Impacts of development on ancient woodland and trees: evidence review 2012-2021

A report for the Woodland Trust

By

Dr Andrew Carr

Carr Ecology

andrew.carr@carrecology.uk

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NOTICE TO READERS

This report is based on the information collected during the period of study and within the parameters of and resources available for the project. The possibility of important information being found through further investigation cannot be eliminated. Reference to sections of text or paragraphs of this document taken out of context may lead to misrepresentation. Whilst this report has not gone through formal peer review, efforts have been taken to ensure a robust approach to searching and reporting the literature.

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Contents

Executive summary

In 2008 the Woodland Trust published a report on the impacts of nearby development on the ecology of ancient woodland. An addendum was completed in 2012 to include additional evidence between 2008 and 2012. This report was commissioned to review relevant evidence since 2012 to provide the Woodland Trust up to date evidence of the impact of development on the ecosystem functioning of ancient woodland and trees, and veteran trees.

Ancient woodland within the UK continues to decline and makes up only a small percentage of the landscape. Ancient woodland, ancient and veteran trees are recognised as high value ecological receptors and yet it remains unclear as to the impact development has on these habitats.

The aim of this report is to review and synthesise evidence of the impacts of development on ancient woodland and trees, and veteran trees since 2012. The collated evidence will be used by the Woodland Trust to develop technical notes on the impact of development on ancient woodland and trees in order to provide due regard before, during and post development. Secondary objectives of the report are to highlight evidence led mitigation and identify evidence gaps that require further investigation.

Impacts of development on ancient woodland, ancient and veteran trees include air pollution, hydrology, light pollution, noise pollution, recreation, root damage, fragmentation and habitat loss, and functional habitat loss. Development often has combination effects. Road infrastructure projects have shown to negatively impact ancient woodland and woodland dependent wildlife through increasing air, light and noise pollution, changing hydrology, fragmentating habitat, direct habitat loss and functional habitat loss. The impacts can be conspicuous, for example direct habitat removal, or subtle, for example the likely impact of noise pollution on telomere shortening in birds or foliar nutrient concentration imbalance in trees following nitrogen enrichment.

Distances from a development and sensitive habitat through buffer zones are a practical and logical mitigation approach. Buffers are suitable at small spatial scales, for example root protection zones around ancient and trees or larger scales, for example the distance required to ensure emitted airborne particulate matter from a development does not deposit on a sensitive site. Although minimum distances can be proposed it is important to consider that site specific characteristics may mean the proposed minimum distances will not be effective and larger distances may be required. Minimum buffer zones must not be used as a default when a development is assessed.

Other practical steps have shown to be effective when applying a mitigation hierarchy. Recreation impacts can be reduced through locating facilities away from sensitive areas within a woodland. Reducing the size of parking facilities may reduce users as access to sites through cars is commonplace. Engagement to alter the behaviour of visitors deemed to be negative may reduce degradation. Providing baseline information before development and monitoring post development can be achieved with relatively straightforward protocols such as surveying lichen communities within woodland and on ancient and veteran trees. This should be a priority as a lack of post development monitoring negates the collection of any meaningful evidence of effectiveness. Currently data on mitigation strategies outcome is not available, possible because post monitoring is not undertaken although most likely due to a lack of data collation and publication. The use of modelling to predict levels of pollution form development to allow better assessment of likely impact has shown to be effective at predicting light spill. This method is currently underused and could be expanded to include noise pollution in and around ancient woodland.

As concluded in previous evidence reviews research gaps remain a problem when assessing the likely impact of development on ancient woodland and trees. This leads to inappropriate or overly cautious mitigation. Some important gaps have been identified within this report. The negative impact of dust load on tree development and leaf growth within the UK is required. The impacts of nitrogen mediated inhibition of mycorrhiza could be having a significant impact on woodland health throughout the UK and Europe and requires further investigation. Housing developments close to ancient woodland likely change the hydrology within the woodland. Sustainable drainage systems and other measures including the use of permeable surface material have the potential to limit peaks and flows and negate significant hydrological changes in the local area. Research is needed to assess their suitability. The use of modelling to assess light spill from proposed development within SACs in the southwest of England is currently used. Modelling likely light level and spread allows planners to assess the likely impact on sensitive receptors and can be used during the design stage of developments to reduce light levels to agreed threshold levels. Research is needed to assess the robustness of modelling as it has the potential to be used for other pollution sources including noise. Railway infrastructures provide negative and positive impacts to woodland dependent wildlife. More research is needed to fully understand the role of railway lines near to and through ancient woodlands on ecological function.

Ancient woodland is a finite resource which cannot be replicated once lost. Pressures from development are varied and not always obvious. Without a thorough understanding of the ecology of individual woodland and trees these pressures are difficult to predict, assess and mitigate. This report reviews evidence, recommends mitigation and management, identifies evidence gaps, and proposes some research properties.

1. Introduction

Woodland is considered ancient if the land it occupies has been continuously wooded since 1600 AD (1750 in Scotland). An ancient tree is one that has passed beyond maturity and is old in comparison to other trees of the same species. Veteran trees are not as old or complex as ancient trees but may have many characteristics of ancient trees. Ancient woodland and trees are considered irreplaceable due their complexity developed over long periods of time with specific seasonal stressors that are unlikely to be repeated. By definition these are habitats which would be technically very difficult (or take a very significant time) to restore, recreate or replace once destroyed, taking into account their age, uniqueness, species diversity or rarity (NPPF, 2019).

The amount of ancient woodland in the UK has been in decline for centuries with only small and isolated remnants remaining. The landscape in the UK is subject to multiple uses and as a result is highly fragmented. Ancient woodland is often under pressure from encroaching development with removal, degradation and fragmentation still occurring despite their recognised value. The impacts on woodland from development are not always clear as they tend to be insidious and cumulative. Managing and monitoring the effects of development is difficult and the need to continually review evidence is important.

In 2008 the Woodland Trust published a report on the impacts of nearby development on the ecology of ancient woodland. An addendum was completed in 2012 to include additional evidence between 2008 and 2012. This report was commissioned to review relevant evidence since 2012 to provide the Woodland Trust additional up to date evidence of the impact of development on the ecosystem functioning of ancient woods and trees, and veteran trees. Mitigation and management recommendations are made, important evidence gaps identified, and research properties proposed.

2. Method

A search was conducted using a search strategy tailored to the question and sources of evidence. This included a search of primary and review academic articles. Relevant government and non-government organisations were searched for grey literature including technical reports and reviews. As this report was to update previous evidence reviews (Corney et al., 2008; Ryan, 2012) the method used aligned with the 2008 and 2012 evidence reviews.

The words 'woodland' and 'tree' were used as primary search terms because they fitted most closely with the objective of this report. Additional keywords and themes were used in combination with the primary search terms. These included keywords relevant to agreed topics, broadly including air [pollution]; hydrology; light [pollution]; noise [pollution]; recreation. Each topic question was searched following a hierarchy as used by Corney et al. (2008) and Ryan (2012) using the following steps:

1. Woodland AND Keyword AND Research Topic AND Theme

2. Woodland AND Keyword AND Research Topic

3. Woodland AND Keyword

4. Forest AND Keyword

If no results were returned in step 1 then the theme was dropped, then the research topic. If no results were returned using the word 'woodland' with a keyword, then the word 'forest' was used instead.

Three main online databases were searched including google scholar, JSTOR and science direct. Only articles and reports from 2012 onwards were searched for as this included all publications from the year of the last evidence review. Some articles and reports within both the 2008 and 2012 reports are included in this report to provide background and to ensure completeness. Google scholar consistently provided the most returns and was suitable for searching for grey literature.

Using the above methodology 103 papers and reports contained material potentially relevant to this review. All documents were further assessed for relevance by reading the abstracts or summaries. Documents considered out of scope during this initial assessment were not reviewed further. Those that had clear relevance, i.e. related to UK woodland, research targeting ancient woodland or ancient trees, or woodland and development were included.

In addition to the steps above, further literature was identified through searching the reference lists in all research articles and reports. This yielded additional literature that was directly relevant and provided important evidence. Seventy-three articles and reports are included in this review.

3. Impacts of development

3.1. Air pollution

3.1.1. Airborne particulate matter

The concentration of many air pollutants has decreased throughout Europe during the last decade, but particulate matter (PM) remains above recommended levels (Degtjarenko et al., 2018). Dust pollution is PM consisting of a complex heterogeneous mixture of solid particles suspended in the air ranging between 0.1-10 µm (Degtjarenko et al*.,* 2018). Dust pollution usually refers to primary and coarse PM originating from natural or anthropogenic sources. Rock quarrying, combustion processes, kiln grinding or roads (friction from brakes and tyres, dust from road surfaces and diesel engines) are the commonest anthropogenic sources (Degtjarenko et al., 2018). These anthropogenic activities release carbon, complex organic chemicals, sulphates, nitrates, mineral dust, and water suspended in the air (Corney et al., 2008).

Deposition of PM onto vegetation, soil and water can damage vegetation directly or indirectly through the addition of nutrients or changes in acidity levels within a habitat (Degtjarenko et al., 2018). These can cause a shift in the competitive balance between species, changes in plant species composition or subtle changes in vegetation structure, which can affect the use of habitat by an animal species (Holman et al., 2019). High levels of PM deposition has the potential to excessively disrupt ecosystem functioning and changes in composition of biological communities (Corney et al., 2008).

Trees and woodlands remove PM from the atmosphere through wet deposition (rain, fog and snow) and dry deposition (direct uptake on surfaces) when particles are deposited on solid surfaces (Jalón et al., 2019). Both dry and wet deposition occurs in the UK although dry deposition should be considered the dominant pathway as most days do not see rainfall (Eugster and Haeni, 2013). A large amount of research has focussed on quantifying the human health and economic benefit of tree and woodland removing pollutants from the air (Janhall, 2015). The overall conclusion is that trees and woodland are good at removing air pollutants to the benefit of human health. Little emphasis is given to the potential negative impact on individual trees or woodland tree communities themselves.

A 2008 literature review looked at the potential negative impact of industrial dust pollution on woodland in the vicinity of mining sites (Corney et al., 2008). Calcium deposition in a woodland 500 m from a lime quarry and adjacent to cement works was five times higher than in woodland 30 km away. Metal concentrations in soil samples along transects close to a lead smelting and former mine were higher in wooded habitat than other habitats suggesting woodland habitat accumulates dust particles more readily than other habitats (Corney et al., 2008). A review of urban vegetation and particulate air pollution highlighted that the amount of deposition positively correlates to the concentration of PM (Janhall et al., 2019). Simon et al. (2016) tested the hypothesis that the amount of dust and elemental concentrations in leaves were higher in areas close to abandoned cement and steel factories, then urban areas, than in the suburban and rural areas. Plane *Platanus* spp., ash *Fraxinus excelsior* and maple *Acer campestre* were surveyed for surface and tissue concentration of Al, Ba, Cd, Cr, Fe, Na, Pb, Si, Sr and Zn. Significantly lower amounts of deposited dust on leaves were found in the suburban area than in the rural area ($p = 0.02$). Urbanisation is resulting in high concentrations of deposited dust on trees and warn that pollution from dust continues after factories closed even after several decades.

Although there is a current lack of research of broadleaved trees native to the UK it is possible to consider the likely impact of PM from industrial activity and vehicle traffic using evidence gained for tree and shrub species native to other regions. For example, dust load on urban trees in India, including fig *Ficus* species, has negative impacts on leaf growth, leaf micro morphological and photosynthetic compound (Chaudhary and Rathore, 2019). Dust deposition was found to induce changes in physiological and micro-morphological characteristics of trees and these changes increased with road traffic volume and presence of industrial activities including combustion in power plants (Chaudhary and Rathore, 2019). It can be assumed, with some caution, that the negative impact on leaf growth and photosynthesis seen in *Ficus* species can be extrapolated to native UK trees with broad leaves that rely on high rates of photosynthesis.

Increased nitrogen load through deposition encourages growth rates in individual trees in the short term (Eugster and Haeni, 2013). However, long term ongoing nitrogen increases negatively affect individual trees and whole woodland stands by restricting nutrients. An imbalance of nitrogen to nutrient ratios in leaves results in a shortage of nutrients leading to enhanced sensitivity to natural stress factors such as frost damage and enhanced susceptibility to disease (Eugster and Haeni, 2013). Throughout Europe foliar phosphorus concentrations have shown to deteriorate in beech *Fagus sylvatica* and oak *Quercus* species (Jonard et al., 2015). Broadleaved trees inhabiting resource poor ecosystems are likely negatively impacted by nitrogen deposition by shifting biomass partitioning and altering allometric ratios such as leaf area/sap wood or root/leaf biomass (Ochoa-Hueso et al., 2017). Their ability to deal with environmental stresses such as droughts is likely further reduced as a result. Understory vegetation will be influenced by nutrient increases such as nitrogen with rarer species becoming outcompeted (Eugster and Haeni, 2013).

Beech *Fagus sylvatica* sapling growth was monitored over a 15-year period within woodland plots in Switzerland (Braun et al., 2010). Dry nitrogen was applied annually at concentrations between 0 – 160 kg per Ha^{-1} between 1992 and 2006. Nitrogen levels negatively correlated to growth rate. Reduced phosphorus concentrations after nitrogen addition in the experiments indicates that nitrogen deposition may have played an important role for inducing phosphorus limitation, with altered uptake being the more likely reason than phosphorus deficiency in the soil (Braun et al., 2010). To test this Braun et al., (2010) monitored mycelium density in mycorrhizal in-growth bags after two years of exposure to nitrogen in the woodland plots. Using a scoring system of 1 (no mycelium) to 5 (high mycelium density) the density of mycelium decreased as the concentration of nitrogen increased. Nitrogen mediated inhibition of mycorrhiza is one potential reason why some European woodlands are displaying decreased growth due to a reduction in phosphorus uptake as mycorrhiza play an important role in phosphorus uptake by trees (Braun et al., 2010).

The available evidence suggests long term nitrogen increases through deposition should be viewed as negative to woodland function and individual tree health (Braun et al., 2010; Eugster and Haeni., 2013; Stevens et al., 2016; Ochoa-Hueso et al., 2017). Predictions of woodland change in the UK by 2030 highlights the likely negative impacts of high levels of continued nitrogen deposition (Stevens et al., 2016). There will be increases in the cover and occurrence of more nitrophilic vascular plant species displacing other species such as heather *Calluna vulgaris* and wood-sorrel *Oxalis acetosella.* A projected increase in the average Ellenberg N score (see Hill et al., 1999 for technical description) will result in a more eutrophic vegetation composition in broadleaved woodland (Eugster and Haeni, 2013). Epiphytic bryophyte and lichen communities are likely to change species composition and numerous lichens are likely to reduce in occurrence. Although the findings of this study are invaluable as evidence for the likely degradation of species richness in woodland habitat, research targeting the likely effect of ancient woodland indicator species using the approach by Eugster and

Haeni, (2013) whilst accounting for management interventions if present, is required. This would be particularly beneficial for areas that currently experience low levels of nitrogen deposition as they are likely to be most sensitive to increases in deposition (Eugster and Haeni, 2013).

If deposition of PM changes morphological and physiological attributes of leaves, and degrades woodland species communities, and distance to the pollution source increases deposition, mitigating the effect of dust pollution through buffer zones seems practical. Reduction at source is another potential mitigation measure although Braun et al. (2010) found even small amounts of nitrogen deposition resulted in saturation within beech *F. sylvatica* and Norway spruce *Picea abies* experimental plots which, at least for nitrogen, indicates this approach may not be practical. To minimise impact buffer size should be decided primarily by the estimated concentration of the proposed developments PM release during the operational phase and its distance to the ancient woodland, ancient tree or veteran tree receptor, whilst considering environmental attributes such as wind. There is not a suitable amount of available evidence to define buffer zones based on development type although previously it has been proposed that most deposition occurs within 200 m of its source (RoTAP., 2012). This is not necessarily accurate or applicable to all dust pollution activity as calcium deposition from a lime kiln will occur at high levels at 500 m from the source (Corney et al., 2008). Research is required to accurately determine suitable buffer zones.

Lichens are considered good indicators of air pollution and are a well-studied group. Lichens are dependent on the atmosphere for nutrition due to their physiological and metabolic features (Degtjarenko et al., 2018). They absorb nutrients directly from the atmosphere, including atmospheric pollutants. Trait-based metrics are being applied to lichen communities to quantify ecosystem functionality. Morphological or physiological attributes (functional traits) are influenced by PM which has been shown to change lichen communities over gradients from pollution sources (Degtjarenko et al., 2018). The applicability of using lichen traits to track the effects of dust pollution was tested along a gradient of alkaline dust pollution released from limestone quarrying. Lichen communities shifted from crustose species (*least amount of surface area for respiring = more pollutant tolerant*) near the pollution source (quarry) to foliose species (*most amount of surface area for respiring = pollutant sensitive*) further away from the pollution source (Degtjarenko et al., 2018). The value of lichens as a barometer for pollution levels is evident, and rarer foliose lichen groups will be lost in woodlands and on trees as a direct result of nearby anthropogenic pollution sources.

In addition to alkaline dust, lichen community composition has been used to identify nitrogen levels at a large scale (i.e. national) (Seed et al., 2013). Nitrogen deposition mostly occurs within 200 m of its source (RoTAP. 2012) which suggests small scale monitoring of nitrogen levels may be more suitable to consider the impact of a development to a specific site. A caveat to this would be that site specific characteristics such as stacks on intensive livestock may result in increased spread of deposition for example. Seed et al. (2013) selected six widespread lichen species and a citizen science approach to evaluate the potential for measuring nitrogenous pollutants. Targeted lichens included nitrogen tolerant and nitrogen sensitive species (see Seed et al., 2013 for sampled species). Their results showed derived lichen indices are suitable as a tool to provide information on local, site-specific levels of air quality, and that lichens sampled only on *Quercus* species can be targeted. Seed et al. (2013) also found that nitrogen sensitive lichens are more affected by reduced forms of nitrogen which are associated with agriculture, while nitrogen tolerant lichens were more strongly related with oxidised forms of nitrogen associated with emissions from traffic and industry.

Understanding the community of lichens on *Quercus* species within an ancient woodland indicates current nitrogen levels and could provide robust evidence on whether nitrogen polluting developments within 200 m of the woodland should be allowed. If the surveyed lichen distribution is such that baseline nitrogen levels are high an application for development should be considered to further degrade and damaged site. If the surveyed lichen community identifies negligible to low nitrogen levels then a nitrogen polluting development should be considered as having the potential to damage an otherwise functional ancient woodland. The latter situation can be argued as suitable to reject a development application. An alternative could be if baseline nitrogen levels are low the proposed development could be accepted with the caveat that lichen communities would be an effective way of measuring nitrogen level increases over time and should be included as part of the development. Lichens closer to the edge of the ancient woodland could be targeted during monitoring. Observed changes would provide an early warning that the development is increase nitrogen levels and that action is needed. This could be particularly useful when assessing development or anthropogenic activity that will increase nitrogen levels such as; burning fossil fuels (including increased internal combustion vehicle use), farming and agriculture (including the use of nitrogen-based fertilizers), housing development, and industrial development.

3.1.2. Nitrogen oxide

The two main air pollutants affecting vegetation and ecosystems are nitrogen oxides (NO_x) and ammonia (NH_3) (Holman et al., 2019). The effect of ammonia on ancient woodland is covered in a Woodland Trust technical note (Hotchkiss, 2019). In summary, concentrations of ammonia are highest closest to intensive livestock units with emissions from a 160,000 bird poultry unit detected 2.8 km away (Jones et al., 2013). Ammonia exposure results in increased nitrogen load compounding direct nitrogen deposition (section 3.1.1) and nitrogen oxide concentrations (section 3.1.2). The cumulative effect of these three pathways should be considered during assessment.

Nitrogen oxide (NO_x) consists of nitrogen dioxide (NO_2) and nitric oxide (NO) produced mainly from combustion processes with almost half of UK NO_x emissions coming from road vehicles (mostly diesel engines), a further 25% from power generation, and the remainder from other industrial and domestic combustion processes (Holman et al., 2019). The general long-term UK trend in NO_x has been one of improvement despite an increase in vehicles on the roads. NO_x can affect plants directly through NO and NO_2 entering the stomata and indirectly through deposition onto the substrate, leading to nitrate enriched soil and eventual eutrophication (Holman et al., 2019).

Critical level thresholds are defined by the United Nations Economic Commission for Europe (UNECE; https://unece.org/) 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'. Ecosystem effects relate to impacts on plant physiology, growth and vitality, and are expressed as atmospheric concentrations over a particular averaging time (hours to years). Plants are important indicators of direct adverse effects on ecological receptors (Holman et al., 2019).

The long term (annual average) critical level for NO_x in the UK is 30 $\mu g/m^3$. Concentration levels above this have shown to elicit responses in plants (Holman et al., 2019). A United Nations Economic Commission for Europe (UNECE) working group recommended the use of the annual mean average value, as the long-term impacts of NO_x are thought to be more significant than short term effects (Holman et al., 2019). Increasing nitrogen levels may alter the outcome of competitive species interactions. Species shown to increase as nitrogen levels increase include nettle *Urtica dioica*, rough meadow grass *Poa trivialis* and pendulous sedge *Carex pendula* (Corney et al., 2008). These species are provided a competitive advantage over nitrogen sensitive species potentially reducing overall species richness.

Environmental assessments should therefore use 30 $\mu g/m^3$ as a measure to assess the likely impact of a development on habitats regardless of habitat type. The exposure of strawberry *Fragaria* spp. plants to increasing amounts of NO_x showed reduced photosynthesis ability as doses were increased from low (25 ppm NO_x), medium (50 ppm NO_x) and high (199 ppm NO_x) (Muneer et al., 2013). This is clear evidence that concentration levels are important and reducing exposure level of NO_x at ancient woodland, ancient tree and veteran tree sites can be used as mitigation. This could be achieved through reduction at source and or imposing a suitable buffer zone.

Using roads as an example, air pollution levels fall sharply within the first 30 m from a road before reducing more slowly with distance (Holman et al., 2019). The Defra/Environment Agency's Air emissions risk assessment for environmental permits (which applies to industrial emission sources) currently identifies distances of 2 km for local and nationally important sites and areas of ancient woodland. According to the Design Manual for Roads and Bridges (DMRB) standards for highways (https://www.standardsforhighways.co.uk/dmrb) designated sites such as ancient woodland would be subject to an air quality assessment if the proposed new road (or widening scheme) is within 200 m of an ancient woodland. This assumes that at the roadside the amount of NO_x will be greatest before steeply declining within the first 100 m (Holman et al., 2019; https://www.standardsforhighways.co.uk/dmrb). The process of scoping in would occur if an ancient woodland was within 200 m of the road scheme. Whether a full impact assessment would be undertaken would depend on the outcome of a screening assessment. The distance from the source (e.g. road) to the designated site (e.g. ancient woodland) would be a crucial factor to further assessments. A proposed buffer of 200 m agrees with previous research summarised by Ryan (2012) that found physiological changes in certain plant species was observed up to 200 m from a road and this was directly related to nitrogen dioxide levels.

Assuming NO_x level declines mostly within 100 m (Holman et al., 2019) an assessment of likely effects could use the annual average (mean) critical level of 30 $\mu g/m^3$ and model the likely increase that would occur within 100 m of the proposed development. If it is determined that additional levels are less than the critical level then no likely significant effects are recorded. This assumes the critical level is robust and that NO_x levels reduce steeply within 100 m from source.

Animal groups have shown to be negatively impacted by air pollution including nitrogen oxide. The ability of trained honeybees Apis spp. to recognise a synthetic blend of floral chemicals has shown to be significantly reduced when the chemical mix was exposed to diesel exhaust pollution (Girling et al. 2013). Girling et al. (2013) identified mono-nitrogen oxide (NOx) as a key facilitator of degrading odour. Honeybees appear to rely on the full scent profile of flowers and their ability to recognise food sources is reduced when the full scent profile is altered (Girling et al., 2013). More generally flowers emit a complex blend of volatile compounds that have shown to react with pollutants in the air. Insect pollinators use scent to locate pollen sources. Insect success rates of locating plumes of floral scents have shown to reduce and foraging times increase in polluted air masses due to degradation and changes in the composition of floral scents (Fuentes et al., 2016). Increased foraging times may result in reduced fitness as less time is available for other essential tasks (Fuentes et al., 2016). Premature telomere shortening in great tits (*Parus major*) through environmental stressors associated with traffic related pollution, possibly including NO_x, may be occurring (see section 3.4 for further detail).

In addition, it would be safe to assume that negative impacts of NO_x such as encouraging invasive plants or general habitat species richness declines will affect animals such as pollinators and so result in bottom-up degradation of the food chain.

3.2. Hydrology

Expansion of urban space results in an increase of impervious landscape and expansion of artificial drainage networks that can facilitate dramatic changes to the magnitude, pathways and timing of runoff at a range of scales, from individual buildings to larger developments (McGrane, 2016). Artificial drainage systems and increases in impermeable surface cover (including housing developments and road networks) are likely the most impactful and will be considered in this review. Other potential impacts of hydrology include urbanisation's role in artificially inflating local temperatures and altering downwind precipitation (McGrane, 2016) although these potential impacts are not well understood and beyond the scope of this review.

The urban landscape has a demonstrable impact on hydrological dynamics (McGrane, 2016). Urbanisation and associated housing developments changes the natural hydrological cycle by increasing peak flow and decreasing lag times of precipitation discharge (Harker and Rickard, 2003). This results in increased flooding in urban areas and degradation of the environment in terms of accelerated erosion and increased pollution. In addition, runoff from urban surfaces can carry a suite of contaminants including heavy metals, major nutrients (e.g. sodium, nitrate and phosphorus), litter and rubber residue from roads (McGrane, 2016).

Sustainable Drainage Systems (SuDS) are alternatives to traditional drainage systems and often consist of wetlands (including ponds), vegetation and selection of permeable surfaces where possible. The use of SuDS has shown to reduce variation of water movement and can provide benefits such as additions of wildlife type ponds as part of housing developments whilst diverting water run off away from a development to a suitable receptor. Suitably designed SuDS basins positioned between a development and a woodland will mitigate pollution run off (see Harker and Rickard, (2003) for estimate) and minimise flooding events that might otherwise occur when permanent non permeable surfaces are introduced. It is equally likely that a housing development situated on a grassland close to veteran trees and ancient woodland will change local hydrology regardless of the drainage solution and may inadvertently reduce the availability of water resulting in drought stress.

The author did not identify any literature on the effectiveness of SuDS basins to semi-natural habitat despite widespread use in planning. Post monitoring works would be suitable to provide evidence of the appropriateness of SuDS for protecting nearby ancient woodland and trees. A neutral change in hydrology of nearby semi-natural habitat and filtering of contaminates, and the direct value of SuDS on wildlife would be the target outcomes.

If increased rainwater run-off is expected a housing development could decrease the amount of water run-off by carefully selecting the most appropriate construction materials. Brickwork paving facilitates infiltration losses of 54% through combined joints and pores. Asphalt and bitumen preclude any infiltration but facilitate a high level of evaporative losses. In addition, implementation of sustainable urban drainage techniques, such as infiltration trenches, biofiltration swales, permeable paving and widespread plantation of trees and vegetation facilitates infiltration (McGrane, 2016).

Raiter et al. (2018) show that linear infrastructure changes ephemeral streamflow and water movement at a landscape scale. Although this study was interested in semi-arid environments in Australia their findings that variable amounts of engineering within road systems dictate the amount of impact to surrounding hydrology of habitats is applicable to UK roads. Importantly their study found that the presence of culverts reduced but did not fully mitigate hydrology change as a result of linear infrastructure. Changes in hydrology affect the morphology of river and stream channels, may increase fine sediments downstream, and pollutants can be transported long distances throughout the surrounding ecosystems (Lazaro-Lobo and Ervin, 2019). Developments upstream of ancient woodland and trees will be more likely to change the hydrology of surface and near surface water within or surrounding the woodland or tree than developments downstream. Direct pathways, such as watercourses, should therefore be identified and assessed for their ability to change hydrological conditions and transport potential pollutants.

3.3. Light pollution

Light pollution from industrial sites, housing developments and transport infrastructure has the potential to negatively impact on nearby sensitive receptors. Light spill may not directly impact on ancient woodland or trees but has the potential to degrade or remove the ecological function of these habitats and features by affecting the behaviour and distribution of dependent wildlife.

Bats are a group of nocturnal animals that use woodland and trees for some or all their ecological requirements including foraging and roosting. Bats are afforded full UK and European protection and certain species such as horseshoe bats *Rhinolopus* spp. are afforded SAC protection (https://sac.jncc.gov.uk/species/S1304/). Bats can be categorised into two groups; those that tolerate artificial lighting and those that avoid areas of anthropogenic lighting. Bat responses to lighting are species-specific and reflect differences in flight morphology and performance; fast-flying aerial hawking species frequently feed around streetlights, whereas relatively slow flying bats that forage in more confined spaces are often light-averse (Rowse et al., 2015). The impact of street lighting on bats in urban areas has been explored and the findings have direct relevance to woodland dependent bats as species such as brown long eared bats *Plecotus auritus* and the myotis spp. group tend to be light-adverse. Rowse et al. (2018) investigated the change in bat presence and activity around street lighting when lighting intensity was reduced. They found that higher light intensity reduced light-adverse bat activity but that dimming street lighting to 25% of the original intensity did not significantly reduce the activity of bats within the myotis group when compared to areas without street lighting (Rowse et al., 2018). This observed response by bats to street lighting dimming is encouraging because it provides evidence that reducing lighting may negate the potential negative impact of light pollution to an important woodland dependent animal group. Potential impacts of other sources of light pollution including vehicle headlights needs researching.

Work on lesser horseshoe bats *Rhinolophus hipposideros* found a strong aversion to street lighting with significant declines in activity near to street lighting along hedgerows (Zeale et al., 2018). The study selectively placed streetlights along commuting corridors that were known to be used by several bats during nightly movements to and from their foraging grounds. They recorded individuals switching from one side of the hedgerow (lit) to the other side (unlit). This observed behavioural response does indicate some plasticity even with light avoiding bat species and highlights that 'dark corridors' may be suitable mitigation when lighting is proposed. The use of 'dark corridors' is used in and around SACs selected for lesser horseshoe bats and these are achieved through additional vegetation, lighting baffles and fencing (figure 1; see BCT, 2018 for details and recommended process). Light level simulations are expected for developments deemed within the zone of influence of these designated sites. Lesser horseshoe bats use broadleaved woodland more than any other habitat for foraging. The quantity and quality of habitat within the sustenance zone of maternity colonies is considered key to the long-term success of the species. Anthropogenic illumination within woodland and around mature trees will degrade the ecological function (BCT, 2018; Rowse et al., 2018; Zeale et al., 2018).

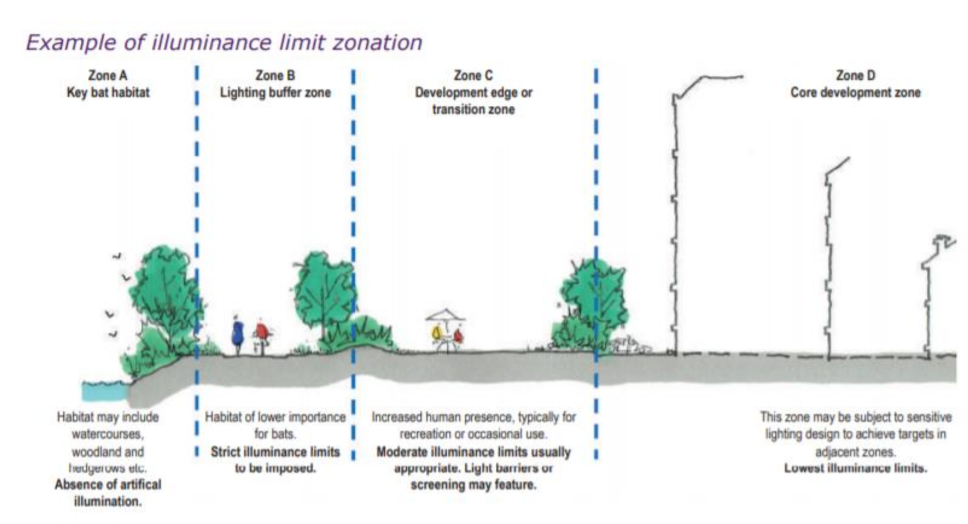

Figure 1. An example of potential mitigation to remove the adverse impact of increased light pollution on bats during development. Each zone will have decreased lux levels with Zone A lux level being within a defined threshold which could be as low as 0.1 lux (Azam et al., 2018). The illustration is taken from a Bat Conservation Trust Guidance Note (BCT, 2018).

Bats are unique in that they are nocturnal and navigate through echolocation. However, this does not mean light pollution will not impact on other woodland dependent groups. The behaviour of avian species changes when exposed to artificial light. Captive great tits (*Parus major*) exposed to simulated light pollution through the night (1.5 lux) increased their night time activity (Dominoni et al., 2020). The negative impact of light pollution on insects may not be obvious. Although avoiding areas of anthropogenic lighting has not been documented (to the author's knowledge) lighting likely reduces the fitness of some insect groups. Many nocturnal Lepidoptera have evolved 'ears' that listen for sound associated with approaching predators such as bats. It has been confirmed that moths exposed to light resort less often to last-ditch manoeuvres in response to attacking nearby bats (Hügel and Goerlitz, 2019). The predator has an advantage over prey in this situation although it should be noted that this particular example may not be a representation of the predator prey dynamic between moth and bat in ancient woodland as bat species associated with these habitats are themselves considered light-adverse.

3.4. Noise pollution

Noise pollution from industrial sites, housing developments and transport infrastructure has the potential to negatively impact on nearby sensitive receptors. Noise may not directly impact on ancient woodland or trees but has the potential to degrade or remove the ecology function of these habitats and features by affecting the behaviour and distribution of dependent wildlife.

Noise pollution influences the behaviour of animals. Captive great tits *Parus major* exposed to simulated anthropogenic noise (considered similar to road traffic noise) in nest boxes reduce their daytime activity (Dominoni et al., 2020). Vocal traits and diet explain avoidance behaviour in European woodland dwelling bird species (Francis, 2015). Species with animal based diets were susceptible to anthropogenic noise more often than non-predators. The best explanation is that animals that depend on sound to capture food are disadvantaged in noisy environments and will avoid them. Francis (2015) also found that birds with vocal traits within the lower frequencies were most affected as anthropogenic noise pollution, whether chronic (industrial) or intermittent (traffic noise), tends to be within the subsonic frequencies.

The tawny owl *Strix aluco* is a nocturnal acoustic predator. Generalized linear mixed modelling has shown that the presence and size of natural woodland within urban environments are good predictors of owl occurrence (Frohlich and Ciach, 2018). Importantly, owls were less likely to occur in urban woodlands if high levels of noise pollution (traffic noise) was documented regardless of woodland size. The probability of owl occurrence decreased when dB levels increased above 45 dB with zero probability of occurrence in woodland with noise levels above 50 dB (Frohlich and Caich, 2018). It is likely that noise reduced their ability to capture prey resulting in owls' avoidance areas with relatively high noise levels. In this example, a road running through a woodland would result in reduced hunting ability, increased edge effect and likely reduce the effective size of foraging habitat for tawny owls.

The influence of traffic noise on animals may not be obvious. Research in the US measured the response of cardinals *Cardinalis* to alarm calls by other bird species (Grade and Sieving, 2016). Cardinals eavesdrop on the alarm calls of other birds to avoid predation. It was found that all observed cardinals did not respond to playback alarm calls when in proximity to a highway (Grade and Sieving, 2016). Communication disruption may explain the pattern of reduced biodiversity next to roads. The role of chronic noise exposure on the longer-term fitness of animals is unclear. The house sparrow *Passer domesticus* increases vigilance around nest boxes when exposed to traffic noise playback but this change in behaviour did not appear to reduce reproductive fitness which was measured by egg hatching success (Meillère et al., 2015). The authors do warn that the study coincided with a poor season for chick success which may have influenced the result – despite this their results do raise the question that disturbance through noise pollution may not result in fitness consequences.

The construction of railways often pass through or very near to ancient woodland as evident during the development of HS2. Recent research on overwintering birds in woodland near to railway lines in Puławy Forest District in eastern Poland recorded three hundred and forty-eight birds from 20 species (Wiącek et al., 2019). The study concludes that noise of passing trains does not appear to negatively impact on birds and that abundance and species diversity was actually greater closer to the railway line than deeper in the woodland interior (Wiącek et al., 2019). Their interpretation was that the railway line created a rich woodland edge which was an attractive habitat for the sampled bird species. The conclusion that railway embankments provide good quality edge habitat is valid (Warwick, 2017). Research by the same lead author that targeted road traffic noise of overwintering birds was less clear but did manage to conclude that road traffic noise (which is more consistent than passing train noise) did result in reduced abundance and number of species closer to the road at certain times of the year (Wiącek and Polak, 2015). It would therefore appear that annual life strategies and needs at certain times of the year influence whether traffic noise is tolerated by birds, and importantly that the woodland edge habitat created by roads is degraded by a more consistent source of noise pollution, that is unlikely true for railway lines. Some cation is required when considering this research for ancient woodland in the UK as the study focussed on coniferous forest with dominant scots pine *Pinus sylvestris*.

Anthropogenic noise levels negatively influence wild animals most obviously through avoidance behaviours (Francis, 2015; Wiącek and Polak, 2015; Grade and Sieving, 2016; Frohlich and Ciach, 2018). Whether reducing the noise level would be less impactful is less clear. Male European robins *Erithacus rubecula* will move from an area of high background noise and modify their song (Mclaughlin and Kunc, 2015). In situ experimental design identified that the level of noise plays a crucial role in response to noise by robins. This is encouraging for mitigation strategies as the central aim is to reduce the level of noise through physical barriers or buffer zones.

Premature telomere (*a region of repetitive nucleotide sequences at each end of a chromosome which protects the end of the chromosome from deterioration*) shortening can lead to genomic instability, disease, and reduced longevity (Grunst et al., 2019). Stressors that could shorten telomeres in juveniles and adults are likely subtle but potentially profound. Grunst et al. (2019) found that telomeres in nestling great tits *Parus major* shortened between day 8 and 15 of age when the nest boxes were close to a road. They discounted metal accumulation, light pollution and reduced body condition and proposed that either noise pollution or air pollution (or a combination) were the responsible environmental stressors. Although traffic-associated air pollutants such as NO_x have been associated with telomere shortening (Grunst et al., 2019) experimental research on house sparrow *Passer domesticus* nestlings exposed to traffic noise identified shorter telomeres close to fledgling time when compared to birds not exposed to traffic noise (Meillère et al., 2015). These results provide the first experimental evidence that noise alone can affect a wild vertebrate's early-life telomere length and suggests that noise exposure may entail important costs for developing organisms.

Terrestrial mammals have also shown to avoid areas with increased noise levels. Mount Graham red squirrel *Tamiasciurus hudsonicus grahamensis* is a US subspecies of squirrel that has a similar life strategy to the Eurasian red squirrel *Scuirus vulgaris*. The Mount Graham red squirrel is an endangered subspecies that has been documented as avoiding roads (Chen and Koprowski, 2015). Traffic noise was found to be the influential factor that determined the probability of presence of squirrels surrounding road networks in the US and the squirrel’s core home ranges generally had lower levels of traffic noise.

Bats make up approximately 20% of mammal species and are considered particularly vulnerable to anthropogenic noise pollution due to their evolved echolocation navigation and hunting life strategies. The impact of traffic noise on bats has been researched during laboratory type experiments and during in situ field experiments (Luo et al., 2015; Finch et al., 2020). Traffic noise play back (a single randomly selected 1.4s clip of a vehicle pass) along linear features including tree lines found the number of bat passes (a measure of use) significantly reduced with traffic noise (Finch at al., 2020). Luo et al. (2015) conclude that playback noise reduced foraging efficiency. Both research projects identified that lower frequency sound waves, more associated with road surface noise rather than engine components, had a greater impact on bat use reduction than ultrasound.

Lower frequency sound attenuates in air less than ultrasound and so will be capable of eliciting avoidance behaviour (as observed) at greater distances than ultrasound (Finch et al., 2020). Although reductions in bat passes were observed more acutely near to the traffic noise a response by bats was still evident 20 m from the source of the noise. In addition, the results suggest that the response of bats to traffic noise is a generalised phenomenon that has a negative impact across all functional groups examined (Finch et al., 2020). Bats are dispersed by the noise generated by roads up to, and possibly beyond 20 m from the road and this phenomenon is likely correlated to the number of vehicles using a road. Traffic along all roads reduces through night time periods which is likely positive as it will reduce possible negative outcomes and it is safe to consider b-roads will have less impact on bats than dual carriageways and motorways. Common and adaptable bat species such as common pipistrelles *Pipistrellus pipistrellus* are frequently recorded foraging along tree lined b-roads.

Insects use sound for many reasons and auditory systems have evolved many times within the insect order. Sound is used for predator avoidance in moths (Hügal and Goerlitz, 2019), and mate location, attraction, and courtship in many groups. It is therefore possible that noise pollution has the potential to influence behaviour that relies on sound. Some evidence is available for long-term physiological and short-term behavioural adaptations to ambient noise levels (Morley et al., 2014) but the direct response of invertebrates to noise pollution has not been tested. Reductions in insect numbers because of noise pollution will likely impact animals that feed on them and other interactions with habitat such as pollination. Research which targets the effect of noise on insect groups is required.

A review of literature between 1990 and 2013 found terrestrial wildlife responses begin at noise levels of 40 dB (Shannon et al., 2015). Research since 2013 have proposed varying noise level thresholds ranging from 42 dB to 50 dB (see Votsi et al., 2016; Madadi et al., 2017) which indicates 40 dB is a conservative threshold that will ensure the most susceptible species are considered. Sound above 40 dB will elicit responses in some animals which increases to functional habitat loss as dB levels continue to rise.

3.5. Recreation

There are many benefits of recreation, including health and well-being and connectedness to nature (Lake et al., 2020). However, the pressures placed on ancient woodland through increased recreational users should be balanced against their benefits to human health. Potential impacts on woodland from recreation may include:

- contamination, e.g. litter, dog fouling, spread of invasive species and pathogens; waste water from campervans;
- disturbance of woodland dependent wildlife, e.g. through avoidance of breeding habitat, physiological impacts, and reduced breeding success;
- facilities, e.g. toilets and car parking;
- harvesting, e.g. collection of wood, fungi, and flowers;
- trampling, e.g. soil compaction, erosion, direct damage to breeding sites, and expansion of path networks;
- visitor expectation, e.g. management of the resource to provide a perceived experience rather than management to achieve the best ecological function (this could include felling trees for safety or tidying a woodland).

3.5.1. Contamination

Dog fouling and urination has been highlighted as a detrimental side effect of recreational use (Lake et al., 2020). Low nutrient habitats may be negatively impacted by the introduction of nitrogen and phosphorus through dog fouling although this is unlikely to be a significant issue in woodlands. Urination for scent marking in woodlands with a density of dog walkers is very likely to have significant impacts at an individual tree level. Ammonium in urine is toxic in quantity and may harm the tree bark and potentially the cambium layer. The build-up of nutrients may also damage mycorrhizal associations (Lake et al., 2020).

3.5.2. Disturbance

The potential impacts of disturbance in woodland are multifaceted and range from short-term to chronic. Disturbance can have a range of different impacts to woodland dependent wildlife, potentially affecting distribution, breeding success and health. Disturbance to wildlife is evident with over 90% of research studies identifying impacts of recreational disturbance on birds (Steven et al., 2011; Lake et al., 2020). Avian species are the most studied and therefore most suitable to identify potential disturbance through recreation and provide suitable mitigation. Birds might be temporarily displaced from a location with resulting energetic costs, even if only very short term in duration. Impacts can also include indirect mortality, for example through increased predation associated with disturbance (Lake et al., 2020). These responses are easily observed and measured. Physiological effects, for example related to stress are less observable although it should be considered as occurring and reducing overall fitness.

Observed responses of woodland birds to walkers include increased alertness, anti-predator adaptations (e.g. avoidance), food conditioning and displacement. Avian species have shown to flee from cover or nests impacting on their energy balances, feeding behaviour and the vulnerability of young, eggs or fledglings (Marzano and Dandy, 2012). Walkers affect the behaviour of birds in woodland and approaches such as vertical vegetation structure may mitigate continued disturbance (Marzano and Dandy, 2012). It is not as clear whether the responses observed in bird communities are comparable to other faunal species although some evidence may suggest species groups habituate to disturbance associated with recreational disturbance.

A useful study to highlight potential mitigation looked at habitat use and reproductive success of European nightjar *Caprimulgus europaeus* over 10 years in a breeding population on 1335 ha of Forestry Commission managed woodland in Nottinghamshire (Lowe et al., 2014). This study site was divided into a heavily disturbed section and a less disturbed section of equal habitat availability. The heavily disturbed area was that close to amenities and the area where most visitors remained. The less disturbed section included an area away from site amenities with only walking and cycling tracks. Lowe et al. (2013) found that overall nightjar density was significantly lower and there were significantly fewer breeding pairs in the heavily disturbed habitat compared with the less disturbed habitat. This study offers a comparison between disturbed and less disturbed areas rather than disturbed and not disturbed. The differences found showed that the level of disturbance is important. The number of breeding pairs in the heavily disturbed area had declined by 71% between 2001 and 2010, whereas in the less disturbed area, the number of pairs declined by only 10% across the course of the study (Lowe et al. 2013). Level of disturbance was clearly important to nightjars and was the observable reduction in visitor numbers away from the site's amenities and carpark.

Wild roe deer *Capreolus capreolus* have shown not to flee or otherwise change their behaviour when disturbed at night but do avoid footpaths and roads even at night when human activity is very low

(Marzano and Dandy, 2012). Radio tracking of barbastelle *Barbastella barbastellus* maternity roosting sites within Dartmoor National Park over three years observed the same colony of bats roosting in both undisturbed (a mostly inaccessible area of a semi-natural ancient wooded valley) and heavily disturbed (high footfall visitor attraction - https://www.beckyfalls.com/) ancient semi-natural ancient woodland (Carr et al., 2018). Despite anecdotal evidence that bats will fly from roosts when disturbed by people on foot (pers.com) this colony remained unaffected by high levels of disturbance by visitors (time in roost and nightly foraging behaviour was not different). It is likely that the availability and quality of roosting sites was key to their presence and disturbance did not degrade the suitability of the roosting sites which would agree with Marzano and Dandy (2012) that the structural attributes of a woodland may mitigate potential negative impact of disturbance. These two sites would make excellent comparison studies on the impact of footfall level on ancient woodland flora and fauna.

3.5.3. Harvesting

Removal of deadwood reduces available habitat for saproxylic (deadwood) invertebrates. Although this is likely more of an issue during forestry operations (mismanagement), Lake et al. (2020) proposes collection of deadwood for campfires and by children to create dens may impact on the availability and distribution of fallen deadwood. An important characteristic of ancient woodland in good condition is the amount of standing and fallen deadwood.

Fungi collection in ancient woodland may need further research to identify the effect of harvesting on the abundance of spores required to maintain populations although picking the fruit bodies themselves does not reduce the abundance or diversity of fungi (Egli et al. 2006). Despite this, Forestry England discourage the harvesting of fungi within the New Forest (Lake et al., 2020). It could be argued that compaction of soil through trampling will be detrimental to fungi through damage to mycelia but this appears not so. Trampling destroys mushrooms and toadstools during the early stages of growth prior to fruiting but does little or no damage to the mycelia (Egli et al., 2006).

3.5.4. Trampling

Excessive trampling by people along tracks can result in the localised loss of ground flora. Trampling resulting in compaction around the roots will have a detrimental effect on roots and associated soil fungi and can lead to tree death in veteran trees (Lake et al., 2020). Other recreational activities will lead to soil compaction. Mountain biking is a common activity in woodland and a small-scale experimental study has shown the potential for soil compaction and loss of vegetation (Martin et al., 2018). Low level trampling through footfall did not show obvious compaction or vegetation change but this changed with the level of trampling (Martin et al., 2018).

An example of the difficulties of balancing recreation against woodland functionality can be overviewed for the Woodland Trust's recently planted Heartwood Forest with stands of ancient woodland near Sandridge which had an estimated 180,000 visitors in 2015/2016 (Wright, 2016). The widening and erosion of pathways through the ancient woodland stands, degradation of bluebells (*Hyacinthoides* non-scripta) and disturbance to woodland dependent wildlife was noted in a long-term monitoring programme (Wright, 2016). Mitigation through visitor engagement and ropes along footpaths is ongoing and may reduce these observed negative impacts but it should be noted that the above impacts are apparent; less obvious degradation may be occurring that is overlooked or under-acknowledged by volunteers. Degradation of bluebells are easily observed due to their cover and flowering pattern. Changes to other floral species, lichens, moss and fungi communities may be less obvious. Badgers *Meles meles* are noted as being disturbed by dogs. Less conspicuous avian species, reptiles and other mammals may also be exposed to stresses associated with regular footfall.

A housing development near to an ancient woodland has the potential to increase footfall around and within the woodland. The author has first hand experience of housing development designs proposing recreation, in the form of children's play areas, within existing boundary woodland. This is likely encouraged by the developer's aim of providing a recreational element to their development to appease local planning authorities. It also means that the woodland is retained and there is no loss in physical habitat which although positive does not account for functional habitat loss. The trend for placing lodges within woodland (including ancient semi-natural woodland) is considered by developers and planners as less impactful if foundations are not required (pers.com). This highlights a potential perception that important ecological receptors such as ancient woodland, ancient trees and veteran trees can exist in and around housing and recreation development, and that residents and holiday makers can exploit these habitats without degrading or removing ecological function.

3.6. Root damage

Direct impacts of development on the root systems may include the severing of roots, ground compaction and increases in ground-levels, which may suffocate areas of the root system (Ryan, 2012). Providing an appropriate physical buffer zone from ancient semi-natural woodland, ancient trees and veteran trees is important to safeguard the root system, whilst facilitating sustainable development. Current standing advice was updated in 2018 (Natural England and Forestry Commission, 2018). The advice of a 50 m buffer zone to mitigate the effects of pollution and trampling has been removed following queries. This leaves a stated minimum of 15 m buffer to avoid direct impacts to a tree's root system but that development will likely affect both woodland and individual trees beyond this distance and so an assessment of impacts will highlight the need for larger buffer zones (Natural England and Forestry Commission, 2018). This standing advice provides several suggestions about buffer size but where space between important receptors and development is limited it would be easy to default to the minimum buffer required (15 m) without considering site specific circumstances. This has been highlighted in previous reviews (Corney et al., 2008; Ryan, 2012). The Forestry Commission has successfully bid for DEFRA funds to address this lack of evidence and recent research is providing some evidence to better formulate strategies to provide appropriate buffers in some situations (Andrews et al., 2019).

In the absence of mitigation such as exclusion zones during construction activities the potential to negatively impact on nearby trees is high. Urbanisation has shown to degrade the structural complexity of forest edges which has been associated with mortality and canopy damage following construction activity (De Chant et al., 2010). Following construction, structural complexity increases (likely as a result of tree recruitment) although a return to pre-development structural complexity may take anywhere between seven to 30 years (De Chant et al., 2010).

Andrews et al. (2019) argue that current standing advice (Natural England and Forestry Commission, 2018) for the protection of root zones for ancient semi-natural woodland and trees, and veteran trees does not account for species specific variation and is insufficient to ensure roots are protected from development activity. The standing advice recommends a distance of 15 m buffer zone from ancient semi-natural woodland and at least 15 times larger than the diameter of ancient and veteran trees or 5 m from the canopy edge (whichever is largest) (Natural England and Forestry Commission, 2018). The standing advice states that a distance of 15 m is the minimum buffer required to protect the roots of trees. As highlighted by Andrews et al. (2019) it is likely that 15 m is used as a maximum, or at least will be used as a standard buffer when development is assessed for its potential impact of the root system of trees.

The suitability of a 'one size fits all' approach does not account for species variations, management or historical stochastic events. To address this concern and provide data driven evidence which appears lacking in the current standing advice, Andrews et al. (2019) propose a 'Derived Root-system Radius' (DRSR) measurement as an alternative. The DRSR represents the estimated spread of the root system in any direction from the stem of a tree, based on the tree crown size.

To test the appropriateness of the standing advice buffer zones, Andrews et al. (2019) collated previous data and collected their own field measurements. They found that a single fixed buffer zone does not account for differences in tree root spread of individual species or trees. Standing advice buffers underestimated the likely root spread of trees on some occasions and overestimated on others. Neither the standing advice nor proposed DRSR consider tree management. The authors suggest a sensible approach would be to anticipate management influence, by applying the diameter approach of the standing advice, as well as the DRSR, apply an additional error margin of 2 m to allow for capillary-range, and adopt whichever is the greater buffer zone distance.

This would consist of two measurements per tree and the following three steps:

1. Measure 15 times larger than the diameter of the tree. The buffer zone should be 5 m from the edge of the tree's canopy if that area is larger than 15 times the tree's diameter (Natural England and Forestry Commission, 2018).

2. Measure the maximum living canopy radius. Calculate the canopy area. Calculate the estimated root-system area. Calculate the estimated DRSR (Andrews et al., 2019).

3. Include an additional 2 m radius and select the largest buffer.

An important point raised is that any calculation used to estimate the root spread of a tree by measuring the canopy or stem diameter will only determine the buffer required to protect the tree roots at that time (Andrews et al., 2019). This will be useful to protect the health of the tree during short term temporary ground works such as pipeline installation. However, if the tree has not reached its maximum size the above approach would not be suitable to protect the future growth of a tree when permanent developments are proposed such as housing developments, railways or roads. Trees impacted by permanent development using this approach may be constrained at their current size. This would likely occur despite good intentions of the developer and environmental assessor.

It is therefore most suitable to assess the zone of influence by development type, i.e. temporary and permanent. Temporary works would be guided by the maximum root buffer estimate using the current size of the canopy spread of the tree being assessed; and permanent works would be guided by the maximum root buffer estimate for the maximum recorded canopy spread of the species (Andrews et al., 2019). For developments deemed permanent (e.g. railway lines and roads) the buffer required to protect the root zones of trees should be the DRSR calculated using the maximum recorded canopy spread of the species.

3.7. Site-level fragmentation

Landscape scale fragmentation is not included as it is beyond the scope of this review.

Transport infrastructures impact habitat most obviously through direct removal. Less obvious is the potential change in floral communities and health through pollution and hydrological changes and negative impacts on habitat dependent wildlife. Wildlife populations may be affected in four different ways. Roads may reduce habitat area and quality, increase wildlife mortality due to collisions with vehicles, prevent accessibility to resources on the other side of the roads and thus subdivide wildlife population (Jaeger et al., 2005).

The construction and improvements of road and rail infrastructure is detrimental to woodland ecosystems. Although tree-lined roads and railway verges are considered to provide habitat for wildlife (Warwick, 2017) the characteristics of linear features means that they remove habitat and fragment the landscape. Local scale ecological impacts and landscape scale environmental impacts must be considered particularly as road and rail network density increases over large areas. There are two distinct phases associated with these infrastructure projects; the construction phase and the operational phase. Direct impact during the construction phase will remove habitat, increase short term noise, light, dust and air pollution, and will likely cover a larger footprint than the operational phase. The operational phase is the continued degradation of habitat through fragmentation and traffic-road-rail associated pollution.

3.7.1. Structural Fragmentation

Initial road construction is detrimental to local woodland species richness (Lazaro-lobo et al., 2019). The operational stage of roads adjacent to woodland has shown to modify woodland interior conditions and species composition (Watkins et al., 2003). Species richness of native plants were lower on the roadside when compared to interior levels up to 5 m from the kerb, and the abundance of exotic species were most prevalent within 15 m of roads occurring infrequently in the interior. The observable negative impact of the road was therefore 15 m from the road kerbside. The 15 m distance of observable change is half the distance proposed by expert opinion (Eycott et al., 2011). Balancing expert opinion and actual measurable findings may be required to propose a suitable distance. Encouragingly plant assemblage of woodland roadsides recover over time although woody species will take longer than herbaceous species (Lazaro-lobo et al., 2019). The abundance of native species in woodland roadsides increases and the frequency of exotic weed species decreases over time (Lazaro-lobo et al., 2019) which indicates woodland severed by new roads may recover in species richness and abundance given time. A likely reason for the observed increase in native species and decrease in exotics may be bare soil availability shortly after development work which is later covered removing that microhabitat.

There is evidence that roads negatively impact on local bat populations through fragmentation of habitat, severing commuting routes, reducing foraging grounds, and potentially reducing prey resources (Berthinussen and Altringham, 2012). The use of structures such as bat gantries have shown to be ineffective as mitigation for new dual carriageways or to re-establish historic commuting corridors (Berthinussen and Altringham, 2012; https://www.standardsforhighways.co.uk/dmrb). Gantries are not suitable mitigation, but large culverts do provide the ability for bats to pass roads (major and minor). Green bridges are likely suitable if positioned along known commuting routes although the costs associated with green bridges make their construction (new or retrofit) sparse which questions their usefulness in increasing the permeability of roads for wildlife at scale.

National reports of owl collisions with vehicles killed on England's roads are made daily. The effect of this mortality on the long-term persistence of owl populations is still uncertain, therefore impact assessment and mitigation should be based on a thorough understanding of the species most vulnerable to road mortality. To put this in perspective a study in Portugal recorded 2080 passerine carcasses along 50 km of roads surveyed over a three-year period (March to June each year) (Santos et al., 2016). Surveys were conducted from a car travelling at 20-40 km per hour. Although surveys were conducted at sunrise to avoid missed carcasses due to scavengers it is likely many carcasses were missed. Passerine bird collision mortality was high and the number of individuals of a given species dying on roads was strongly correlated with its relative abundance in nearby habitat (<500 m) (Santos et al., 2016). It remains uncertain whether abundance was shaped by adjacent habitat. Santos et al. (2016) found higher risk for foliage and bark foragers (e.g. Blue tit, Blackcap and European goldfinch) which further identifies the risk of roads through woodlands on woodland dependant bird species. Roads within 500 m of woodland should be considered to increase road collision mortality of avian species.

Structural fragmentation resulting from railway infrastructure is different to structural fragmentation because of roads in some ways. Bats are an example of a species group that may benefit from rail infrastructure in some landscapes in the UK, relative to roads. Railway lines may provide habitat for common pipistrelles *Pipistrellus pipistrellus*, Leisler's *Nyctalus leislerii* and *Nyctalus* spp. in otherwise poor-quality intensive agricultural landscapes where semi-natural elements tend to disappear (Vandevelde et al., 2014). And so, foraging and commuting ability of generalist bat species is not ubiquitously negatively impacted by railway lines (Vandevelde et al., 2014) with edge foraging species likely to benefit.

3.7.2. Functional habitat loss

It is important to consider that transport infrastructure may have a larger impact than its physical footprint when operational impacts such as noise and pollutants are considered. Roads can fragment significantly larger areas of woodland than structural fragmentation through functional habitat loss. For example noise pollution may cause functional fragmentation that will impact a woodland beyond its physical boundary (figure 2; Madadi et al., 2017).

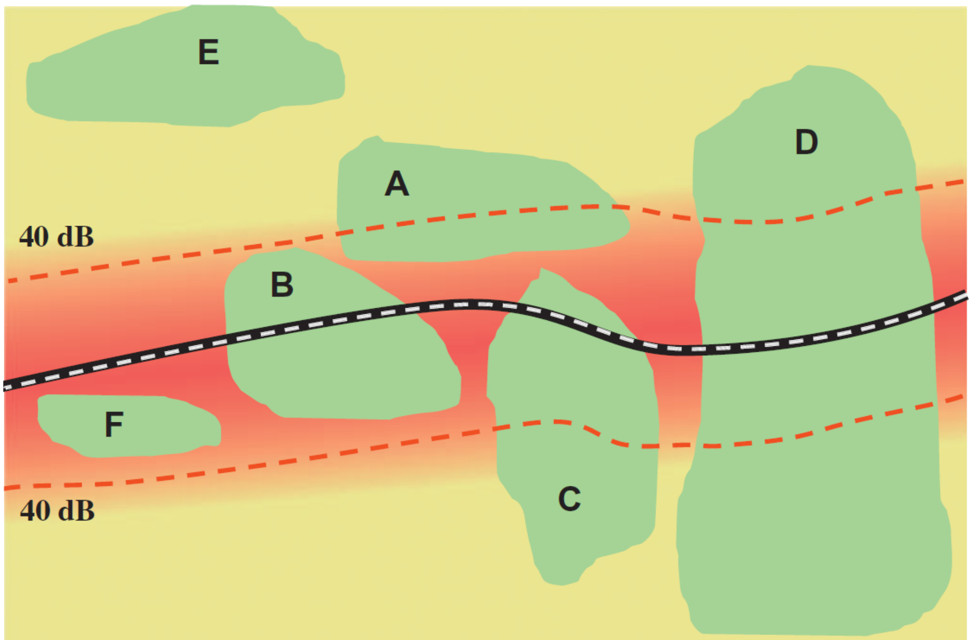

Figure 2. A concept for structural and functional habitat degradation as proposed by Madadi et al. (2017). The original habitat patches are indicated in green within the yellow matrix. The road is indicated by a black line with white dashes, the noise effect zone by red, and the dotted lines indicate the 40 dB threshold for noise affecting wildlife.

Madadi et al. (2017) highlight that traffic noise may be responsible for functional habitat loss of partial patches (a woodland or an individual tree) or complete loss of a patch. In figure 2 patch D is partially fragmented and patch B is completely lost. If structural habitat loss is the only consideration patches such as A and F or not considered to be directly impacted by the road.

Traffic noise modelling in western Iran applying a threshold of 40 dB found that oak forest and scattered woodland showed differences in the structural (direct removal of habitat) and functional habitat loss due to roads with traffic volumes of 1000 or more vehicles per day. Oak forest structural loss was 0.22% with functional loss of 7.2%. Scattered woodland structural loss was 0.22% with functional loss of 11.5% (Madadi et al., 2017). When considering fragmentation over their entire study area the proportion of habitat affected by land-take was 19.4% whereas functional habitat fragmentation amounted to 45.2%. Noise propagation modelling found the road effect zone ranges from 50 to 2000 m based on a noise level threshold of 40 dB and was variable due to topographic conditions (Madadi et al., 2017).

Wiacek et al. (2015) found that avian species during the autumn period including Eurasian jay, great spotted woodpecker, siskin, mistle thrush and nuthatch increased in density when measured at 60 m, 310 m and 560 m from a road. Noise levels above 49 dB significantly influence the number of birds or species richness (Wiacek et al., 2015).

The distance from a road to ancient woodland and trees will influence any observable impacts on the habitats. Total bat activity, the number of species and the activity of common pipistrelle *Pipistrellus pipistrellus* has shown to positively correlate to distance from roads (Berthinussen and Altringham, 2012). This was observed along sections of the M6 in Cumbria. Species richness (the number of different species) increased at monitoring points further away from the road. Their research showed that the M6 motorway negatively impacted on bats up to 1.6 km from the road. The authors do note that although habitats such as woodland and water bodies were avoided to limit their influence on the results some subtle influence is likely. It is also important to consider that the most abundant species was the common pipistrelle which is a highly adaptable bat that on balance has benefited from urbanisation. The potential effects of noise, hydrology and light pollution were discounted as the motorway was not lit and light from vehicles and these other impacts were considered unlikely to reach 1.6 km. The observed reduction in bat activity over the relatively large distances was explained by the combination of a barrier effect and increased mortality because of roadkill (Berthinussen and Altringham, 2012). Road kill numbers of bats is speculation as finding carcasses on the road side is not practical because of their size and removal by scavengers. Searches for bat carcasses by dogs at windfarms are providing numbers of strike deaths in those areas but this is not practical at the roadside due to safety. Berthinussen and Altringham (2012) warn that the observed reductions of bat activity due to roads are long lasting as the reduction in bat presence evident decades after a road is constructed.

Bats are faithful to both roosting sites and foraging grounds, and tree-dwelling bats of different species will use the same collection of roosts over many years (Carr et al., 2020). They are also faithful to foraging patches and generally follow one or a small number of commuting routes to traverse between roosting site and foraging ground. It is possible to identify the sustenance zone of different bats species. This is an area that a colony of bats requires for foraging (and the ability to reach foraging grounds) to sustain the colony (BCT, 2016). For example the barbastelle *Barbastella barbastellus* has a sustenance zone of 6.5 km around its nursery colony (Carr et al., 2020). The barbastelle is a tree roosting bat that is mostly associated with old growth ancient woodland. In order for a colony to successfully use a potential roosting site (e.g. collection of tree cavities within a woodland) it must have an appropriate amount of foraging habitat within a 6.5 km buffer surrounding that woodland. Any development that reduces, degrades or fragments the habitat within that buffer has the potential to impact the colony within the woodland which at the extreme may lead to colony collapse.

Identifying and protecting core sustenance zones is considered important to the success of woodland dwelling bat species (BCT, 2016; Carr et al., 2020). This approach would be particularly important for species that have shown not to cross open linear features such as roads because a road running north to south at the east side of an ancient woodland would render any area to the east of the woodland unusable. A study that addressed the likelihood of bats crossing a road found gaps of 2 m or greater (including the road itself) elicited an avoidance response (Bennet and Zurcher, 2012). Their research also found that avoidance responses (bats turning away from the road during a commute) increased as road noise increased. Following the conclusions of the research by Benner and Zurcher (2012) a threshold of 88 dB should be applied when considering the impact of road traffic noise on bats passing over roads. Light pollution from headlights and road lighting also appears to deter bats crossing roads (Bhardwaj et al., 2020). Although this threshold may be different for various bat species it is a measurable level that would aid assessments of developments including new roads and widening projects.

4. Mitigation and management measures

4.1. Buffer zones

Buffer zones are suitable to protect ancient woodland, ancient trees and veteran trees from nearby development and pollution sources. Establishing the zone of influence of a development at different scales is required to ensure a buffer zone is effective. This requires full understanding and evidence of impacts on ancient woodland and trees. To date, published literature provides some evidence but is incomplete. Table 1 proposes buffer zones based on available literature between 2012 and 2021.

Table 1. Proposed buffer zones summarised using research evidence between 2012 and 2021. The buffer zone is the recommended distance from a development or pollution source to a sensitive receptor including ancient woodland, and ancient and veteran trees. Using a conservative approach where a distance measurement is considered variable the threshold of the pollution type that has shown to result in negative impacts is used. The proposed buffers should be considered as minimum distances/levels. Site /development specific factors may require larger buffer zones.

Impact	Buffer zone	Literature	Strength of evidence
Air pollution			
Nitrogen deposition	200 m	RoTAP. 2012	Weak
Nitrogen oxide	200 m	Ryan, 2012; Holman et al., 2019	Moderate
Light pollution	0.1 lux*	Azam et al., 2018	Moderate
Noise pollution	40 dB*	Shannon et al., 2015; Votsi et al., 2016; Madadi et al., 2017; Frohlich and Caich, 2018	Strong
Road	15 - 1600 m	Watkins et al., 2003; Berthinussen and Altringham, 2012	Weak
Root damage	≥15 m (variable)	Wolf and Croft, 2014; Natural England and Forestry Commission, 2018; Andrews et al., 2019	Strong

* buffer would be the distance needed to achieve recommended threshold level

4.2. Hydrology

Appropriate construction materials selection should be encouraged for any development close to ancient woodland and trees that will substantially change the substrate. The principal aim would be to have a neutral impact to surrounding ancient woodland and trees by ensuring no hydrological change post development.

The careful selection of construction material is appropriate mitigation. This may be permeable materials such as brickwork paving, or surfaces known for their high level of evaporative losses.

Implementation of sustainable urban drainage systems, such as infiltration trenches, biofiltration swales, permeable paving and widespread plantation of trees and vegetation facilitates infiltration (McGrane, 2016) and so will reduce peak flows and filter contaminants. These may provide a high level of protection to nearby ancient woodland and trees although caution is recommended until a better amount of evidence is available.

4.3. Recreation

Recreational use of ancient woodland and habitats with ancient and veteran trees (such as parks) can be detrimental to individual trees (e.g. the toxicity of ammonium in dog urine and soil compaction), woodland habitat (e.g. increased spread of invasive species), and dependant wildlife (e.g. disturbance). Levels of disturbance through recreation users are greater near to facilities such as cafes, toilets and car parks than away from these facilities (Lowe et al., 2014).

Placement of facilities in areas of a woodland or habitats deemed less sensitive or of lower importance to biodiversity is appropriate mitigation. Management or enhancement of an ancient woodland to encourage high quality ecological function near to facilities is arguably not possible as these are the areas with high levels of disturbance. Managing these areas for recreational users and dedicating resources for ecological function away from high levels of recreational users would be more achievable. The number of visitors to an ancient woodland site could be controlled through parking provisions. Smaller carparks will reduce overall visitor numbers.

Path networks can be managed by ensuring good maintenance of paths that should be used. This should also negate path widening through detours around boggy paths for example. Paths near sensitive habitat receptors could be closed or encouraged to overgrow to discourage recreationists from certain sensitive areas. Signage can be important. For example, establishing good practice by users such as keeping dogs on leads, prohibiting barbecues, encouraging individuals to take their litter with them, and cleaning boots to minimise spread of invasives.

New developments potentially leading to increased footfall in an ancient woodland could provide Suitable Alternative Natural Green Space (SANGS) to relieve the pressure as required as part of development proposals close to Natura 2000 sites.

4.4. Reduction at source

4.4.1. Air pollution

The amount of deposition on urban vegetation positively correlates to the concentration of particulate matter (Janhall et al., 2019). Dust and elemental concentrations in leaves are higher in areas closer to particulate matter producing areas such as towns and factories (Simon et al., 2016). Vegetation is efficient at collecting air pollution. Planting species known for their ability to remove air pollutants between the source of pollution and sensitive receptors is well-studied for human health. The same principles can be applied in town planning that protect people and dwellings from air pollution to the reduction of air pollution from developments on ancient woodland or around ancient and veteran trees. Specifically identifying individual floral species, planting schemes, vegetation placement is not covered as it is beyond the scope of this review. However, it is noted that there is a large amount of research targeting the use of vegetation to reduce pollution in urban habitats.

4.4.2. Light pollution

Light pollution from industrial sites, housing developments and transport infrastructure has the potential to negatively impact on nearby sensitive receptors. Light spill may not directly impact on ancient woodland or trees but has the potential to degrade or remove the ecological function of these habitats and features by affecting the behaviour and distribution of dependent wildlife.

The evidence within this report suggests light pollution above 0.1 lux within ancient woodland and around ancient and veteran trees will elicit responses in animals (Azam et al., 2018). Mitigation of light pollution through buffers and screened zones that result in light pollution levels of 0.1 lux or below is suitable mitigation. All development that will produce artificial light should be required to model their potential to project light onto nearby ancient woodland and trees. Development in which modelling identifies >0.1 lux levels at nearby ancient woodland and trees should be rejected.

Buildings can be positioned to reduce light spill through windows. Vegetation, screens and lighting baffles could be incorporated into designs to reduce the level of lux. The intensity of light (LEDs) has shown to be important for dependent wildlife (Rowse et al., 2015, 2018). Dimming lights at their source and turning lights off between certain time periods are good mitigation strategies and should be explored further.

4.4.3. Noise pollution

The reduction of noise pollution below levels shown to negatively impact wildlife could be achieved within the distances (buffers) proposed (see section 4.1) if physical structures are present between the noise source and the ecological receptor. Noise attenuates as it travels through air and is absorbed or diffracted by physical objects (Attenborough et al., 2016). Mitigating the effect of noise can be as straight forward as recommending a buffer. If the recommended buffers are not possible then physical barriers may be considered. It may be possible to plant additional rows of trees or woodland between the noise pollution source and ancient woodland receptor. To maximise the usefulness of trees to reduce noise careful design is crucial. Attenborough et al. (2016) conclude that soft ground effect and visco-thermal attenuation of foliage are two important elements that influence sound propagation. Decaying leaf litter (humus) has shown to reduce traffic noise in the 500 hz to 1 khz range which corresponds to tyre on road surface frequency (Attenborough et al., 2016). In combination with thin course road surfacing (https://www.standardsforhighways.co.uk/dmrb) the potential impact of traffic noise pollution could be greatly reduced on UK roads.

Traffic noise modelling can be applied in ecological impact assessment (EIA) of transport infrastructure projects and will increase chances for successful implementation of mitigation measures of roads. This approach can help to assess the ecological impacts throughout the EIA process from the planning to the construction and operation phase of linear infrastructural projects.

Dominoni et al. (2020) argue that multisensory pollution should be considered for sources of pollution to wildlife. An example of this is the apparent interactive influence of light and noise pollution on birds. Their point is likely valid but practically it would be more difficult to determine combined effects than aim to mitigate pollution sources in isolation (i.e. mitigate noise and mitigate light rather than try to understand the combined interactive impacts).

4.5. Root damage

Standing advice (Natural England and Forestry Commission, 2018) proposes ancient woodlands should have a buffer zone of at least 15 metres to avoid root damage. This is straight forward to follow but is not based on evidence (Ryan, 2012; Andrews et al., 2019) which may lead to unsuitable or ineffective buffers. The standing advice goes on to say where assessment shows other impacts are likely to extend beyond this distance, you are likely to need a larger buffer zone. For example, the effect of air pollution from development that results in a significant increase in traffic. Although true it fails to address the question of what size of buffer would be required in this example or for other potential indirect impacts at different scales.

A method has been developed which aims to establish appropriate buffer zones that are proportionate whilst ensuring a suitable distance when protecting the root zones of trees and woodland stands (Andrews et al., 2019). This method is backed by evidence and could be adopted into standing advice.

In addition, temporary works should be guided by the maximum root buffer estimate using the current size of the canopy spread of the tree being assessed; and permanent works should be guided by the maximum root buffer estimate for the maximum recorded canopy spread of the species.

5. Knowledge gaps and research priorities

5.1. Air pollution

Dust load on urban trees in India, including fig *Ficus* species, negatively impacts on leaf growth, leaf micro morphological and photosynthetic compound (Chaudhary and Rathore, 2019). This phenomenon has not been studied for trees native to the UK. The potential role of particulate matter and deposition on native broadleaved trees requires research.

Lichen communities provide an opportunity for rapid assessment of nitrogen levels in the atmosphere. Nitrogen mediated inhibition of mycorrhiza is one potential reason why some European woodlands are displaying decreased growth due to a reduction in phosphorus uptake as mycorrhiza play an important role in phosphorus uptake by trees (Braun et al., 2010). More research is needed to test the hypothesis proposed by Braun et al. (2010).

5.2. Hydrology

Sustainable drainage systems may have ecological benefits and may be suitable to neutralise impacts on the hydrology of sensitive receptors from nearby developments. Research should be undertaken that measures the hydrological conditions in ancient woodland and around trees before and after developments that propose sustainable drainage systems. Research objectives should include:

- Does the hydrology of the nearby sensitive receptor change following development?
- Does the water table increase or decrease following development?
- Is there an increase in contaminants following development?

This would provide the evidence needed to evaluate the role of sustainable drainage systems in mitigating potentially negative hydrological changes in and around ancient woodland and trees. Control sites (development near ancient woodland and trees that do not proposed sustainable drainage systems) could be included to assess the value of sustainable drainage systems as mitigation when compared to no mitigation.

5.3. Noise and light pollution

Votsi et al. (2016) provides buffer zone recommendations based on the source of noise pollution ranging from motorways to recreational activity. Their results were based on the known source level of dB and the attenuation of sound until a threshold of 50 dB level was reached. This evidence review identified additional research that recorded the level of sound energy required to elicit responses of woodland dependent wildlife as low as 40 dB. The process used by Votsi et al. (2016) should be revisited using 40 dB as the threshold and buffer distances recalculated.

The same process is suitable to identify the buffer zones needed for light pollution by firstly identifying the lux level of different light pollution sources such as window openings of dwellings, traffic headlights, and street lighting, and secondly modelling the intensity of light spill over distance until a threshold of 0.1 lux is reached. Light spill modelling is successfully used to determine dark zones for bats in designated SACs in the southwest of England.

The author recognises that noise and light modelling is complex, and that the above recommendation may be overly simple. It is however considered an important area needing research.

The available literature identifies that railway lines through or near to ancient woodland increases avian species diversity. An interpretation is that the railway line created a rich woodland edge which was an attractive habitat for the sampled bird species. The amount of targeted research on the impact of railway lines on wildlife is limited and this topic has not been covered in any part of the UK. It could be argued that UK train networks are busier than other European countries and so the impact through noise of passing trains may be greater. Research on road networks shows a threshold in relation to noise of passing vehicles and bird presence. It would therefore be prudent to further consider noise levels of UK railway lines to wildlife.

5.4. Recreation

Balancing recreation against woodland functionality is complex. The intensity of disturbance through recreational users is important, but the available evidence is not robust enough to state that a certain threshold of user numbers could be used as a guide to woodland functionality degradation or loss. Evidence is available to show that visitors to woodlands congregate mostly around provided facilities such as cafes, toilets and car parks. Further research to explore whether it is possible to use this evidence to better manage ancient and semi-natural woodland sites while allowing recreational access is required.

For example, urination for scent marking in woodlands with a high density of dog walkers is very likely to have significant impacts at an individual tree level. How much of a problem this is for ancient and veteran trees needs researching. In addition, cumulative impacts of trampling would also need including as areas that suffer from continued scent marking by dogs likely suffer from soil compaction and direct root damage through footfall.

Testing the effectiveness of different interventions to mitigate the impact of recreation is required. There is a need to be more systematic when applying mitigation to observed recreational impacts in woodland habitat. When mitigation is proposed a method of before and after monitoring should be included so that crucial evidence of what works, and what does not, is identified.

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