a level 230m distance from the roads where the influence of traffic was negligible.

Impacts on plant-insect interactions

> Conclusions from the 2004 review
>
> *"**Most studies on plant-insect interactions concentrate on the road verge or central reservation of a motorway**, which is outside the scope of this review. However, there is a lack of information on plant-insect interactions further from the road. Therefore, it is worthwhile considering these studies to determine the sorts of effects that might be expected further from this zone of immediate impact adjacent to roads.*
>
> *…Motor vehicle pollution interacts with plant-insect relationships in varying ways. **Some insects,** such as aphids**, appear to benefit from pollution induced stress to roadside plants and an improved food source. Other insects suffer from a poorer quality food source,** for example, due to metal contamination**. Some insects, including aphids, may benefit from a relaxation of predation** pressure if their predators are unable to tolerate the roadside environment. The increase in certain insect groups is problematic if these insects graze on plants contaminated with metals thereby passing them up through the food chain, perhaps to birds and small mammals. Increased insect herbivory can also affect plant health through defoliation or inducing stress. It is difficult to assess the extent of influence of a road on these interactions as most studies relate to the road verge or within tens of metres of the road."*

The targeted literature search only located one additional study that specifically addressed the impact of road traffic emissions on plant-insect interactions. Bignal and others (2007; see Section 3.3 Impacts on habitats and communities) reported that the number of sessile oak and beech trees showing signs of insect damage, at Bradley Wood and Aston Rowant NNR respectively, was greatest within the first 100m of the motorways. It was concluded that the increased nitrogen content of leaves, as a result of road traffic emissions, reduced their defences or increased their palatability; a suggestion which is consistent with the conclusions of the 2004 review.

While the studies described in Section 3.3 (Effects on individual species) evidence that vehicle emissions are a significant source of metal contamination for roadside vegetation, they do not add weight to concerns expressed in the 2004 review about the impact of heavy metals on the food chain. The concentrations of metals recorded in leaves are not only unlikely to present a significant immediate toxic risk to plants but also Peachey and others (2009) note that the risk to primary consumers is relatively low even from vegetation in Central London parks.

Controlled fumigation and filtration studies

Introduction

The 2004 review found few fumigation experiments using motor vehicle exhaust and considered other studies that addressed the individual components of vehicle exhaust to assess and predict impacts on natural communities in the vicinity of roads. The targeted literature search identified only a handful of studies using vehicle exhaust or its components published since 2004 that are relevant to this review. These latest studies are described below.

Effects of vehicle exhaust

> Conclusions from the 2004 review
>
> *"The advantages of controlled fumigations over field-based studies is that the effects of pollutants can be separated from other environmental factors.* ***Very few fumigation studies using motor vehicle exhaust have been conducted.***
>
> ***…exposure to vehicle emissions at roadside concentrations affects growth, physiology, phenology and leaf surface characteristics of a range of species. Additionally, changes in the response of plants to biotic and abiotic stresses were found. Effects were species specific, sometimes changed over time, and acted in both directions. Many responses tested showed no significant differences between controls and polluted plants.***
>
> *The effects seen could lead to changes in the competitive ability of certain species in the vicinity of roads, subsequently leading to changes in species composition."*

Honour and others (2009) and Bell and others (2011) studied the effects of diesel exhaust emissions on 12 herbaceous species selected to cover a range of morphologies and functional types. A diesel generator was used in conjunction with solar domes to produce a good experimental simulation of polluted roadside environments. A wide range of species-specific effects on plants grown in this environment were detected, including: growth stimulation and inhibition; premature leaf senescence and delayed flowering; and changes in gas exchange. Measurements of the static contact angle of water drops on individual leaves pointed to the influence of pollutants on leaf surface structure, indicating changes in surface wax structure. Thus, the studies demonstrated that realistic levels of vehicle exhaust pollution have potential direct and differential impact on plants species in urban areas.

Sakugawa and others (2011) examined the potential of vehicle exhaust fumes to generate free radicals and the mechanism by which they damage higher plants, focusing on the hydroxyl (OH) radical and Japanese red pine trees *Pinus densiflora*. Petrol and diesel exhaust gases were scrubbed into pure water. Nitrite (NO_{2-}) was responsible for 70–90% of the photochemical formation of the OH radical from petrol and diesel exhausts. Pine tree seedlings in open-top chambers were sprayed six times per week for two months with either pure water, the scrubbed solution of diesel exhaust gas alone, the scrubbed solution plus mannitol (added to scavenge the OH radical), or a solution with NO_{2-} plus NO_{3-} equivalent to levels in the exhaust gas. The results indicated that OH radicals generated primarily from photolysis of NO_{2-} in the scrubbed solution of diesel exhaust gas were responsible for reducing maximum photosynthetic rate and stomata conductance.

Girling and others (2013) determined that diesel exhaust fumes may impact on honeybees' identification of floral odours when foraging for flowers, which may undermine their foraging efficiency and provision of pollination services (see Section 3.3 Impacts on plant-insect interactions).

These recent studies using vehicle exhaust reinforce the conclusions from the 2004 review. They highlight that diesel exhaust emissions not only have potential to lead to changes in competitive advantage between plant species due to species-specific responses but also changes in interactions across wildlife food chains, which could both have knock on implications for habitats and communities close to roads.

Impacts on plant-insect interactions

> Conclusions from the 2004 review
>
> ***"…in the lab.-based fumigations with motor vehicle exhaust, similar plant responses to those observed in the field were seen, but aphids did not respond in the same way. In the field-based filtration studies, however, effects on both aphids and host plants agree with the roadside studies.*** *It is possible that there is an additional factor or factors affecting aphid performance in the field aside from the host plant food quality. This could be the influence of salt from de-icing and/or the removal of predation pressure. However, this is based on the results of just one lab.-based fumigation study. Further investigations are required with different plant and insect species, over longer time periods, and with lower pollution levels to reflect greater distances from roads or different traffic densities."*

The targeted literature search only identified one fumigation study published since 2004 that has considered the impact of vehicle emissions on plant-insect interactions. Girling and others (2013) investigated whether diesel vehicle emissions could impact on honeybees' identification of floral odours when foraging for flowers. Honeybees were trained to recognise a mixture of eight chemicals found in oilseed rape flowers. Exposing these chemicals to diesel exhaust fumes significantly reduced the abundance of four of them within one minute; two to levels that were undetectable. NO_x was found to be a key driver of this degradation. Removing the two chemicals that had become undetectable significantly reduced the ability of the trained honeybees to recognise the mixture. Thus emissions from diesel vehicles may undermine honeybees' foraging efficiency and their provision of pollination services.

Effects of specific road transport pollutants

> Conclusions from the 2004 review
>
> *"The following section considers evidence for the effects of the following road transport pollutants: NO, NO_2, VOCs, NH_3, nitrogen, metals and particulates/dust. It is important to bear in mind that* ***the effect of these pollutants in combination may be different from that of these pollutants in isolation."***

NO_x (NO, NO_2)

> Conclusions from the 2004 review
>
> ***"Early fumigation studies used concentrations of NO2 or NO far higher than those found in roadside conditions*** *(up to 250 ppm in some cases; Mansfield, 2002). The highest maximum NO, NO_2 and NO_x hourly concentrations at the kerbside of Marylebone Road, London (one of the most polluted road sites in the UK) for 2001 were 749, 143 and 860 ppb, respectively. The annual mean concentrations were 132, 44 and 176 ppb for NO, NO_2 and NO_x, respectively. Therefore, studies are excluded from this review that used levels greater than 1000 ppb and the emphasis is on studies that used lower concentrations.*
>
> *…Fumigations have covered both the short and long-term, a range of pollution levels, and a range of plant types.* ***NO has been neglected, and more work on this pollutant is needed in order to assess the impacts of elevated NO_x concentrations close to the road. Effects are seen in low concentrations for some species and so the impact of NO_x arising from motor vehicles may be found tens to 100m or more from major roads"***

The fumigation study undertaken by Honour and others (2009; Section 3.3 Effects of vehicle exhaust) and resultant species-specific effects on growth, phenology and leaf surface characteristics, were associated with NO_x concentrations representative of polluted roadside environments, ranging from 77–98µg/m^3, with NO:NO_2 ratios of 1.4–2.2.

In addition to undertaking a fumigation experiment using a mixture of diesel exhaust gases (Section 3.3 Effects of vehicle exhaust) and a complementary transect study (Section 3.3 Effects on individual species), Bell and others (2011) carried out a second fumigation experiment to determine the relative toxicity to plants of NO and NO_2 in diesel exhaust gases at concentrations typical of locations close to busy inner London roads. Seven species were selected to represent a range of ecological types and a range of sensitivities. Relatively few significant effects on growth were detected, although above-ground biomass growth was reduced by up to 39% and a similar trend was found for root dry weight. The combined evidence from the two fumigation experiments and transect study suggests that NO_x is the key phytotoxic component of exhaust emissions.

VOCs

Conclusions from the 2004 review

*"**Most studies testing the responses of plants to exposure to VOCs have used high concentrations over short exposure periods** (hours or days). Few of these studies test the responses of vegetation to the species of VOCs emitted by vehicles. The effect of exposure to low concentrations of VOCs over the long-term is therefore difficult to assess.*

*…**there is little evidence of ecological damage by VOCs emitted by motor vehicles, with the exception of ethylene.** However, this is due to the bias in laboratory based-studies that have concentrated on the effects of ethylene and neglected other species of VOCs either singly, or in combination with other VOCs and/or other gaseous pollutants. Plant response to ethylene exposure is well characterised, and levels of ethylene likely to be found in the vicinity of roads may be high enough to adversely affect sensitive species. **The response of vegetation to other VOCs emitted by motor vehicles is unclear**; although possible effects are degradation of leaf surface waxes, pigment bleaching and ultra-structural changes."*

The targeted literature search found no new evidence specific to road emissions from controlled fumigation and filtration studies of VOCs.

NH_3

Conclusions from the 2004 review

*"Ammonia is emitted in small amounts by vehicles with catalytic converters and roadside atmospheric concentrations are well below critical levels for this pollutant (UK CLAG 1996). **Gaseous ammonia is thus unlikely to be a key issue, and effects on vegetation are more likely to arise from enhanced deposition of nitrogen to the soil environment.** This elevation in soil nitrogen will be limited to areas within tens of metres of roads due to the high rates of deposition of this gas."*

The targeted literature search found no new evidence specific to road emissions from controlled fumigation and filtration studies of NH_3.

Nitrogen deposition

Conclusions from the 2004 review

"NO_x, NH_3 and HONO emissions from roads may all contribute to local increases in the total deposition of nitrogen; these emissions only contribute to increased dry deposition and will not influence wet deposition. The impacts of total nitrogen deposition are outside the scope of this review…"

The targeted literature search found no new evidence specific to road emissions from controlled fumigation and filtration studies of nitrogen deposition.

Metals

Conclusions from the 2004 review

*“**Heavy metals derived from motor vehicles will exert an influence mainly through changes in soil chemistry.** Uptake of metals is largely via the roots of plants with only minor amounts being taken up from deposition onto plant surfaces (Fangmeier and others 2002). Metals occur naturally in soils and some metals found in elevated concentrations near to roads, such as Zn and Cu, are required in small amounts by plants as nutrients; it is only above certain concentrations that toxicity occurs (Ross and Kaye 1994). Metals are likely to persist in soils and levels may therefore build up over time in the vicinity of roads. A number of laboratory studies have cultured a variety of plant species in soil containing elevated concentrations of heavy metals and have found a range of tolerances depending on the species tested.”*

The targeted literature search found no new evidence specific to road emissions from controlled fumigation and filtration studies of heavy metals.

Particulates/dust

Conclusions from the 2004 review

*“**Few attempts have been made to assess the impacts of particulates and dust from motor vehicles on vegetation under controlled conditions**….The authors conclude that it is difficult to assess the significance of these results for roadside plants under realistic conditions.”*

The targeted literature search found no new evidence specific to road emissions from controlled fumigation and filtration studies of particulates and dust.

3.4 Methods to mitigate

Introduction

As noted in Section 2.1, use of the search term ‘mitigation’ identified a large number of documents. Only those consistently identified by ‘mitigation’ in combination with other search terms were, therefore, selected for further consideration on the assumption that they were likely to be of most wide-ranging importance. These studies focus on shelterbelts and are described below. Section 3.4 (Habitat management) was not covered by Bignal and others (2004), so conclusions from a ‘Review of the effectiveness of on-site habitat management to reduce atmospheric nitrogen deposition impacts on terrestrial habitats’ (Stevens and others 2013), are cited here.

Shelterbelts

Conclusions from the 2004 review

*“From this discussion it is clear that **wooded shelterbelts effectively capture particulates**, including their metal component, thereby reducing transport to sites further away from the road. However, their role in preventing the spread of gaseous pollutants is less clear, although **there is some evidence to suggest that they act as a physical barrier to NO_2 transport**, changing dispersal patterns rather than taking up the pollutant. There is evidence to suggest that plants can act as temporary and even permanent sinks for VOCs, but more research is needed to determine which species or vegetation types have the highest uptake.”*

Building on existing knowledge of deposition velocities, Freer-Smith and others (2004) and Fuji and Lawton (2008) undertook studies looking at trees' removal of particles from the atmosphere in the field and under laboratory conditions respectively. Freer-Smith and others 2004 measured how particle size affected the deposition velocity of particles to five urban tree species (coniferous and broadleaved) at an urban, polluted site and a more rural one. The study confirmed greater uptake by conifers. Deposition velocities for all coniferous and broadleaved trees was greater for ultra-fine particles than for coarser particles. This is important as the study showed that finer particles can be transported further from roads. Chemical analysis of the fractions of all particles that were soluble in water pointed to the importance of nitrates, chloride and phosphates in all size categories at both locations. Using wind tunnel and chamber studies, Fuji and Lawton (2008) also demonstrated that vegetation removes particles from the atmosphere, especially very fine particles, such as in diesel exhaust gases. Coniferous species were the most effective at removing particles, twice as good as the broadleaved species studied. Particle removal in the chamber studies was so rapid that the chamber could not be filled with aerosols until the branch area had been reduced by a factor of 10 from a chamber filled with branches. As a result, the authors suggest that when vegetation is placed alongside roads, there will be mitigation at source before particles are dispersed.

Recent field studies of the effectiveness of shelterbelts alongside roads in reducing dispersal of pollutants from vehicle exhausts have looked at trees in isolation, trees in association with noise barriers and noise barriers in isolation.

Baldauf and others (2008) assessed the effects of a noise barrier on local air quality at Raleigh, North Carolina. The study considered air quality along transects perpendicular from a highway with no barriers, with a noise barrier only, and with a noise barrier and vegetation adjacent to the road. The noise barrier alone reduced average concentrations of particulate matter by 15–25% within the first 50m of the road and continued to have an effect for 150–200m. The transect with a noise barrier and trees, generally greater than 10m in height with leaves, resulted in the greatest reductions in pollutant concentrations for both 20nm and 75nm particle sizes and continued to have an impact for more than 300m from the road.

Hagler and others (2012) measured concentrations of ultra-fine particles on major roads and in nearby locations at three sites in central North Carolina, USA. Two of the sites had relatively thin shelterbelts, one evergreen and one deciduous, alongside part of the road. The third site had a brick noise barrier alongside part of the road. Concentrations of ultra-fine particles were consistently reduced by about 50% at 10m from the road behind the wall, as compared to a nearby location without a barrier under a wide range of weather conditions. Trends in concentrations of ultra-fine particles at the sites with thin shelterbelts were variable and the barrier effect was uncertain. Higher concentrations were sometimes observed behind the shelterbelts, which the authors suggest may be due to gaps in the line of trees allowing pollutants through. These findings suggest that solid roadside barriers may mitigate near-road impact but the authors noted that further research was required to assess the mitigation potential of shelterbelts with different densities of tree cover and different widths.

Assessing the role of roadside shelterbelts in reducing air pollution in a megacity of Bangladesh, Islam and others (2012) sought to correlate canopy density and shelterbelt porosity with the percentage of total suspended particles removed. Their results showed that shelterbelts reduced total suspended particles by up to 65% and that it was correlated with crown density, i.e. areas with roadside shelterbelts with higher crown densities were less polluted than areas where shelterbelts had lower crown density. Performance was better in summer time than winter.

Brantley and others (2014) claim to have undertaken the first field study that has investigated the effect of the width of a vegetation barrier on attenuation of road traffic emissions. They considered a triangular stand of trees approximately 5–78m in width alongside an interstate six-lane highway carrying a daily average of 120,000 vehicles. The trees were primarily maple *Acer sp.* and oak *Quercus sp.* with a shrub layer, creating a barrier from ground-level to about 10m high. Stationary and mobile approaches were used to monitor black carbon and particulate matter concentrations. Reductions in black carbon behind the trees varied with wind direction and time of day by 12.4% downwind, 7.8% in parallel wind conditions, and 22% in late afternoon when the wind was perpendicular to the road. The stand of trees had no impact on $PM_{2.5}$ or PM_{10} counts. Downwind attenuation of black carbon did not increase strongly with width of vegetation or distance from the road. The authors suggest that while shelterbelts may reduce near-field concentrations, recirculation downwind of buffers may slow dispersion and attenuation and actually increase concentrations. However, they also note that the triangular shape of the stand may have contributed to pollutants collecting behind the vegetation stand and may not reflect the impact of a continuous shelterbelt of uniform depth.

Field studies have also been supported by work on modelling note in an effort to understand the mechanisms by which different types of roadside shelterbelts affect dispersal and transformation of pollutants under differing conditions. Steffens and others (2012) incorporated particle aerodynamics and deposition mechanisms into the Comprehensive Turbulent Aerosol Dynamics and Gas Chemistry (CTAG) model, and explored the effects of shelterbelts on particulates close to roads by comparing model results with field measurements. There was reasonable agreement for particles larger than 50nm, but the model tended to over-predict concentrations of smaller particles beyond shelterbelts. Sensitivity tests indicated that particle concentrations are reduced non-linearly with increasing leaf area density. Increases in wind speed were also shown to enhance particle impaction, but reduce particle diffusion, reducing concentrations of particles larger than 50nm but with minimal effect on particles smaller than 50nm. The authors suggested that representation of particle deposition and aerodynamics needed further improvement in order to capture the complex effects of roadside shelterbelts.

Mao and others (2013) combined experimental investigation of the impact of a roadside shelterbelt on the downwind concentration of dust raised by a passing vehicle with numerical modelling. The concentration of small particles (predominantly c. 6μm) measured 60m or more downwind from the road was unaffected by the presence of the shelterbelt. Using standard formulae for spheres in an airstream negotiating obstacles, Mao and others (2013) suggest such fine particles may stand little chance of interception by the shelterbelt because they will accelerate with the wind and deviate around foliage. While this was consistent in some respects with what was observed, they also suggest that the shelterbelt may increase the length of time fine particles remaining airborne.

While the findings of papers located by the targeted literature happen to interconnect neatly in relation to the ability of shelterbelts to reduce dispersal of particulate pollution from roads, the evidence is ultimately more equivocal than suggested by the conclusion of the 2004 review, particularly in relation to finer particles.

Only one paper pointed to the possible role of shelterbelts in reducing spread of gaseous pollutants to add to the limited evidence from the 2004 review. As with papers cited there, the study by Lee and Power (2012: Section 3.3 Effects on individual species) suggests that shelterbelts may reduce dispersal of NO_2 by acting as a physical barrier rather than by taking up the pollutant. They noted that at two of their sites, Seale Chalk Pit SSSI and Stockbridge Down SSSI, that overestimation of measured NO_2 by the model indicated pollutant deposition may have been diminished by roadside trees, and also when the site was raised above the road. However, an important caveat is that on-site monitoring only took place over a two-month period.

The targeted literature search did not find any further research considering the potential for shelterbelts to act as sinks for VOCs, so which species or vegetation types have the highest uptake remains unresolved.

Buffer zones

Conclusions from the 2004 review

*“**Buffer zones… may be best seen as providing a physical distance between the road and the protected site, rather than an area of vegetation that is able to remove pollutants from the atmosphere.**”*

While no new papers relating to roadside buffer zones were identified from recent literature, Bignal and others (2008) note that based on their data and the literature, new road building and road expansion should avoid a buffer zone of up to 100–200m from sensitive sites, particularly those where bryophytes are an important component of habitats.

Compensatory habitat creation

Conclusions from the 2004 review

“Mitigation by compensation of the effects of road transport pollutants is an alternative approach, but one that often requires ongoing management, and for which care is needed to minimise the impact of air pollution from roads.’

*‘…However, **re-creation of typically nutrient-poor habitats in the vicinity of roads is not recommended.** It is the low nutrient status of these systems that are key to their species diversity and inclusion of rare species. Inputs of nitrogen from motor vehicles on the road in the form of NO_x, NH_3 and HONO could be significant. These pollutants may act as fertilisers, changing the nature of the habitat and perhaps losing its ecological interest or conservation value”.*

The terms mitigation and compensation have very specific meanings in relation to Natura 2000 sites. Mitigation measures are confined to those that minimise impacts whilst compensation measures are those required to maintain the coherence of a Natura 2000 site if an adverse effect on its integrity cannot be ruled out, there are no alternative solutions, and there are over-riding public interests in favour of development http://www.cieem.net/mitigation-compensation-and-enhancement (Accessed December 2014).

The targeted literature review did not identify any additional papers on compensatory habitat creation in relation to the impact of air pollution from road transport on semi-natural habitats. However, the concept of ‘biodiversity offsetting’ may be relevant here, particularly when new roads are proposed. *“Biodiversity offsets are conservation activities designed to deliver biodiversity benefits in compensation for losses, in a measurable way. Biodiversity offsets are distinguished from other forms of ecological compensation by the requirement for measurable outcomes: the losses resulting from the impact of the development and the gains achieved through an offset are measured in the same way”* (Defra 2012). In relation to offsetting the impact of a new road, consideration could, therefore, be given not only to loss of habitat arising from its construction but also to loss of habitat quality arising from the subsequent impact of air pollution from traffic.

Habitat management

Conclusions from Stevens and others (2013), as not included in 2004 review

“There is some potential for mitigating the impacts of nitrogen deposition through on-site management although this varies greatly between habitat and management practice. It is likely that small changes in management and adherence to appropriate guidelines could partially improve habitat suitability and/or increase nitrogen removal.

The majority of management practices do not remove significant quantities of nitrogen (with the exception of removing biomass or topsoil). Furthermore, management of a suitable intensity to remove sufficient nitrogen to fully offset nitrogen added by atmospheric deposition is likely to damage the habitat and result in a number of unintended consequences.

Further research is needed to determine the impacts of individual management practices on the nitrogen budget in different habitats. Further research is also needed to explore the potential for novel management techniques to remove nitrogen from sites.

For an individual site where nitrogen is identified as a pressure, a manager can look at current management and compare this with the management recommendations in the report to make changes where appropriate.

All management recommendations that remove nitrogen from the site move it elsewhere and have the potential for unintended consequences. Consequently there is no substitute for reducing the amount of nitrogen deposited onto a site which can only be achieved through emission controls”.

Further evidence was not secured by this review in relation to the potential for on-site management to mitigate nitrogen deposition associated with road traffic emissions.

4 Road traffic measures

To supplement the results of the literature review, a summary of actions related to reducing emissions through road-traffic measures are provided in this section, which were not covered in Bignal and others (2004). This summary has been written by a Ricardo-AEA expert (Guy Hitchcock) who has experience of working in this area. Although it cites recent literature, it is not the result of a targeted literature search.

4.1 Introduction

Traffic emissions generated at any given site are essentially determined by three factors:

- The amount and type of vehicles flowing past a site;
- The way vehicles are driven (eg their speed) and the level of congestion;
- The emissions performance of vehicles, which is dependent on age and technology.

Traffic emissions can, therefore, be reduced or mitigated by implementing measures that address these factors, for example, by reducing traffic flows. The highways authorities primarily responsible for implementing such measures are the Highways Agency in relation to motorways and trunk roads and county councils and unitary authorities with regard to all other roads. Other actors including the planning authority, transport providers and local businesses can also be involved in providing solutions.

Overviews of the types of measures that can be used to reduce traffic emissions and improve air quality are provided by Defra (2009a) and the Highways Agency (2005). While many of these measures have been predominantly implemented in urban areas, there may also be potential for them to be used more widely, for example, in relation to emissions from roads that threaten sites designated for their nature conservation importance. These potential mitigation measures are explored below in relation to each of the three key factors that determine transport emissions.

4.2 Reducing traffic flows

The most direct way to reduce traffic emissions is to limit the number of vehicles passing a site, or to prevent particular types of vehicle from doing so. This can be achieved directly through traffic restrictions or relocating a road, or more indirectly by influencing peoples' travel behaviour. In general, such measures will reduce all types of vehicle emissions in equal measure proportionate to the level of traffic reduction.

Traffic restrictions and relocation

The most drastic approaches to reducing traffic flow are to relocate the road or construct a bypass, which may be appropriate for sites of European importance for nature conservation that are particularly sensitive to air pollution. Clearly, these are very expensive options and are unlikely to be implemented unless they deliver other socio-economic benefits or are integral to wider development. For example, at Brierly Hill, Dudley a new road, plus additional transport measures, was implemented as part of a wider development and to reduce traffic issues in the centre of town resulting in a 16% reduction in roadside NO_2 in the high street (Fawthrop and others 2010).

Under the Road Traffic Regulations Act 1984, highways authorities can prohibit, restrict or regulate particular types of vehicle that use a road (e.g. through vehicle weight restrictions). These powers may be useful where goods traffic passing a site is generating significant emissions and alternative more appropriate routes exist. They can also be used to prevent through traffic, for example, by only allowing passage for local buses, service vehicles, cyclists and walkers. Such restrictions can be applied at all hours or during specific periods when problems arise. Where it is deemed inappropriate to enforce such measures highways authorities may simply use signage and information to encourage through traffic or large vehicles onto alternative routes. This approach is often used in small villages or markets towns that suffer from congestion.

Influencing travel behaviour

Travel behaviour can be influenced at a local level and more generally through travel awareness campaigns, walking and cycling campaigns and promotion of public transport. Detailed assessment of the 'Sustainable Travel Town' demonstrations in Darlington, Peterborough and Worcester between 2004–2009 estimated that their comprehensive set of measures to adjust travel behaviour reduced car trips and traffic volumes by 7%. Promoting this behavioural shift cost an estimated 4p/vehicle km removed (Sloman and others 2010).

Travel behaviour can be addressed at a specific location working with organisations and individuals, for example, in relation to schools, businesses and tourist attractions. Schemes have been developed in small towns, such as Kendal in Cumbria (http://www.goeasy.org.uk/ Accessed April 2014), as well as in larger urban areas. Travel plans can reduce vehicle trips by 10-15% (Sloman and others 2010; Cairns and others 2004).

4.3 Improving traffic flow and efficiency

The way vehicles are driven can have a significant effect on their emissions. The effect will vary depending on vehicle type and the vehicle emissions standard to which it conforms. These standards are known as Euro standards and are determined by European Directives which have become stricter over time. Figures 2 and 3 respectively show the impact of average speed on emissions of NO_x from a diesel car and from a small heavy goods vehicle (HGV). In general, emissions increase at low speeds (eg in congested conditions) and at high speeds (eg on motorways). However, the latter is less relevant to HGVs, as they are speed limited.

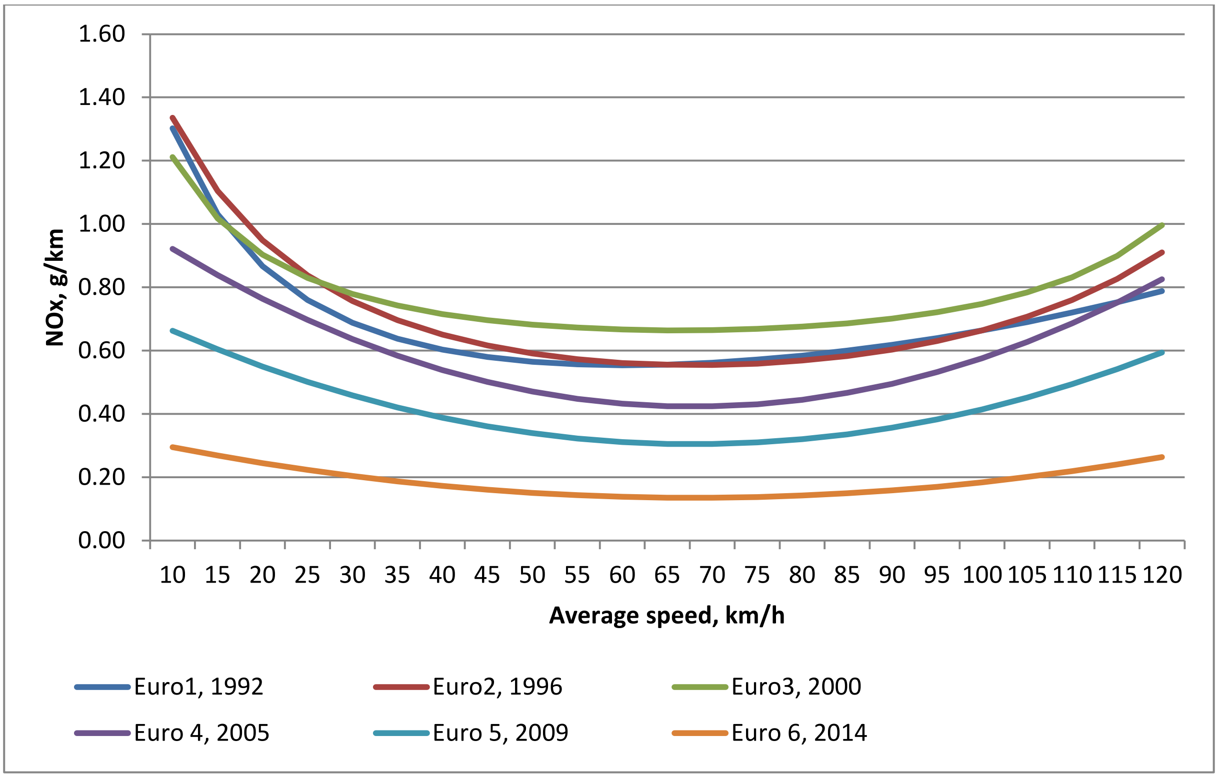

Figure 2 Effect of speed on NOx emissions from a diesel car

Source: National Atmospheric Emissions Inventory (2013) Emissions data for a diesel car, engine size < 2l.
Note: Curves shown by Euro emissions standard

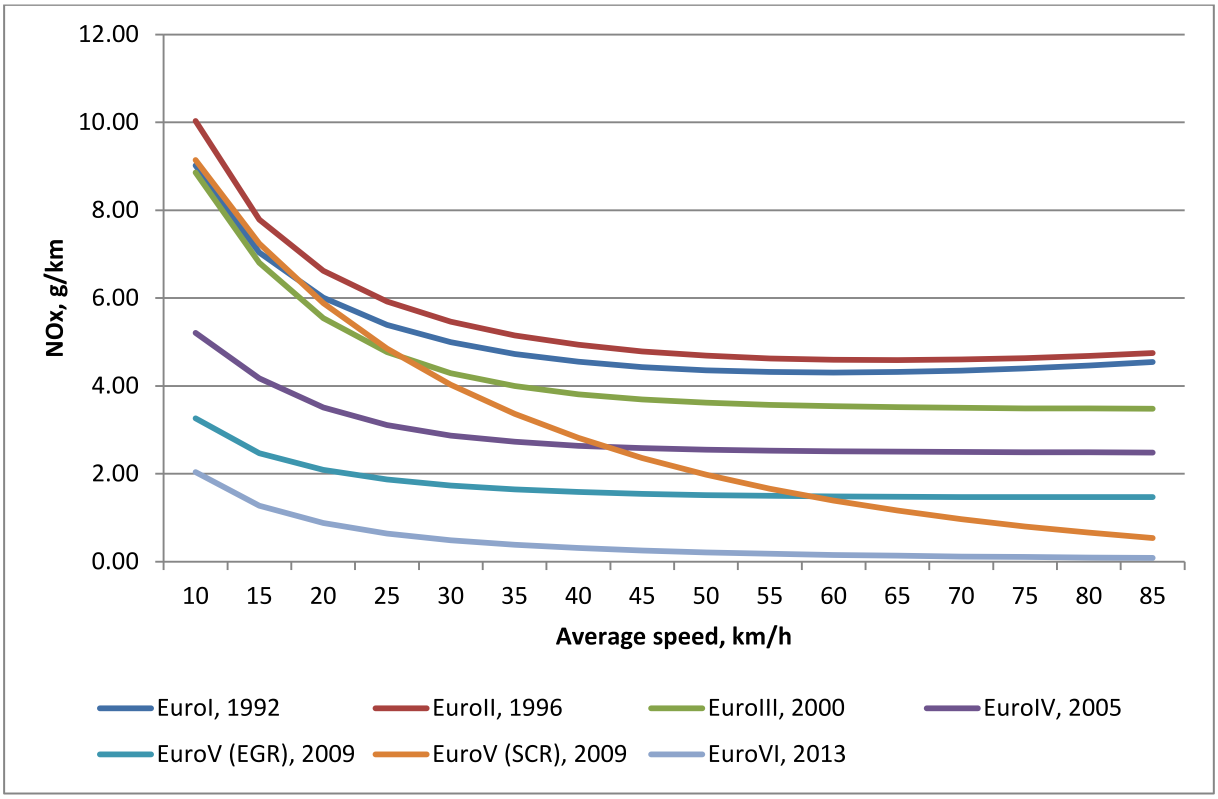

Figure 3 Effect of speed on NOx emissions from a small HGV

Source: National Atmospheric Emissions Inventory (2013) Emissions data for a 7.5 tonne HGV
Note: Curves shown by Euro emissions standard, EGR and SCR are specific technologies used to meet the Euro V standard.

Traffic control systems

Intelligent traffic-light systems can help to control the flow of vehicles around a road network. They are widely used in cities and at key road junctions to reduce congestion and improve traffic flow, thereby reducing vehicle emissions.

Innovative traffic-control strategies are increasingly being used and include use of ‘gating’ and/or real-time air-quality data. Gating involves keeping traffic away from areas of sensitive exposure, such as schools or busy pedestrian areas, or from congested junctions. A particular example is known as ‘ramp metering’ where vehicles are released in small groups to join a trunk road or motorway and thereby prevent congestion. This has been shown to increase traffic speed past such junctions by 7.5% (Highways Agency undated). Some cities, such as Leicester, are integrating real-time air quality data with their traffic management systems to help reduce vehicle emissions and improve air quality (European Space Agency 2012).

Road space design and management

Physical changes to road layout, designed for the specific location under consideration, can also help to improve overall vehicle flow or promote priority vehicles. Such measures include:

- Priority lanes for buses, freight vehicles or high occupancy vehicles;
- Junction improvements to ease the flow of vehicles;
- Parking management to prevent obstructions to traffic flow.

Further details are provided in Defra’s and Highways Agency’s guidance (Defra 2009; Highways Agency 2005).

Driver education

Another approach to managing vehicle speed and behaviour is through driver education. This can range from use of speed limits, speed messaging and enforcement activity, through to direct training of drivers. At specific hotspots, signage and enforcement may be the most appropriate approach to reduce pollutant emissions and fuel use from aggressive driving. A targeted campaign with local drivers in the area can also provide significant benefits, with training courses shown to reduce fuel use and emissions by up to 15% (Energy Saving Trust 2013).

4.4 Promoting low-emission vehicles

The inherent emissions performance of any vehicle is determined by its fuel type, such as petrol, diesel or electric, and the vehicle emissions standard to which it conforms (Section 4.3). Hence, newer vehicles have lower emissions. Encouraging retrofitting of emissions-control equipment or enabling use of alternative low-emission fuels, such as electricity or gas, would also help to reduce vehicle emissions significantly.

Low Emission Zones

Traffic regulations can be used to restrict vehicles not meeting a specific emission standard from entering an area or using a particular road and are known as Low Emission Zones (LEZs). The most high profile of these is in London, which is focused on reducing particulates by targeting HGVs and vans. A study (Barratt 2013) has shown that the LEZ has significantly reduced black carbon and fine particulates ($PM_{2.5}$) by 20% over 4 years, although it has had no impact on coarser particulates (PM_{10}) or on nitrogen dioxide levels.

Smaller UK cities with LEZs include Norwich and Oxford, and a number of places are assessing their potential use (Low Emission Zones in Europe, 2013). Norwich has adopted a limited approach confined to a single road, which could be adopted in more rural areas. Defra has provided guidance for local authorities in relation to LEZs and the promotion of retrofit emission-exhaust control technology (Defra 2009b/c).

Planning and infrastructure

Local planning policy instruments, such as Section 106 and the Community Infrastructure Levy, can be used to encourage new developments near a site to adopt low-emission vehicles and implement support infrastructure, such as electric-vehicle charging points. A number of local authorities are using this type of approach to help mitigate transport-related air-quality problems. Several leading local authorities have developed associated guidance with Defra (Low Emission Strategies Partnership 2010).

Partnership working and promotion

A voluntary approach to reducing emissions from road traffic can be achieved by working in partnership with local transport operators or businesses whose vehicles regularly drive past a site. Local authorities have used the framework of bus and freight quality partnerships to establish such voluntary agreements (Confederation of Passenger Transport 2010). These have been used to set emission criteria for vehicles operating on certain routes or areas within a city or town.

5 Summary of current evidence

Conclusions from the 2004 review

"Motor vehicle pollution has been demonstrated to affect vegetation, plant-insect interactions and soil fauna in both field and lab.-based studies. Impacts have been found to occur up to 200m from roads, with the greatest impacts likely to occur in the first 50 to 100m.

It is impossible to predict and understand exactly what will happen in a habitat exposed to motor vehicle pollutants, both in terms of the response of individual species and in terms of the whole community or habitat. *This is due to the range of responses of individual species that have been demonstrated, not all of them negative. In addition, there is a lack of information on the subsequent effects on the rest of the community perhaps arising from shifts in competitive ability. Furthermore, there will be interactions with other environmental factors and stresses and exactly how these exert an influence is unknown. Thus what occurs in the field is quite complex and further research is necessary to elucidate this problem".*

Recent field studies of individual species on transects away from roadsides reinforce the conclusions from the 2004 review. They provide further evidence of the impacts on individual species from exposure to NO_x and NO_2 associated with vehicle emissions and that these are greatest within the first 50-100m from roads but may be discernible at greater distances. The studies also evidence that traffic emissions are a significant source of metal contamination for vegetation close to roads, although the leaf concentrations recorded are unlikely to present a significant immediate toxic risk to plants.

A range of field studies undertaken since 2004 have sought to investigate the effect of nitrogen emissions from road traffic on habitats or communities. The findings of many of these studies suggest that NO_2 from road traffic emissions, rather than other forms of dry or wet nitrogen deposition, are the likely driver of changes in the composition of roadside plant communities. All of the studies reinforce the provisional conclusions of the 2004 review in highlighting that differential effects may lead to changes in competitive advantage between species with resultant implications for the composition of vegetation, management of roadside sites and nature conservation.

The targeted literature search did not unearth any recent studies that provide further evidence of the impact of road traffic emissions on below-ground biodiversity. However, a number of the field studies did sample and analyse soils. These studies are consistent in demonstrating that concentrations of heavy metals from vehicle emissions decline rapidly within the first 5–10m and may not be discernible beyond 50m from roadsides. In contrast, analysis of soils samples from 520m transects perpendicular to motorways dissecting a coniferous forest found that the concentration of NO_{3-} and NH_{4+} in soils decreased with distance to a level 230m distance from the roads where the influence of traffic was negligible.

The targeted literature search only located one additional study that specifically addressed the impact of road traffic emissions on plant-insect interactions. While other studies evidence that vehicle emissions are a significant source of metal contamination for roadside vegetation, they do not add weight to concerns expressed in the 2004 review about the impact of heavy metals on the wildlife food chain.

Recent fumigation studies using vehicle exhaust reinforce the conclusions from the 2004 review. They highlight that diesel exhaust emissions not only have potential to lead to changes in competitive advantage between plant species due to species-specific responses but also changes in interactions across wildlife food chains, which could both have knock on implications for habitats and communities close to roads. The targeted literature search only identified one fumigation study published since 2004 that has considered the impact of vehicle emissions on plant-insect interactions.

Looking to the effects of specific road transport pollutants, the combined evidence from the two fumigation experiments and a transect study suggests that NO_x is the key phytotoxic component of exhaust emissions. The targeted literature search found no new evidence specific to road emissions from controlled fumigation and filtration studies of VOCs, NH_3, nitrogen deposition, metals or particulates/dust.

The targeted literature search identified a large number of studies focused on the ability of shelterbelts to reduce dispersal of particulate pollution from roads. While the findings of the papers happen to interconnect neatly, the evidence is ultimately more equivocal than suggested by the conclusion of the 2004 review, particularly in relation to finer particles. Only one paper pointed to the possible role of shelterbelts in reducing spread of gaseous pollutants to add to the limited evidence from the 2004 review. As with papers cited there, the study suggests that shelterbelts may reduce dispersal of NO_2 by acting as a physical barrier rather than by taking up the pollutant. The targeted literature search did not find any further research considering the potential for shelterbelts to act as sinks for VOCs, so which species or vegetation types have the highest uptake remains unresolved.

While no new papers relating to roadside buffer zones were identified from recent literature, one group of researchers noted that based on their data and the literature, new road building and road expansion should avoid a buffer zone of up to 100–200m from sensitive sites, particularly those where bryophytes are an important component of habitats.

The targeted literature review did not identify any additional papers on compensatory habitat creation in relation to the impact of air pollution from road transport on semi-natural habitats. However, the concept of ‘biodiversity offsetting’ may be relevant here, particularly when new roads are proposed. Consideration could be given not only to loss of habitat arising from its construction but also to loss of habitat quality arising from the subsequent impact of air pollution from traffic.

Although the 2004 review did not address the potential for on-site management to mitigate nitrogen deposition associated with road traffic emissions, a review of this issue has recently been published. This identified that the potential varies greatly between habitat and management practice. Further evidence was not secured by the targeted literature search in this regard.

To supplement the results of the literature review, a summary of actions related to reducing emissions through road-traffic measures has been provided drawing upon recent literature but based on expert experience rather than on a targeted literature review. Traffic emissions generated at any given site can be reduced or mitigated by implementing measures that address the three factors determining emissions: the amount and type of vehicles flowing past a site; the way vehicles are driven (eg their speed) and the level of congestion; and the emissions performance of vehicles, which is dependent on age and technology.

6 Future research

Conclusions from the 2004 review

"The two main issues that need to be addressed are:

- ***What is the current and future ecological impact of motor vehicle pollution from the existing road network;***
- ***What is the local ecological impact of motor vehicle pollution from new road construction schemes (including realignment or dualling/expansion of existing roads), and would the choice of alternative routes influence these impacts?***

In summary, we propose a research programme with the following components:

- ***Geographical analysis of the number of designated sites and the different habitats which are at risk;***
- ***Field surveys to assess the distance from major roads at which significant effects can be detected in different habitats;***
- ***Controlled field and laboratory experiments to evaluate:***
    - ***The importance of air- and soil-mediated effects;***
    - ***The chemical components of vehicle exhaust of greatest concern;***
    - ***The threshold concentrations of specific pollutants or the vehicle exhaust mix at which adverse effects are observed".***

In relation to the components of the research programme proposed by Bignal and others (2004):

- A geographical analysis of designated sites is currently being addressed by Ricardo-AEA in association with this project for Natural England. A matrix approach has been developed and is being applied to screen and assess the potential risk to SSSIs, SACs and SPAs of impacts from road traffic emissions. It will provide national summary statistics to demonstrate the number and proportion of SSSIs, SACs and SPAs in England at potential risk from air pollution from roads and the associated condition of these sites;
- This targeted literature search identified quite a number of new transect studies that have sought to assess the distance from major roads over which road traffic pollution has an impact on individual species, habitats and communities. However, there remains substantial scope to increase understanding through further such studies in order to address the full range of habitats, traffic flows and meteorological conditions;
- Notably, there are still no known studies that have considered sites before and after road construction in order to assess changes, and it would be highly beneficial if transect studies could be established in relation to all future major road schemes that have potential to affect designated nature conservation sites;
- While the targeted literature search found no new evidence specific to road emissions from controlled fumigation and filtration studies of VOCs, NH_3, nitrogen deposition, metals or particulates/dust, this review has identified that NO_2 and NO_x are the chemical components of vehicle exhausts of greatest concern and further research in their regard remains a priority;
- The fact that a recent study has detected that nitrogen deposition below Critical Loads may be associated with changes in some species and ecosystem function indices, and that changes in species and ecosystem function indices continue above Critical Loads, highlights a need for further research to inform any further refinement, use, and interpretation of Critical Loads for nitrogen deposition and the Critical Level for NO_x. This is of particular importance to the consideration of the potential impacts from existing and proposed roads on delivery of current conservation commitments and biodiversity targets.

Bignal and others (2004) focused the need for future research on the current and future ecological impact of motor vehicle pollution from the existing road network and on the local ecological impact of road traffic pollution from new road construction schemes. However, it is apparent from this latest targeted literature review that further research into the efficacy of mitigation measures is required, including:

- Field studies and accurate modelling of the relationships between roadside topography, physical barriers (including width and density of shelterbelts) and pollutant dispersal, particularly NO_2 and NO_x;
- Studies to determine the impacts of individual management practices on nitrogen across a range of habitats and to explore the potential for novel management techniques to remove nitrogen from sites;
- Piloting and monitoring the application of road traffic measures in the vicinity of designated nature conservation sites at high risk of impacts from road traffic pollution.

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8 Appendices

Appendix 1 Collated documents from the targeted literature search

Appendix 1 Collated documents from the targeted literature search

								Roadside/field studies				Controlled fumigation and filtration studies			Mitigation			
Author	Year	Title	Source	Location	Data Pedigree	Data Quality	Strength of data	Effects on individual species	Impacts on habitats and communities	Below-ground impacts	Impacts on plant-insect interactions	Effects of vehicle exhaust	Impacts on plant-insect interactions	Effects of specific road transport pollutants	Shelterbelts	Buffer zones	Compensatory habitat creation	URL [Accessed April 2014]
Baldauf, R., Thoma, E., Khlystov, A., Isakov, V., Bowker, G., Long, T. & Snow, R.	2008	Impacts of noise barriers on near-road air quality	*Atmospheric Environment*	International	Good (11)	Peer-reviewed	Evidence-based								*			http://www.sciencedirect.com/science/article/pii/S1352231008005311
Bell, J.N.B., Honour, S.L. & Power S.A.	2011	Effects of vehicle exhaust emissions on urban wild plant species	*Environmental Pollution*	England	Very Good (15)	Peer-reviewed	Evidence-based	*				*		*				http://www.sciencedirect.com/science/article/pii/S0269749111001357
Bernhardt-Römermann, M., Kirchner, M., Kudernatsch, T., Jakobi, G. & Fischer, A.	2006	Changed vegetation composition in coniferous forest near motorways in southern Germany: the effects of traffic-borne pollution	*Environmental Pollution*	EU	Very Good (15)	Peer-reviewed			*	*								http://www.sciencedirect.com/science/article/pii/S026974910500638X
Bignal, K.L., Ashmore, M.R., Headley, A.D., Stewart, K. & Weigert, K.	2007	Ecological impacts of air pollution from road transport on local vegetation	*Applied Geochemistry*	England	Very Good (13)	Peer-reviewed	Evidence-based	*	*		*							http://www.sciencedirect.com/science/article/pii/S0883292707000637
Bignal, K.L., Ashmore, M.R. & Headley, A.D.	2008	Effects of air pollution from road transport on growth and physiology of six transplanted bryophyte species	*Environmental Pollution*	England	Very Good (14)	Peer-reviewed	Evidence-based	*	*							*		http://www.sciencedirect.com/science/article/pii/S0269749108000985
Brantley, H.L., Hagler, G.S.W., Deshmukh, P.J. & Baldauf, R.W.	2014	Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter	*Science of The Total Environment*	International	Good (11)	Peer-reviewed	Evidence-based								*			http://www.sciencedirect.com/science/article/pii/S0048969713009145
Davies, L., Bates, J.W., Bell, J.N.B., James, P.W. & Purvis, O.W.	2007	Diversity and sensitivity of epiphytes to oxides of nitrogen in London	*Environmental Pollution*	England	Very Good (14)	Peer-reviewed	Evidence-based	*	*									http://www.sciencedirect.com/science/article/pii/S0269749106002144
Frati, L., Caprasecca, E., Santoni, S., Gaggi, C., Guttova, A., Gaudino, S., Pati, A., Rosamilia, S., Pirintsos, S.A., Loppi, S.,	2006	Effects of NO_2 and NH_3 from road traffic on epiphytic lichens	*Environmental Pollution*	EU	Very Good (13)	Peer-reviewed	Evidence-based		*									http://www.sciencedirect.com/science/article/pii/S0269749105004872
Freer-Smith, P.H., Beckett, K.P. & Taylor, G.	2004	Deposition velocities to *Sorbus aria*, *Acer campestre*, *Populus deltoides trichocarpa* 'Beaupre´', *Pinus nigra* and *Cupressocyparis leylandii* for coarse, fine and ultra-fine particles in the urban environment	*Environmental Pollution*	England	Good (11)	Peer-reviewed	Evidence-based								*			http://ac.els-cdn.com/S0269749104001228/1-s2.0-S0269749104001228-main.pdf?_tid=960c0b4e-3fc6-11e3-a38d-00000aacb361&acdnat=1382960970_ad7f3b0ff9198babf5d7bafdedab8708

Fuji, E. & Lawton, J.	2008	Removal rates of particulate matter onto vegetation as a function of particle size	Health Effect Task Force and Sacramento Metropolitan Air Quality Management District	International	Good (9)	3rd Party	Evidence-based							*		http://www.sacbreathe.org/Local%20Studies/Vegetation%20Study.pdf
Gadsdon, S.R. & Power, S.A.	2009	Quantifying local traffic contributions to NO$_2$ and NH$_3$ concentrations in natural habitats	*Environmental Pollution*	England	Very Good (13)	Peer-reviewed	Evidence-based		*							http://www.sciencedirect.com/science/article/pii/S0269749109002024
Girling, R.D., Lusebrink, I., Farthing, E., Newman, T.A. & Poppy, G.M.	2013	Diesel exhaust rapidly degrades floral odours used by honeybees	*Scientific Reports*	England	Good (11)	Peer-reviewed	Evidence-based				*	*				http://www.nature.com/srep/2013/131003/srep02779/full/srep02779.html
Hagler, G.S.W., Lin, M-Y., Khlystov, A., Baldauf, R.W., Isakov, V., Faircloth, J. & Jackson, L.E.	2012	Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions	*Science of The Total Environment*	International	Good (11)	Peer-reviewed	Evidence-based							*		http://www.sciencedirect.com/science/article/pii/S0048969711014070
Honour,S.L., Bell, J.N.B., Ashenden, T.W., Cape J.N. & Power, S.A.	2009	Responses of herbaceous plants to urban air pollution: Effects on growth, phenology and leaf surface characteristics	*Environmental Pollution*	England	Very Good (14)	Peer-reviewed	Evidence-based				*		*			http://www.sciencedirect.com/science/article/pii/S026974910800660X
Islam, N., Rahman, K-S., Bahar, M., Habib, A., Ando, K. & Hattori, N.	2012	Pollution attenuation by roadside greenbelt in and around urban areas	*Urban Forestry & Urban Greening*	International	Good (10)	Peer-reviewed	Evidence-based							*	*	http://www.sciencedirect.com/science/article/pii/S1618866712000672
Laffray, X., Rose, C. & Garrec, J-P.	2010	Biomonitoring of traffic-related nitrogen oxides in the Maurienne valley (Savoie, France), using purple moor grass growth parameters and leaf 15N/14N ratio	*Environmental Pollution*	EU	Very Good (13)	Peer-reviewed	Evidence-based	*								http://www.sciencedirect.com/science/article/pii/S0269749109005995
Lee, M.A., Davies, L. & Power, S.A.	2012	Effects of roads on adjacent plant community composition and ecosystem function: An example from three calcareous ecosystems	*Environmental Pollution*	England	Very Good (14)	Peer-reviewed	Evidence-based		*	*						http://www.sciencedirect.com/science/article/pii/S0269749111007081
Lee, M.A. & Power, S.A.	2013	Direct and indirect effects of roads and road vehicles on the plant community composition of calcareous grasslands. Environmental Pollution	*Environmental Pollution*	England	Very Good (13)	Peer-reviewed	Evidence-based	*	*	*				*		http://www.sciencedirect.com/science/article/pii/S026974911300033X
Mao, Y., Wilson, J. & Kort, J.	2013	Effects of a shelterbelt on road dust dispersion	*Atmospheric Environment*	International	Good (11)	Peer-reviewed								*		http://www.sciencedirect.com/science/article/pii/S1352231013005360
Peachey, C.J., Sinnett, D., Wilkinson, M., Morgan, G.W., Freer-Smith, P.H. & Hutchings, T.R.	2009	Deposition and solubility of airborne metals to four plant species grown at varying distances from two heavily trafficked roads in London	*Environmental Pollution*	England	Good (11)	Peer-reviewed	Evidence-based	*		*						http://www.sciencedirect.com/science/article/pii/S0269749109001729
Pourkhabbaz, A., Rastin, N., Olbrich, A., Langenfeld-Heyser, R. & Polle, A.	2010	Influence of Environmental Pollution on Leaf Properties of Urban Plane Trees, *Platanus orientalis* L.	*Bulletin of Environmental Contamination and Toxicology*	International	Good (12)	Peer-reviewed	Evidence-based	*		*						http://link.springer.com/article/10.1007/s00128-010-0047-4#page-1
Sakugawa, H., Matsuda, T. & Nakatani, N.	2011	Automobile exhaust gas as a source of aqueous phase OH radical in the atmosphere and its effects on physiological status of pine trees	*Chemosphere*	International	Good (10)	Peer-reviewed	Evidence-based				*					http://www.sciencedirect.com/science/article/pii/S0045653511007375
Steffens, J.T., Wang, Y.J. & Zhang, K.M.	2012	Exploration of effects of a vegetation barrier on particle size distributions in a near-road environment	*Atmospheric Environment*	International	Good (9)	Peer-reviewed	Evidence-based							*		http://www.sciencedirect.com/science/article/pii/S1352231011013410
Truscott, A.M., Palmer, S.C.F., McGowan, G.M., Cape, J.N. & Smart, S.	2005	Vegetation composition of roadside verges in Scotland: the effects of nitrogen deposition, disturbance and management	*Environmental Pollution*	UK	Good (12)	Peer-reviewed	Evidence-based		*							http://www.sciencedirect.com/science/article/pii/S0269749105000229
Viard, B., Pihan, F., Promeyrat, S. & Pihan, J-C.	2004	Integrated assessment of heavy metal (Pb, Zn, Cd) highway pollution: bioaccumulation in soil, Graminaceae and land snails	*Chemosphere*	EU	Good (11)	Peer-reviewed	Evidence-based	*		*						http://www.sciencedirect.com/science/article/pii/S0045653504000293

RICARDO-AEA

The Gemini Building
Fermi Avenue
Harwell
Didcot
Oxfordshire
OX11 0QR

Tel: 01235 75 3000
Web: www.ricardo-aea.com