Road verges and their potential for pollinators

A review of the costs, benefits and management options

4th February 2019

Beth Roberts and Ben Phillips

Saving the small things that run the planet

Contents

Executive summary

This report summarises the current scientific literature on the use of road verges by pollinators, and how they can be managed to support them. Insect pollinators have experienced global declines, largely due to habitat loss and fragmentation through land-use changes. Providing suitable habitats is therefore a conservation priority. Road verges provide a significant opportunity to support pollinators due to the large area of land that they cover, both within the UK and globally.

Pollinators are commonly found to use road verges as they provide food resources throughout the season for both adult pollinators and their larvae. They also provide areas for shelter, nesting and overwintering. However, the close proximity of roads means there are a number of potential threats. Road deaths through collisions with traffic can kill substantial numbers of pollinators, although it is unknown whether this causes significant population-level effects. Roads and road traffic also produce various forms of pollution that may affect pollinators. Contamination of the soil and plants can affect individual pollinators, such as causing reduced reproductive success and weakened immune systems, but there is limited research into the impacts on pollinator populations. Road verges are a barrier to movement for pollinators, and the ability of pollinators to cross roads depends on the road size, traffic volume and size of the pollinator species. There is limited evidence to support road verges being used as dispersal corridors by pollinators, though other linear features are known to be used. The use of road verges by pollinators can be influenced by the surrounding habitat, with road verges in agricultural landscapes generally containing fewer pollinators than those within more natural landscapes. However, road verges have been shown to be particularly important for pollinators in florally-poor landscapes such as farmland due to a limited availability of other resources. The size of a road verge can affect its value to pollinators; larger patches are preferred by wild bees, and butterflies are less likely to disperse from larger patches, which could lead to fewer road deaths.

The way that road verges are managed can have a major impact on their value to wildlife, but there are relatively few studies on pollinators, and most focus on butterflies. Cutting vegetation benefits plants, flower and local pollinator diversity and abundance, with most studies showing that one or two cuts is best. The timing of cutting is important due to the activity cycles of pollinators, and delaying cutting from spring to summer was found to benefit the abundance and species richness of wild bees and hoverflies, whilst cutting in early summer and early autumn was found to be best for butterflies and plant species richness. However, the long-term population effects of cutting are unclear and cutting in early summer will remove flowers and destroy pollinator eggs, so staggered cutting regimes are recommended. Removing hay after cutting benefits plant species richness and results in a greater abundance and species richness of flowers and pollinators, likely due to the space created for seeds to come through rather than due to nutrient removal.

Based on the summarised literature, we provide a management hierarchy that can be adopted by road verge managers in order to improve the value of road verges for pollinators. The hierarchy starts at a ‘baseline’ level, which is the management regime we assumed most road verge managers are using. From this, each step along the hierarchy provides incremental benefits to pollinators, but also incremental investment to implement. Therefore, road verge managers are able to select the best plausible management option to benefit pollinators, based on monetary and time budgets.

1 Introduction

Insect pollinators have experienced global declines (Goulson *et al.*, 2015; Potts *et al.*, 2010; Vanbergen and Insect Pollinators Initiative, 2013). This is in major part due to the loss and fragmentation of habitats (Kennedy *et al.*, 2013). To support pollinators, it is necessary to increase the quality and quantity of semi-natural habitats, which provide food (flowers, nectar and pollen), shelter, nesting sites, and hibernation sites (Senapathi *et al.*, 2017). Road verges are one such habitat, with a particularly high potential to support pollinators due to their widespread nature, with 397,025 kilometres of roads in the UK (Department for Transport, 2018). Road verges are the areas of land that lie between the road surface and the boundary of the road e.g. a fence or hedgerow. The purpose of road verges is to provide visibility for drivers, road drainage, access for pedestrians, and areas for road users to pull over, though they also help roads to blend into the surrounding landscape. They comprise of vegetated areas of varying size and shape, which are managed accordingly. The ubiquity of road verges means that they may make a significant contribution to nature conservation. In the UK we have around 238,000 ha of road verges, compared with only 85,000 ha of flower-rich grassland (Plantlife, 2012).

Road verges are often remnants of the habitats which previously surrounded them but have disappeared through land-use changes such as through agricultural expansion. As such, road verges can represent a wide range of different habitat types, including: grassland including amenity, species-rich, heath and moorland; woodland including scrub and scattered trees; hedgerows including native and ornamental; and water bodies including banks, ditches and reed beds (Highways Agency 2001). Each of these habitat types may have different management plans (Highways Agency 2001), and management will also depend on a number of site-specific factors, including road managers budgets. Road verges can support a wide range of wildlife including plants (Austed *et al.*, 2011; Suárez-Esteban *et al.*, 2016), insects (Heneberg, Bogusch, and Řezáč 2017), birds (Meunier *et al.*, 2000), and mammals (Bellamy *et al.*, 2000; Jumeau *et al.*, 2017; Ruiz-Capillas *et al.*, 2013). However, their value to wildlife is affected by a range of negative impacts of traffic and associated pollutants (Forman and Alexander, 1998), and by the way that they are managed (Jakobsson *et al.*, 2018).

This report explores the use of road verges by pollinators. It summarises the evidence and limitations of existing research on the benefits of road verges to pollinators, the possible negative impacts of traffic and associated pollutants, and the impacts of different management regimes. It concludes by providing recommendations for the management of road verges that benefit pollinators, based upon the available research.

2 How do road verges support pollinators?

Road verges have been shown to contain significant numbers and species of pollinators, and they can support similar pollinator communities to other surrounding habitats (Villemey *et al.*, 2018). Rare species can be found along road verges (Heneberg, Bogusch, and Řezáč 2017; Raemakers et al. 2001), and some species are completely dependent upon road verges in otherwise unsuitable landscapes (Heneberg *et al.*, 2017)**.** A study in Ayrshire, Scotland found that butterfly, bee and hoverfly abundances, diversity and species richness were greater in road verges than in many other habitats, including arable farmland, intensive and rough grassland, woodland, hedgerows and open scrub (Cole *et al.*, 2017). Road verges can provide beneficial habitats within the agricultural landscape, with bumblebee abundance found to be higher along road verges compared to the field margins of conventionally managed arable fields (Hanley and Wilkins, 2015). Pollinators have been recorded along road verges of many different types and sizes from rural roads to highways (Free *et al.*, 1975; Ouin *et al.*, 2004; Villemey *et al.*, 2018). But what makes a road verge beneficial for pollinators? In the following sections we summarise the evidence on how pollinators are utilising road verges; as food sources and as shelter, nesting and hibernation sites.

2.1 *Food source*

Road verges often provide a high abundance of flowers in otherwise florally-poor landscapes (Hanley and Wilkins, 2015; Osgathorpe *et al.*, 2012)**,** and can be a good source of food later in the season (Cole *et al.*, 2017). Baude *et al.* (2016) estimated that road verges produce an average of 60.63 kg of sugar/ha/year, compared to 6.90 kg of sugar/ha/year in arable farmland. Butterfly and bee abundance were both found to be positively affected by plant diversity and species richness (Hopwood, 2008; Skórka *et al.*, 2013)**.** Cole *et al.* (2017) found that flower cover, diversity and species richness were greater in road verges than in all other habitats, which included arable farmland, intensive and rough grassland, woodland, hedgerows and open scrub. However, not all species will benefit from road verges in the same way; for example, Osgathorpe et al. (2012) found that road verges were providing a better habitat for long-tongued bumblebees, such as *Bombus hortorum* compared to short-tongue species, such as *Bombus terrestris*. This is likely due to the different habitats supporting different communities of flower species. There are a large number of studies on plant communities in road verges, some of which may provide insight into their value for pollinators, but these have not been included here in order to focus on direct studies of pollinators. Based on the described studies, we can conclude that road verges provide important foraging habitats for pollinators, particularly when there are few other floral resources around such as in agricultural landscapes.

2.2 *Shelter, nesting and hibernation sites*

Road verges may also provide shelter, nesting and hibernation sites for pollinators, which benefit their survival and reproductive success. Munguira and Thomas (1992) found strong evidence that butterflies and moths were breeding along road verges, finding the larval stages of 11 species, even within the first 1 m of the road verge. Having a variety of habitat types present within a road verge can increase pollinator diversity, as many Lepidopterans prefer road verges with long vegetation (Ouin *et al.*, 2004), which is used to shelter in (Saarinen *et al.*, 2005). Having a variety of habitats also can promote reproduction through ensuring the features required for reproduction are present, such as larval host plants for butterflies and moths (Hopwood *et al.*, 2015) or bare ground and tussock grasses for wild bees, which are required for nesting (Hopwood, 2008). For example, one study in Kansas, USA found that the presence of bare earth resulted in higher abundances of solitary and ground-nesting bee species along road verges (Hopwood, 2008). Few studies have explicitly looked into whether road verges are being used for reproduction, but the presence of larvae in another study suggests that reproduction was occurring in road verges (Schaffers, Raemakers, and Sýkora, 2012). There are no studies that have looked at use of road verges by pollinators for hibernation, and more research is needed to explore the potential of road verges as nest sites (Wojcik and Buchmann, 2012).

3 Is traffic collision a problem for pollinators?

Traffic on roads can be a cause of pollinator mortality through direct collisions (Muñoz *et al.*, 2015). One study found that around 71% of the more than 100,000 dead invertebrates found along a 90 km/h highway with moderate daily traffic rates (average of 9,700 vehicles/day during summer) were pollinators (Lepidoptera and Hymenoptera; excluding Diptera from 2013 due to abnormally high abundances) (Baxter-Gilbert *et al.,* 2015). For Lepidoptera this equated to 10.1 individuals/km/day and for Hymenoptera it was more than double with 26.8 individuals/km/day being killed.

3.1 *Floral availability*

One of the factors influencing pollinator road deaths is floral availability. Floral availability appears to affect bumblebees and butterflies in contrasting ways, highlighting their potentially different uses of road verges. Butterfly mortality is often higher when road verges provide few resources, for example due to regular or recent mowing of verges (Ries *et al.*, 2001; Skórka *et al.*, 2013, 2015). In Poland, low resources and high traffic volume resulted in an extremely high mortality rate of butterflies (Skórka *et al.*, 2015). Removal of resources in this way causes butterflies to disperse from the verge to find new foraging patches. In contrast, bumblebees experienced higher mortalities when road verges are providing a florally-rich resource (Keilsohn *et al.*, 2018)**.** The location of the floral resources can also have an impact, with higher mortalities recorded when a planted central reservation was present (Keilsohn *et al.*, 2018); this was exacerbated when the surrounding habitats were florally poor, such as heavily-mown lawns. In more florally-rich habitats such as meadows or woodlands, having a planted central reservation had no effect. The contradictory effects of floral availability for bees and butterflies make it difficult to draw conclusions. However, it may suggest that having a regularly-mown strip along the edge of road verges, whilst maintaining high floral abundance in the rest of the verge, may keep bumblebees foraging away from the immediate road edge, as well as preventing the need of butterflies to disperse, which may provide a win-win for both pollinator groups. However, research would be needed to test this, and there is a lack of similar studies on other pollinator groups such as flies.

3.2 *Pollinator ecology*

Munguira and Thomas (1992) found that roads had a greater effect on butterflies from open populations, which are made up of highly-mobile species with wide-ranging females that lay their eggs in a number of locations. 7% of such species were killed along roads, compared to only 0.6-1.9% of species from closed populations, which make up the majority of butterfly species and are populations where birth and death rates determine the local abundance. Overall, they concluded that the mortality risk posed by roads for butterflies and burnet moths was insignificant compared to other forms of mortality. This shows that it is important to understand the ecology of species in road verges because their behaviour can determine the level of risk posed to them by roads.

3.3 *Traffic volume*

The volume of traffic present along roads can impact pollinator mortality, with mortality generally increasing with traffic volume for butterflies (Muñoz *et al.*, 2015; Skórka *et al.*, 2013, 2015). Other studies into the impact of traffic volume have used sticky fly traps attached to vehicles to monitor road death. Surprisingly, one study in Illinois, USA found that Lepidoptera death rates were highest at intermediate levels of traffic (average 13,500 cars/hour) (McKenna and McKenna, 2001), but they did not take floral abundance and other factors into account. Road size, which would in theory be related to traffic volume, is not always a predictor of flying insect road deaths. Martin *et al.* (2018) showed that flying insects were less abundant along high traffic roads which resulted in fewer total collisions. However they did not look at whether these abundance differences were related to the floral properties of the verge. More studies on a diverse range of pollinators are needed to allow general conclusions to be made. As one would expect, traffic volume and traffic speed do seem to affect pollinator mortality, but the extent of this appears to be variable and context-dependent.

3.4 *Pollinator body size*

The size of a pollinator may affect the risk of it being killed by road traffic. Smaller butterfly species were more often found dead by the side of the road than larger species, which is possibly due to them crossing the roads closer to the asphalt than larger species which fly at higher altitudes (Skórka *et al.*, 2013). Other pollinators have been recorded flying at similarly low heights above the road, such as Alkali bees (*Nomia melanderi*) (Vinchesi, 2013), making them targets for road deaths. Larger-bodied bees might be underrepresented in road mortality studies as they may bounce off of the sticky traps used in data collection (Hopwood *et al.*, 2010). One study observed that when bees were hit by cars, it was often the air flow going over the cars that threw them to the side of the road, where observations showed they were either dead from impact with the car, the road, or were stunned and then squashed by the cars (Pickles, 1942). These studies show that road mortality affects species disproportionately. When rare or threatened pollinator species are present along road verges, it may be important to consider the ecology and behaviour of the species when carrying out targeted conservation management, especially along high traffic roads (Section 3.2).

3.5 *Case Study: Blackspots in Poland* (Skórka *et al.*, 2015)

A survey of roads in Poland found that certain roads, deemed ‘blackspots’, accounted for 49% of all butterfly road deaths, despite making up only 4% of all roads. In these blackspot areas, mean butterfly road kills were 11.9 ± 0.93 individuals/km, compared to 1.37 ± 0.12 along other areas of the road. These blackspot sites were characterised by florally-poor road verges surrounded by a large amount of grassland habitat in areas with high traffic volume. The habitats surrounding the blackspots had a higher abundance and diversity of butterflies compared to other habitats. Mowing of verges resulted in even higher butterfly death rates in the blackspot areas, as it resulted in the sudden removal of food causing adult butterflies to disperse.

4 Does contamination of road verges by traffic affect pollinators?

Roads and road traffic are a major source of pollution that may affect road verges in a number of ways (Forman and Alexander, 1998). Lead, zinc, cadmium, copper, nickel, manganese and chromium are the main heavy metal pollutants along roads. Lead is becoming less important, as lead petrol was replaced with unleaded (Löfgren and Hammar, 2000), however it is still present. Other heavy metal pollutants arise from the wear and tear of car parts such as tyres, brake linings, motor oil and the road surface itself. These can impact pollinators both at the adult and the larval stages, as foragers can experience behavioural and reproductive changes when consuming contaminated nectar and pollen, larvae foraging on contaminated leaves experience greater mortalities and ground-nesting bees also have the potential to be adversely affected. The various forms of pollutants are discussed separately below because studies have focused on single pollutants, but in reality these will be acting simultaneously and may be acting synergistically.

4.1 *Heavy metals in the air*

Pollutants from car exhausts is aerially deposited onto the surface of plants (Quarles *et al.*, 1974; Swaileh *et al.*, 2004). One study found that levels of lead, cadmium and nickel in the air was highest 0-10 m from the road (Muskett and Jones, 1980). Pollution caused by car exhausts has been found to reduce the distance of scent plumes given off by flowers, which affects the attractiveness of flowers to pollinators (Farre-Armengol *et al.*, 2016), the ability of foragers to recognise the floral scents (Girling *et al.*, 2013) and the amount of time bees spend visiting each flower (Fuentes *et al.*, 2016). It has been estimated that the distance over which floral scent volatiles are able to travel may have decreased from distances of kilometres in pre-industrial times to less than 200 m under current pollution levels (Mcfrederick *et al.*, 2008). This may increase the energy expenditure of pollinators when locating food sources, particularly in patchy and isolated habitats. Most studies have been carried out in the laboratory, so field studies are needed to assess whether road verge pollution is impacting pollinator populations. There are also only a few studies on the effects of air pollution on herbivorous pollinator larvae, and as most roadside pollution is deposited aerially onto plants these will likely be the most affected group. More studies on how they are impacted are needed, and whether the effects continue when they pupate into adults.

4.2 *Heavy metals in the soil*

Heavy metals present from car exhaust fumes are deposited in road verges. Concentrations are very high within 0-5 m from the road surface (Dale and Freedman, 1982), decreasing with distance from the road (Shu *et al.*, 2009) and returning to background levels often within 20-30 m (Dale and Freedman, 1982; Quarles *et al.*, 1974; Swaileh *et al.*, 2004)**.** Heavy metal concentrations are higher near busier roads (Dale and Freedman, 1982), but the degree of soil contamination is related to a number of factors such as soil type, vegetation, wind direction, road exposure, road drainage, frequency of rainfall and the particle size of pollutants (Shu *et al.*, 2009). A number of heavy metals are essential for the growth and development of plants (Rascio and Navari-Izzo, 2011), but become toxic at high levels. Heavy metals contaminate road verge soils and vegetation (Swaileh *et al.*, 2004), which may affect pollinators in road verges when landing on vegetation, during nesting, and during larval stages that are feeding on vegetation. Pollinators may also be affected if heavy metals are transferred to pollen and nectar, which could potentially lead to bioaccumulation within pollinators due to the large numbers of flowers that they visit. Unfortunately there are very few direct studies of the impacts of heavy metals in road verges on pollinators, but insight can be gained from a number of relevant studies, which are described below.

Muskett & Jones (1980) looked at lead, cadmium and nickel (mean soil concentrations of 274.95, 1.81 and 31.67 µg g^{-1} respectively) concentrations in road verges and found no effects on plants, or on the diversity and abundance of spiders, beetles or millipedes, but found weak correlation for higher abundance of Hymenoptera abundance closer to the road. A study on bumblebees in meadows near smelting sites found that the concentrations of heavy metals within their bodies correlated with soil concentrations, but bumblebee diversity was unaffected by levels of lead, zinc and cadmium concentrations (143.87, 325.03 and 4.23 mg kg^{-1}) (Szentgyöryi *et al.,* 2011), which were found in levels similar to those found in road verges. In contrast, Moroń *et al.* (2012) found that the diversity and abundance of wild bees decreased with increasing heavy metal concentrations along a contamination gradient. In their study, Moroń *et al.* (2012) found background levels of cadmium, lead and zinc ranging from 0.8-1.3, 42-43.3 and 56-99.8 mg kg^{-1} respectively, with highly contaminated sites having concentrations of 6.7-9.3, 277-356.2 and 440.01-592.4 mg kg^{-1}. Contamination may disproportionately affect different plants as Mulder *et al.* (2005) found that nectar plants used by adult butterflies were more sensitive to heavy metals than those used by moths and other pollinators, growing less vigorously when exposed to contamination.

4.3 Laboratory studies

A number of laboratory studies have tested the effects of heavy metals at varying concentrations on pollinators. Lepidopterans exposed to field-realistic zinc concentrations (300-750 mg Zn/kg) experienced shorter laying periods, and reduced fecundity and viability of eggs (Shu *et al.*, 2009). Honeybees (*Apis mellifera*) were exposed to lead, copper and cadmium at varying concentrations (0-24.3, 0-40.96 and 0-28.41 mg L^{-1} respectively) and experienced negative effects including increased mortality of larvae and forager bees (Di *et al.,* 2016), lead was the most toxic to foragers, and copper was the least toxic to larvae. Honeybees fed with cadmium (0.1-1 µg ml) experienced a weakening of their immune system leading to a reduced ability to deal with pathogens (Polykretis *et al.*, 2016). Bumblebees exposed to zinc, cadmium, nickel and lead, which had been added into hosta nectar, spent less time foraging on contaminated flowers, but visited flowers more often (Xun *et al.,* 2018). Meindl and Ashman (2013) also found bumblebees spent less time visiting nickel contaminated plants, and avoided foraging on nearby contaminated flowers. Pollen contaminated with zinc from smelting sites was collected by the red mason bee (*Osmia bicornis*) and lead to females producing 25-50% less cells when exposed to the highest zinc concentrations (zinc concentration ranged from 90-300 mg/kg in pollen), emerging bees were also smaller and less males were produced as zinc concentrations increased (Szentgyöryi *et al.*, 2010). There is evidence that some species have mechanisms for dealing with heavy metal exposure, for example two species of caterpillar have been shown to reduce their ingestion of heavy metals when feeding on contaminated plants by excreting it via their faeces (Nieminen *et al.*, 2001; Ping *et al.*, 2013). Whilst the studies above have shown that heavy metals can negatively affect pollinators in laboratory experiments, few studies have looked at how this translates into effects in the field and on pollinator populations.

5 Are roads barriers to movement, or do they aid dispersal?

There are two opposite, but not necessarily opposing ways in which roads and road verges might affect the movement and dispersal of pollinators. Roads may act as barriers to movement if pollinators are not able to cross them, or if they cross them less readily than other habitats. On the other hand, road verges may act as corridors or stepping stones of favourable habitat along which pollinators can navigate, move and disperse.

5.1 *Crossing roads*

Whether a pollinator species readily crosses roads may be linked to its tendency to disperse. Butterfly species that are generally more frequent dispersers were more readily able to cross A-roads in a study in Dorset and Hampshire, with 10-30% of the populations of Meadow browns (*Maniola jurtina*), Marbled whites (*Melanargia galathea*) and Common blues (*Polyommatus icarus*) observed crossing roads (Munguira and Thomas, 1992). However, not all butterfly species will readily cross roads, and butterflies have been observed flying to the edges of roads before turning away or flying along it (Halbritter *et al.*, 2015), although the reasons for this were not explored. Mark-recapture studies on bumblebees found that most bumblebees were recorded on the same side of the road when recaptured 24 hours later (Bhattacharya *et al.*, 2003; Hopwood *et al.*, 2010). It is unclear whether this shows bumblebee's lack of propensity to cross roads, or whether it was due to their faithfulness to flower patches, as they could have been crossing the road to get to the patch, but this would not have shown up in the mark-recapture study.

The width of the road may affect the ability or willingness of pollinators to cross. Bumblebees were found to cross a two-lane 20 m wide road, but not a four-lane 50 m wide road (Hopwood *et al.*, 2010). Wojcik & Buchmann (2012) suggest that bees will cross roads in both cities and suburbs, which implies that traffic volume does not affect road crossing, but they do not give information on the width of the roads. Another study on butterflies found that 40% crossed smaller roads and 10% crossed highways, which suggests that they are able to cross roads of varying sizes, but that larger roads do deter crossing (Valtonen, Anu and Saarinen, 2005). Overall it is likely that pollinators are able to cross roads, but that their capacity and tendency to do so depends on the species and characteristics of the road. Existing studies have primarily been of butterflies, with some for bumblebees, and a lack of studies for other pollinator species such as solitary bees and hoverflies. These other pollinator groups may respond very differently, if only because of differences in size and behaviour.

5.2 *Dispersal corridors*

Road verges may serve as a habitat corridor that facilitates the navigation, movement and dispersal of pollinators. Corridors provide mechanisms through which species can move between habitats, and can be particularly important in fragmented landscapes. There is very limited studies of whether pollinators use road verges as corridors, but insight can be found from studies of other systems. Pollinators have been shown to use corridors, for example Sutcliffe & Thomas (2018) demonstrated that within woodlands, ringlet butterflies (*Aphantopus hyperantus*) use woodland rides to move between habitat patches, rather than moving through the dense woodland. Tewksbury *et al.* (2002) also looked at movement of butterflies in woodland, and found that butterflies were more likely to move between patches connected by 25 m wide corridors, which was a cleared area within the woodland, compared to isolated rectangular patches. Road verges have been shown to aid dispersal in non-pollinating insects such as leafhoppers (Baum *et al.*, 2004) and ground beetles (Vermeulen, 1994). Range expansion, which suggests dispersal, has been observed along road verges for two pollinators: the cinnabar moth (*Tyria jacobaeae*) in Germany (Brunzel *et al.*, 2004) and the Silvery blue butterfly (*Glaucopysche lygdamus coperi*) in Canada (Dirig and Cryan, 1991). In one of the few studies looking at road verges as corridors for pollinators, Öckinger and Smith (2008) found that road verges had no effect on the dispersal of butterflies between pastures, stating that it could have been due to the large size of the road verges in their study as butterflies are less likely to leave larger patches (Marini *et al.*, 2014). Valtonen and Saarinen (2005) did attempt to look at this, and found that when the habitat was connected by a road verge there were twice the number of butterfly movements, but they only had a single sample site and so cannot draw conclusions. Therefore it seems plausible that dispersal is generally linked to patch size, with smaller patches having higher dispersal than larger patches, which rely more on recruitment (Marini *et al.*, 2014). Whilst there are no studies on the use of road verges for movement and dispersal for other pollinator groups, general studies have shown that bumblebees follow other linear features such as hedgerows (Cranmer *et al.*, 2012).

Overall, there are general reasons to believe that road verges may act as corridors for the movement and dispersal of pollinators to some extent, but there are a lack of studies that explicitly test this and the only available studies are limited to butterflies and moths.

6 Does the surrounding landscape affect use of road verges by pollinators?

The surrounding habitat type can affect the abundance, diversity and richness of pollinator species present in road verges. Certain habitats, such as agricultural land and urban areas, tend to cause a reduction in biodiversity along road verges (Saarinen *et al.*, 2005; Villemey *et al.*, 2018). Geographical differences may occur, as one study in the Outer Hebrides did not find any differences in bumblebee abundance between road verges and farmland (Osgathorpe *et al.*, 2012). Other habitat types can have positive effects on road verge biodiversity. For example, the presence of natural and forested areas was found to have a positive effect on insect biodiversity (Villemey *et al.*, 2018), and in particular the species richness of butterflies was highest when the proportion of suitable butterfly habitats (hay, pasture, hedgerows and undifferentiated grassy cover) in the landscape was greater, but butterfly abundance did not respond to these factors (Flick *et al.*, 2012). In the same study, landscape types within 250 m of the road verge impacted butterfly species richness and abundance. This distance is in line with the daily movements of butterflies, which are generally between 200 and 600 m (Davis *et al.*, 2007). In contrast, Munguira and Thomas (1992) found no effect of the adjacent landscape on butterfly abundance, diversity or species richness. Buffer strips and hedgerows were also often beneficial habitats that probably provide a very similar role to road verges, though are potentially complementary in terms of providing different suites of plant species.

The findings of these studies indicate that the importance of road verges depends on the surrounding landscape. In resource-poor landscapes such as farmland, road verges may be providing a crucial habitat as they provide a large amount of flowering resources where there is relatively little else (Baude *et al.*, 2016). This could mean that the impact of road verge mowing in such landscapes has a greater impact on pollinators (Section 6) because it will affect a greater proportion of available floral resources. In more resource-rich habitats, road verges may simply be a complementary habitat that supplements an already present population of pollinators. It may therefore be prudent to take into account the surrounding habitats when thinking about how best to manage road verges, so as not to completely remove a food source in florally-poor landscapes, and also because different habitats will contain different communities of species (Section 6).

7 How does the size and shape of a road verge affect its value to pollinators?

The size and shape of a road verge may affect its value to pollinators. Road verges are often just a few metres wide and a relatively small total area, which may limit their capacity to support pollinators. A general study on the impact of patch size found that honeybees and hoverflies were not affected by increasing patch size, whereas wild bees such as *Bombus*, *Andrenidae* and *Halictidae* occurred in higher densities and richness within 30 m^2 and 100 m^2 compared to the 1 m^2 patch (Blaauw and Isaacs, 2014). The lack of response to patch sizes found for hoverflies could be due to their populations being more limited by prey densities or host quality for oviposition. Thus smaller road verges may be able to successfully support hoverflies as long as they contain suitable prey. Other studies also found that the width and size of road verges had no effect on bee and hoverfly diversity (Hopwood, 2008; Raemakers *et al.*, 2001). Wider verges had a greater abundance of butterflies (Munguira and Thomas, 1992), and butterflies experienced fewer road deaths in wider verges (Skórka *et al.*, 2013), possibly due to butterflies being less inclined to disperse from larger areas (Marini *et al.*, 2014; Valtonen, Anu and Saarinen, 2005). However, the fact that road verges are often narrow means that pollinators using the verge are located within a few metres from the road and are exposed to relatively high levels of pollution from traffic (Section 4).

When considering the size of road verges, the only papers which have made size recommendations suggest providing habitats of at least 0.25 ha (Nowakowski and Pywell, 2016), but state that 0.5 ha and upwards is beneficial (Hopwood *et al.*, 2015; Nowakowski and Pywell, 2016)**.** This would be equivalent to a road verge that was 10 m wide and 500 m long, or 20 m wide and 250 m long.

Overall, wider road verges probably provide better habitats for pollinators, because they contain areas which are less exposed to traffic and pollution and can provide a greater variety of habitats than narrower verges. In theory, narrow road verges are more likely to be regularly completely mowed to maintain sight lines, whereas wider verges could have the first 1-2 m mowed for sight lines whilst other areas of the verge can be managed to support pollinators and other wildlife. Therefore, wider road verges are probably preferable, especially along roads passing through already florally-poor landscapes.

8 How does road verge management affect pollinators?

So far, we have looked at both the positive and negative aspects of road verges as habitats for pollinators. However, the primary factor affecting the value of road verges for pollinators is often how they are managed. Beneficial management needs to encourage plant species richness, flower abundance and habitat diversity in order to support diverse pollinator communities. Management for pollinators needs to consider flowering times and annual cycles of behaviour, such as reproduction and the requirements of different developmental stages of pollinator species. One major project which is championing this is Buglife’s B-Lines project, which looks to undertake habitat restoration and creation to increase the areas of permanent wildflower-rich habitats across the UK, often through getting current management practices changed to benefit pollinators (Buglife, 2018). We explore the available literature around road verge management and its effects on pollinators.

8.1 *Frequency of cutting*

Frequency of cutting affects both the plant and pollinator communities present in road verges. In general, unmanaged road verges become dominated by vigorous species and are succeeded by scrub (Parr and Way, 1988), leading to relatively low abundances of flowers and insects, and a lower species richness of flowers (Noordijk *et al.*, 2009). Annual mowing maintains a grassland community (Parr and Way, 1988), which is beneficial in terms of both flowers and pollinators (Noordijk *et al.,* 2009). One of the main studies of the impacts of management on pollinators was carried out in the Netherlands using 12 x 15 m experimental plots with different cutting regimes along a single road verge that was otherwise managed as a species-rich hay meadow (Noordijk *et al.,* 2009). The study found that mowing once per year in early-autumn resulted in a much greater diversity and abundance of flowers than no management, but no significant effect on insect abundance or flower visits (Noordijk *et al.*, 2009). Adding a second cut at the end of June benefited pollinators later in the season by extending the flowering season, but did not benefit the diversity or abundance of flowers overall due to the loss of flowers after the additional cut (Noordijk *et al.*, 2009). Cutting twice provided substantial benefits in terms of insect abundance and flower visits (Noordijk *et al.*, 2009). However, it is difficult to interpret these results because management options were carried out in relatively small plots, so differences in pollinators in their study is representative of pollinator preference rather than impacts on pollinator populations, which is ultimately what is important. In an 18 year study in the UK, two cuts per year was also found to benefit plant species richness and reduced the amount of plant regrowth by 38% (Parr and Way, 1988). Unmown road verges attracted a higher abundance of butterflies from late-summer to early autumn compared to the mowed treatments (Halbritter *et al.*, 2015) and Valtonen and Saarinen (2005) also found their non-mown areas had the highest butterfly abundances. However these studies do not necessarily contradict the other studies. This is because the first study used relatively intensive mowing treatments as contrasts (mowing every three and six weeks), rather than one or two cuts per year. In the second study, the unmown area was a ruderal area, rather than typical grassland habitat, making it difficult to compare results.

Despite the overall benefits of cutting once or twice per year, there are immediate negative impacts of cutting in terms of direct mortality of pollinators, eggs and larvae and the removal of flowers and larval food plants (Noordijk *et al.*, 2009; Wynhoff *et al.*, 2011). Ideally, verge cutting would be avoided during these times, but negative impacts can be reduced by not mowing the entire verge at once, for example by mowing opposite sides of the verge at different times, or by only partially mowing the verge (Meyer *et al.*, 2017; Noordijk *et al.*, 2009; Skórka *et al.*, 2013). It has been suggested that leaving a strip of the road verge uncut towards the back of the verge will provide permanent undisturbed areas of floral resources and vegetation for pollinator larvae (Noordijk *et al.,* 2009). In support of this, a study on meadows in Switzerland found that leaving a 10-20% uncut area, and cutting between mid-June and early-July benefited bees and hoverflies (Meyer *et al.*, 2017).

8.2 *Timing of cutting*

The time of the year that road verges are cut can impact plant and pollinator communities. Cole *et al.* (2017) found, in their study in Ayrshire, Scotland, that flower species richness peaked between July and early-August, hoverfly abundance, diversity and species richness peaked in late-August and bee abundance and diversity peaked in early-August. Much road verge cutting happens during these peak times of activity and will negatively impact pollinators using road verges. Cutting meadows in late-spring or summer increased species richness of moths and plants, compared to grazing, abandonment and mixed management treatments, in one study in the Czech Republic (Bonari *et al.*, 2017). This could be due to moths being very host-specific, and so this management may have been the most appropriate for their host plants. In Finland, mowing road verges once in mid-summer was found to attract butterflies later in the season when other habitats provided fewer floral resources (Valtonen, Saarinen and Jantunen *et al.*, 2006). A systematic review and meta-analysis of 24 studies found that delaying cutting of European meadows from spring to summer had a positive effect on invertebrate abundance and species richness (Humbert *et al.*, 2012), and a more recent study on meadows found a positive effect on the local abundance and species richness of wild bees and hoverflies (Meyer *et al.*, 2017)**.** One study of butterflies on road verges in Finland found that cutting later in the summer, lead to higher abundances compared to mid-summer mown verges (Valtonen, Saarinen and Jantunen, 2006). Saarinen *et al.* (2005) looked at road verge cutting along different sized roads in Finland: highways (two cuts a year in early summer and early autumn), urban roads (cut 2-3 times a year during the summer) and rural road verges (mown once in late summer) and found no differences in species richness of butterflies and diurnal moths between these different mowing treatments. A study on the large blue butterfly (*Phengaris arion*) found that mowing once per year, either before or after the flight period, was an appropriate management technique (Johst *et al.*, 2006).

From these studies it is clear the timing of cutting is a compromise between different benefits and costs that will affect plant and pollinator communities. Generally, summer cutting was found to benefit butterfly, moth and plant abundances, but these studies do not explore the impact of cutting during these times on larvae and pollinator populations. There are also very few studies looking at bees, flies or beetles, making it is difficult to provide an overall idea of how mowing is affecting pollinators overall.

8.3 *Removal of cuttings*

Removing cuttings after mowing can be beneficial because it may remove the layer of thatch that would otherwise inhibit the growth of less vigorous plant species. It may also provide gaps for germination of seeds, and reduce soil nutrients, with low soil nutrients being an important characteristic of species-rich grasslands, because high nutrients leads to more vigorous species dominating and outcompeting other herbaceous species (Bonanomi, Caporaso and Allegrezza, 2006; Parr and Way, 1988). A systematic review of 54 studies found that removing cuttings benefited plant species richness, when road verges were cut once or twice per year (Jakobsson *et al.*, 2018), which is likely to relate to flower species richness. The study in the Netherlands found that removing cuttings provided a greater abundance of flowers when road verges were cut twice, but not when they were cut once (Noordijk *et al.*, 2009). Removing cuttings appeared to slightly benefit insect abundance and flower visits but differences were not significant (Noordijk *et al.*, 2009). Whilst this is probably the best study available that explores management of road verges for pollinators, it was carried out on a species-rich road verge that was otherwise managed for hay-making. In other words, the grassland in the studies road verge was already of reasonable quality, so there is potential for different results, and arguably greater improvements, if these management regimes were carried out on more typical road verges.

Whilst several studies find benefits of removing cuttings, few explore why this is and whether it is actually due to a reduction in soil nutrients. Two examples of studies looking at this are by Bonanomi, Caporaso, and Allegrezza (2006, 2009) which looked at cutting, nitrogen enrichment and nitrogen removal through removal of cuttings in Mediterranean meadows. They found that removing cuttings caused plant cover to increase, and perennial grasses were less dominant. Nutrient enrichment also had no effect on species diversity. They suggest that any positive effects from the removal of cuttings could be due to greater light availability at ground level, reduced allelopathic effects and allowed for easier seed emergence.

Parr and Way (1988) is one of the few other studies that have looked into the removal of cuttings in road verges. They found that it resulted in a reduction in potassium, but otherwise very little effect on soil nutrients or pH. Overall, they found that removing cuttings resulted in a greater plant species richness but suggest that this was primarily due to the disturbance to the soil through scarification when the hay was being removed, which provided gaps for germination of seeds. This has important implications for management, because it implies that gathering cuttings into a single area of the road verge may provide the same benefits, and that total removal from the site is not necessary.

8.4 *Using yellow rattle* (*Rhinanthus species*) *to reduce vegetation growth*

Yellow rattle (*Rhinanthus* species) is a root-hemiparasite of moderate- to low-fertility grasslands. It has the potential to be used in road verge management as a method of reducing the vigour of dominant plant species (Bullock and Pywell, 2005), as it gains nutrients from nearby plants, helping to maintain an open sward structure and reduces the abundance of more competitive species such as grasses. As a result, it may also reduce the frequency with which road verges need to be cut. One study looked at its effectiveness along two motorway road verges in Belgium and found that it worked best when the number of yellow rattle plants per plot was high, and when grass biomass was not too high to begin with (Ameloot *et al.*, 2006). Because *Rhinanthus* species are annuals, their persistence in a grassland is dependent upon a cutting regime that allows flowers and seeds to be set each year, and populations can be quickly lost if this is not carried out. It appears that *Rhinanthus* species have significant potential for improving plant and flower diversity in road verges, especially on newly constructed road verges or on road verges where it is possible to remove nutrient-rich top soil.

8.5 *Case study: Weymouth Relief Road* (Sterling 2018, pers. comms.)

The Weymouth Relief road was an £89 million project that created 7 ha of wildflower verges as part of a larger road-expansion project. The new habitat is mainly chalk and limestone grassland, which is a naturally nutrient-poor habitat but to create beneficial habitats during construction a very thin layer of topsoil, derived from an area of semi-improved chalk grassland destroyed during construction, was added back onto 4 ha of the steep banks and one adjacent field. Wildflower seed mixes containing plant species such as Kidney vetch (*Anthyllis vulneraria*), Bird's-foot-trefoil (*Lotus *corniculatus*) and Horseshoe vetch (*Hippocrepis comosa*) were hand sown onto the banks. So far, 30 species of butterfly have been recorded on the site, including the Chalkhill blue (*Lysandra coridon*), Adonis blue (*Lysandra bellargus*), Small blue (*Cupido minimus*) and Brown argus (*Aricia agestis*). It currently costs Dorset County Council very little to maintain due to the nutrient-poor soils meaning plant growth is minimal, and grazing is used for short periods during September in some years.

9 Overall conclusion

Overall, there is strong evidence that road verges are important habitats for pollinators. Road verges cover a large area of the UK, connecting many habitats, and are especially important in florally-poor landscapes such as those dominated by agriculture. They are able to support some of our rare as well as our common species, making them a key habitat that can supplement the role of conservation-priority habitats. Improving management of road verges for pollinators on a broad scale should be a priority, as even modest improvements will provide widespread benefits. Long-term monitoring of road verges would be beneficial to give an insight into how management practices effect pollinators over time.

This report has examined the scientific literature to assess the wide range of possible impacts that traffic and roads have on pollinators in road verges. The key areas identified were: pollinator deaths through collisions with traffic; impacts to the health and behaviour of pollinators through pollution; barriers to movement due to roads acting as physical barriers; and the impacts of different road verge management techniques. In most cases, the extent of the impacts are unclear due to the limited number of studies in these areas, which in themselves are heavily focussed on a subset of pollinators groups, primarily butterflies. In particular, there is a lack of information about the collective impact of these multiple threats, and what the population-level impacts might be.

There are various forms of pollution that may affect pollinators, and the available research shows that these operate on different spatial scales. For example, lead, cadmium and nickel in the air was highest 0-10 m from the road whereas lead, zinc and copper in the soil was highest within 0-30m (Dale and Freedman, 1982; Quarles *et al.*, 1974; Swaileh *et al.*, 2004), and particulate matter may have an impact at much greater distances. Pollution can affect adult foragers when present in the nectar and pollen. Pollution is also present on the plant surface through aerial deposition, where it can affect herbivorous larvae, but this has been poorly studied. Due to their location, road verges will always be affected by contamination to some extent, but it is difficult to say whether, at what point and under what conditions the level of contamination becomes high enough that the road verge is no longer beneficial to pollinators.

Road verge management is probably the main factor affecting the value of road verges for pollinators. When considering the creation and management of road verges, wider verges are likely better for pollinators because they have areas that are further from the road and its associated pollution, can provide a greater variety of habitats, and will be less affected by any partial mowing events such as sight line maintenance. Cutting of the whole verge removes the foraging resources that attracted the pollinators, which can, for example, lead to increased road deaths of butterflies as they disperse to find new foraging patches. Mowing also results in direct mortality of eggs and larvae. Avoiding cutting during the main flowering season (early May-late August) would benefit eggs, larvae and pollinators. Studies have shown that cutting twice a year during this time can benefit plant and pollinator diversity and numbers of flowers, but comes at the cost of a period after mowing when few resources are available. This is likely to have implications for pollinator populations that existing studies have not been able to measure due to difficulties of assessing these in the field.

Road verges support a diverse range of pollinators, especially when managed in a way that promotes floral species richness and provides a variety of habitats for both feeding and reproduction. Based on the available evidence, we have suggested an incremental management plan. The aim of this is to provide a flexible management approach that can provide benefits to pollinators, whilst taking into account the resources of road verge managers. Road verges are complex and diverse habitats that are in essence a gateway habitat between the human environment and the natural environment. Ultimately, pollinators will benefit from road verge management that takes into account their diverse needs. If managed well, road verges have the capacity to be a lifeline for pollinators that will help to safeguard pollination of our crops and wild plants into the future.

10 How can road verge management be improved for pollinators?

In order to increase the likelihood of management recommendations being adopted by road verge managers, they need to be simple and pragmatic. Most importantly, recommendations must not compromise safety. The major constraints for road verge managers are likely time, money and difficulty of implementation. With this in mind, the management ladder in Table 1 has been suggested. Rather than a single optimum management recommendation, we have suggested a hierarchy of choices, which starts from an assumed current management regime that cuts once or twice in summer and builds from there so that each step provides incrementally greater benefits to pollinators. These management choices are supported by the studies that have been reviewed in this report. The table outlines simple steps that can be implemented in stages, which can be tailored to the level of resources and commitment of each road verge manager.

Table 1 Recommendations for the management of road verges to support pollinators, based on the evidence summarised within this report. The "Baseline" is the assumed current management regime of most road verges. Each new row represents an incremental step that could be taken by road verge managers that would benefit pollinators. Each subsequent step is of greater benefit to pollinators, but is more costly to carry out, allowing road verge managers to select a plausible option, based on available resources. It includes optional extras that will benefit pollinators, but can be implemented alongside any of the main cutting regimes.

Step	Management action	Expected impacts on vegetation	Expected impacts on pollinators	Relevant section
Baseline	No management, or 1-2 cuts in summer, regular cutting of the sight lines, and no removal of cuttings	Variable sward height, high nutrients, cover of thatch from cuttings, many plant species unable to set seed; resulting in low plant diversity and dominance by few vigorous species such as grasses.	Direct mortality of pollinators, eggs and larvae, removal of larval food plants, and removal of flowers.	Section 3 and 8
Mowing improvement one	One cut/year from September onwards	Prevents loss of grassland to scrub encroachment. May benefit plant diversity because most plant species are able to set seed before cutting.	Reduced mortality of pollinators and loss of flowers because peak flowering and pollinator activity times are avoided.	Section 3 and 8
Mowing improvement two	Two cuts/year between September and March* and removal of cuttings	Should reducing sward height and dominance of vigorous plant species, allowing a greater number of herbaceous species to persist.	May benefit the diversity and abundance of flowers and pollinators.	Section 8
Removing cuttings one	Move cuttings to a single area of the verge	Removal of thatch, allowing less vigorous plant species to grow and providing disturbance gaps for seed germination, resulting in increased plant diversity.	Greater flower abundance and potentially diversity. Probably greater diversity and abundance of pollinators.	Section 8
Removing cuttings two	Remove cuttings from the verge	Removal of nutrients from the road verge, possibly providing further benefits to plant diversity.	May benefit pollinator diversity.	Section 8

Additional management options	10-20% at the back of the verge left uncut	Allows an area of scrub and taller vegetation to persist at the back of the verge, resulting in greater plant and habitat diversity.	Allows larvae, eggs and overwintering species to persist, and provides areas for nesting and sheltering.	Section 2 and 8
	Cut the verge in sections e.g. cut 20 m leave 20 m in order to create a varied habitat and leave areas of scrub	Greater plant and habitat diversity.	Greater pollinator and invertebrate diversity, and provides microclimates.	Section 2, 6, 7 and 8

*The literature suggests mowing twice, once in early summer and once in late summer. This leads to a high plant species richness which is beneficial to insect pollinators. However, this is the peak activity time for all pollinator life-stages from eggs to adults. Mowing during this time would cause direct mortality to pollinators and could therefore impact upon their populations. Unfortunately, there are insufficient studies to enable us to make our current recommendation based on the literature, but do not want to base our recommendations solely off a single study suggesting to cut during the peak pollinator activity. Therefore we are making the above recommendation based upon our knowledge of pollinators and their lifecycle.

Table 2 Table outlining different management regimes and their costs and benefits to different pollinator groups

Management group	Management action	Effect	Focal group	Location	Reference
Number of cuts	No mowing or reduced mowing during peak activity	Highest butterfly abundance from August onwards, compared to mowing frequency of every 3 and 6 weeks	Butterflies	Florida, USA	(Halbritter *et al.*, 2015)
	No mow – ruderal road construction habitats (non-linear feature)	Highest butterfly abundance and fairly low movement, compared to mown and unmown intersections, road verges and roadside fields	Butterflies	Finland	(Valtonen and Saarinen, 2005)
	No mowing or mowing once per year in early autumn and remove cuttings	Low insect abundance, especially if cuttings not removed, compared to mowing twice and removing cuttings	Apoidea, *Bombus*, Diptera, Syrphidae, Coleoptera, Ichneumonidae, Tenthredinidae, Lepidoptera	Netherlands	(Noordijk *et al.*, 2009)
	Mowing once a year – late spring or summer	Best for moths and also plants – moths very host specific, compared to grazing	Moths	Czech Republic	(Bonari *et al.*, 2017)
	Mowing once a year – late summer cut	Best result for butterflies, mainly meadow species, compared to mid-summer mowing	Butterflies and day flying moths	Finland	(Valtonen, Saarinen and Jantunen, 2006)

	Mowing once a year – late summer mowing - verges	Higher abundance of butterflies, which left the patches and crossed the road less often, compared to when verges cut mid-summer	Butterflies	Finland	(Valtonen, Anu and Saarinen, 2005)
	Mowing once a year or every second or third year – before or after flight period	Appropriate management for both species, but ant hosts also needed to be taken into account	Large blue butterfly	Model	(Johst *et al.*, 2006)
	Mow twice a year (early summer and early autumn) and remove cuttings	This caused the highest abundance of insects, and the highest flower visitations, compared to no mow and single mow treatments. Report that after cutting insect abundance heavily reduced but recovered to same level in as little as three weeks	Apoidea, *Bombus*, Diptera, Syrphidae, Coleoptera, Ichneumonidae, Tenthredinidae, Lepidoptera	Netherlands	(Noordijk *et al.*, 2009)
Timing of cuts	Delay cutting from late spring to mid-summer	Positive effect on abundance and species richness of wild bees and hoverflies	Bees and hoverflies	Switzerland	(Meyer *et al.*, 2017)
	Delay cutting from spring to summer	Both positive and neutral effects for plants and invertebrate diversity	Plants and insects	Review	(Humbert *et al.*, 2012)
	Postponing mowing from spring to autumn or early summer to late summer or autumn	Negative impact on plant species richness, but may still benefit invertebrates	Plants and insects	Review	(Humbert *et al.*, 2012)

	Avoid mowing when host plants flowering	Reduces the chances of eggs and larvae being destroyed	Butterflies	Netherlands	(Wynhoff *et al.*, 2011)
Leaving an uncut section	Cut between late spring and mid-summer leaving a 10-20% uncut refuge	Positive effect on abundance and species richness of wild bees and hoverflies	Bees and hoverflies	Switzerland	(Meyer *et al.*, 2017)
	Leave strip of ~10% verge width and cut once per year	This would most benefit larvae	Apoidea, *Bombus*, Diptera, Syrphidae, Coleoptera, Ichneumonidae, Tenthredinidae, Lepidoptera	Netherlands	(Noordijk *et al.*, 2009)
	Partially mowing the verge	Leaves food resources	Butterflies	Poland	(Skórka *et al.*, 2013)
	Mowing the opposite side of the road at different times	Leaves food resources	Butterflies	Poland	(Skórka *et al.*, 2013)
	Split verge into two equal widths – cut one twice per year and remove hay, cut second later e.g. 3 weeks apart	Gives species a chance to recover and flowers to regrow on cut half. This would most benefit feeding insects	Apoidea, *Bombus*, Diptera, Syrphidae,	Netherlands	(Noordijk *et al.*, 2009)

			Coleoptera, Ichneumonidae, Tenthredinidae, Lepidoptera		
Other management options	Mixed management (mowing, grazing and abandonment)	Butterflies favoured this management style	Butterflies	Czech Republic	(Bonari *et al.*, 2017)
	Rotational management – leaving some areas uncut	Benefits short-lived species who would be unable to cope with sudden floral resource loss, and keeps areas for larvae and eggs	Apoidea, *Bombus*, Diptera, Syrphidae, Coleoptera, Ichneumonidae, Tenthredinidae, Lepidoptera	Netherlands	(Noordijk *et al.*, 2009)
	Rotational cutting – including in some cases soil disturbance to leave bare soil, with hay removal	Ensures variety in terms of habitats present and sward height	N/A	Review	(Kirby, 1992)
	Rotational management – e.g. one year in autumn, one year spring or half a patch in autumn and leave half uncut near hedgerow until next spring	Keeps food sources for pollinators and leaves host plants and protects some larvae	N/A	UK	(Nowakowski and Pywell, 2016)
	Wide verges in areas where the surrounding habitat isn't beneficial, with uneven surfaces and no fertilisers added	Good for encouraging butterflies	Butterflies and burnet moths	Dorset and Hampshire, UK	(Munguira and Thomas, 1992)

References

Highways Agency. (2001) *Design manual for roads and bridges*. (Vol. 10).

Ameloot, E., Hermy, M., and Verheyen, K. (2006) Rhinanthus: an effective tool in reducing biomass of road verges? An experiment along two motorways. *Belgium Journal of Botany* 139(2): 173–187.

Austed, I., Rydgren, K., and Austad, I. (2011) Road verges: potential refuges for declining grassland species despite remnant vegetation dynamics. *Annales Botanici Fennici* 48(4): 289–303.

Baude, M., Kunin, W. E., Boatman, N. D., Conyers, S., Davies, N., Gillespie, M. A. K., Morton, R. D., Smart, S. M., and Memmott, J. (2016) Historical nectar assessment reveals the fall and rise of floral resources in Britain. *Nature* 530(7588): 85–88.

Baum, K. A., Haynes, K. J., Dillemuth, F. P., and Cronin, J. T. (2004) The matrix enhances the efffectiveness of corridors and stepping stones. *Ecology* 85(10): 2671–2676.

Baxter-gilbert, J. H., Riley, J. L., Neufeld, C. J. H., Litzgus, J. D., and Lesbarre, D. (2015) Road mortality potentially responsible for billions of pollinating insect deaths annually. *Journal of Insect Conservation* 19(5): 1029–1035.

Bellamy, P. E., Shore, R. F., Ardeshir, D., Treweek, J. R., and Sparks, T. H. (2000) Road verges as habitat for small mammals in Britain. *Mammal Review* 30(2): 131–139.

Bhattacharya, M., Primack, R. B., and Gerwein, J. (2003) Are roads and railroads barriers to bumblebee movement in a temperate suburban conservation area ? *Biological Conservation* 109: 37–45.

Blaauw, B. R., and Isaacs, R. (2014) Larger patches of diverse floral resources increase insect pollinator density, diversity, and their pollination of native wildflowers. *Basic and Applied Ecology* 15(8): 701–711.

Bonanomi, G., Caporaso, S., and Allegrezza, M. (2006) Short-term effects of nitrogen enrichment, litter removal and cutting on a Mediterranean grassland. *Acta Oecologica* 30: 419–425.

Bonanomi, G., Caporaso, S., and Allegrezza, M. (2009) Effects of nitrogen enrichment, plant litter removal and cutting on a species-rich Mediterranean calcareous grassland. *Plant Biosystems* 143(3): 443–455.

Bonari, G., Fajmon, K., Malenovský, I., Zelený, D., Holu, J., Jongepierová, I., Ko, P., Jan, U., and Chytrý, M. (2017) Management of semi-natural grasslands benefiting both plant and insect diversity: The importance of heterogeneity and tradition. *Agriculture, Ecosystems & Environment* 246: 243–252.

Brunzel, S., Elligsen, H., and Frankl, R. (2004) Distribution of the Cinnabar moth Tyria jacobaeae L. at landscape scale: use of linear landscape structures in egg laying on larval hostplant exposures. *Landscape Ecology* 19(1): 21–27.

Buglife (2018) B-Lines Hub. *Www.Buglife.Org.Uk/b-Lines-Hub*.

Bullock, J. M., and Pywell, R. F. (2005) Rhinanthus: a tool for restoring diverse grassland? *Folia Geobotanica* 40: 273–288.

Cole, L. J., Brocklehurst, S., Robertson, D., Harrison, W., and Mccracken, D. I. (2017) Exploring the interactions between resource availability and the utilisation of semi-natural habitats by insect pollinators in an intensive agricultural landscape. *Agriculture, Ecosystems & Environment* 246: 157–

167.

Cranmer, L., McCollin, D., and Ollerton, J. (2012) Landscape structure influences pollinator movements and directly affects plant reproductive success. *Oikos* 121(4): 562–568.

Dale, J. M., and Freedman, B. (1982) Lead and zinc contamination of roadside soil and vegetation in Halifax, Nova Scotia. *Proceedings of the Nova Scotian Institute of Science* 32: 327–336.

Davis, J. D., Debinski, D. M., and Danielson, B. J. (2007) Local and landscape effects on the butterfly community in fragmented Midwest USA prairie habitats. *Landscape Ecology* 22(9): 1341–1354.

Department for Transport (2018) *Road Lengths in Great Britain 2017*.

Di, N., Hladun, K. R., Zhang, K., Liu, T., and Trumble, J. T. (2016) Laboratory bioassays on the impact of cadmium, copper and lead on the development and survival of honeybee (Apis mellifera L.) larvae and foragers. *Chemos* 152: 530–538.

Dirig, R., and Cryan, J. F. (1991) The status of silvery blue subspecies (Glaucopsyche lygdamus lygdamus and G. l. couperi: Lycaenidae) in New York. *Journal of the Lepidopterists' Society* 45(4): 272–290.

Farre-Armengol, G., Penuelas, J., Li, T., Yli-Pirila, P., Filella, I., Llusia, J., and Blande, J. D. (2016) Ozone degrades floral scent and reduces pollinator attraction to flowers. *New Phytologist* 209: 152–160.

Flick, T., Feagan, S., and Fahrig, L. (2012) Effects of landscape structure on butterfly species richness and abundance in agricultural landscapes in eastern Ontario , Canada. *Agriculture, Ecosystems and Environment* 156: 123–133.

Forman, R. T. T., and Alexander, L. E. (1998) Roads and their major ecological effects. *Annual Review of Ecological Systems* 29: 207–231.

Free, J. B., Gennard, D., Stevens, M. H. H., and Williams, I. H. (1975) Beneficial insects present on a motorway verge. *Biological Cons* 8: 61–72.

Fuentes, J. D., Chamecki, M., Roulston, T., Chen, B., and Pratt, K. R. (2016) Air pollutants degrade floral scents and increase insect foraging times. *Atmospheric Environment* 141: 361–374.

Girling, R. D., Lusebrink, I., Farthing, E., Newman, T. A., and Poppy, G. M. (2013) Diesel exhaust rapidly degrades floral odours used by honeybees. *Scientific Reports* 3(2779): 1–5.

Goulson, D., Nicholls, E., Botías, C., and Rotheray, E. L. (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347: 1255957.

Halbritter, D. A., Daniels, J. C., Whitaker, D. C., and Huang, L. (2015) Reducing mowing frequency increases floral resource and butterfly (Lepidoptera: Hesperioidea and Papilionoidea) abundance in managed roadside margins. *Florida Entomologist* 98(4): 1081–1092.

Hanley, M. E., and Wilkins, J. P. (2015) On the verge? Preferential use of road- facing hedgerow margins by bumblebees in agro-ecosystems. *Journal of Insect Conservation* 19(1): 67–74.

Heneberg, P., Bogusch, P., and Řezác, M. (2017) Roadside verges can support spontaneous establishment of steppe-like habitats hosting diverse assemblages of bees and wasps (Hymenoptera: Aculeata) in an intensively cultivated central European landscape. *Biodiversity and Conservation* 26: 843–864.

Hopwood, J. (2008) The contribution of roadside grassland restorations to native bee conservation.

Biological Conservation 141: 2632–2640.

Hopwood, J., Black, S. H., Lee-Mäder, E., Charlap, A., Preston, R., Mozumder, K., and Fleury, S. (2015) *Literature review: Pollinator habitat enhancement and best management practices in highway rights-of-way*.

Hopwood, J., Winkler, L., Deal, B., and Chivvis, M. (2010) *Use of roadside prairie plantings by native bees*.

Humbert, J., Pellet, J., Buri, P., and Arlettaz, R. (2012) Does delaying the first mowing date benefit biodiversity in meadowland? *Environmental Evidence* 1(9): 1–13.

Jakobsson, S., Bernes, C., Bullock, J. M., Verheyen, K., and Lindborg, R. (2018) How does roadside vegetation management affect the diversity of vascular plants and invertebrates? A systematic review. *Environmental Evidence* 7: 1–14.

Johst, K., Drechsler, M., Thomas, J., and Settele, J. (2006) Influence of mowing on the persistence of two endangered large blue butterfly species. *Journal of Applied Ecology* 43: 333–342.

Jumeau, J., Boucharel, P., Handrich, Y., and Burel, F. (2017) Road-related landscape elements as a habitat: A main asset for small mammals in an intensive farming landscape. *Basic and Applied Ecology* 25: 15–27.

Keilsohn, W., Narango, D. L., and Tallamy, D. W. (2018) Roadside habitat impacts insect traffic mortality. *Journal of Insect Conservation* 22(2): 183–188.

Kennedy, C. M., Lonsdorf, E., Neel, M. C., Williams, N. M., Ricketts, T. H., Winfree, R., et al. (2013) A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecology Letters* 16(5): 584–599.

Kirby, P. (1992) *Habitat management for invertebrates: a practical handbook*. Sandy, Bedfordshire: RSPB, JNCC and National Power, UK.

Löfgren, Å., and Hammar, H. (2000) The phase-out of leaded gasoline in the EU: a successful failure? *Transportation Research Part D:* 5(6): 419–431.

Marini, L., Öckinger, E., Bergman, K., Jauker, B., Krauss, J., Kuussaari, M., Pöyry, J., Smith, H. G., Steffan-dewenter, I., and Bommarco, R. (2014) Contrasting effects of habitat area and connectivity on evenness of pollinator communities. *Ecography* 37: 544–551.

Martin, A. E., Graham, S. L., Henry, M., Pervin, E., and Fahrig, L. (2018) Flying insect abundance declines with increasing road traffic. *Insect Conservation and Diversity* : 1–6. doi:10.1111/icad.12300.

Mcfrederick, Q. S., Kathilankal, J. C., and Fuentes, J. D. (2008) Air pollution modifies floral scent trails. *Atmospheric Environment* 42: 2336–2348.

McKenna, D. D., and McKenna, K. M. (2001) Mortality of lepidoptera along roadways in Central Illinois. *Journal of Lepidopteran Society* 55(2): 63–68.

Meindl, G. A., and Ashman, T. (2013) The effects of aluminum and nickel in nectar on the foraging behavior of bumblebees. *Environmental Pollution* 177: 78–81.

Meunier, F. D., Verheyden, C., and Jouventin, P. (2000) Use of roadsides by diurnal raptors in agricultural landscapes. *Biological Conservation* 92: 291–298.

Meyer, S., Unternährer, D., Arlettaz, R., Humbert, J. Y., and Menz, M. H. M. (2017) Promoting diverse communities of wild bees and hoverflies requires a landscape approach to managing meadows. *Agriculture, Ecosystems and Environment* 239: 376–384.

Moroń, D., Grześ, I. M., Skórka, P., Szentgyörgyi, H., Laskowski, R., Potts, S. G., and Woyciechowski, M. (2012) Abundance and diversity of wild bees along gradients of heavy metal pollution. *Journal of Applied Ecology* 49: 118–125.

Mulder, C., Aldenberg, T., de Zwart, D., van Wijnen, H. J., and Breure, A. M. (2005) Evaluating the impact of pollution on plant-Lepidoptera relationships. *Environmetrics* 16: 357–373.

Munguira, M. L., and Thomas, J. A. (1992) Use of road verges by butterfly and burnet populations, and the effect of roads on adult dispersal and mortality. *Journal of Applied Ecology* 29(2): 316–329.

Muñoz, P. T., Torres, F. P., and Megías, A. G. (2015) Effects of roads on insects: a review. *Biodiversity and Conservation* 24: 659–682.

Muskett, C. J., and Jones, M. P. (1980) The dispersal of lead, cadmium and nickel from motor vehicles and effects on roadside invertebrate macrofauna. *Environmental Pollution* 23: 231–242.

Nieminen, M., Nuorteva, P., and Tulisalo, E. (2001) The effect of metals on the mortality of Parnassius apollo larvae (Lepidoptera: Papilionidae). *Journal of Insect Conservation* 5: 1–7.

Noordijk, J., Delille, K., Schaffers, A. P., and Sýkorka, K. V (2009) Optimizing grassland management for flower-visiting insects in roadside verges. *Biological Conservation* 142: 2097–2103.

Nowakowski, M., and Pywell, R. F. (2016) *Habitat creation and management for pollinators*. Wallingford, UK: Centre for Ecology and Hydrology.

Öckinger, E., and Smith, H. G. (2008) Do corridors promote dispersal in grassland butterflies and other insects? *Landscape Ecology* 23: 27–40.

Osgathorpe, L. M., Park, K., and Goulson, D. (2012) The use of off-farm habitats by foraging bumblebees in agricultural landscapes: Implications for conservation management. *Apidologie* 43(2): 113–127.

Ouin, A., Aviron, S., Dover, J., and Burel, F. (2004) Complementation/supplementation of resources for butterflies in agricultural landscapes. *Agriculture, Ecosystems and Environment* 103: 473–479.

Parr, T. W., and Way, J. M. (1988) Management of roadside vegetation: The long-term effects of cutting. *Journal of Applied Ecology* 25(3): 1073–1087.

Pickles, W. (1942) Animal mortality on three miles of Yorkshire roads. *Journal of Animal Ecology* 11(1): 37–43.

Ping, D., Ping, Z., Zhian, L., Hanping, X., and Huanping, L. (2013) Accumulation and detoxification of cadmium by larvae of Prodenia litura (Lepidoptera: Noctuidae) feeding on Cd-enriched amaranth leaves. *Chemosphere* 91: 28–34.

Plantlife (2012) Flowers on the edge. *Plantlife Blog*.

Polykretis, P., Delfino, G., Petrocelli, I., Cervo, R., Tanteri, G., Montori, G., Perito, B., Branca, J. J. V, Morucci, G., and Gulisano, M. (2016) Evidence of immunocompetence reduction induced by cadmium exposure in honey bees (Apis mellifera). *Environmental Pollution* 218: 826–834.

Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., and Kunin, W. E. (2010) Global pollinator declines: trends, impacts and drivers. *Trends in Ecology and Evolution* 25(6): 345–353.

Quarles, H. D., Hanawalt, R. B., and Odum, W. E. (1974) Lead in small mammals, plants, and soil at varying distances from a highway. *Journal of Applied Ecology* 11(3): 937–949.

Raemakers, I., Schaffers, A. P., Sýkorka, K. V, and Heijerman, T. (2001) The importance of plant communities in road verges as habitats for insects. *Proceedings of the Section Experimental and Applied Entomology, Netherlands Entomological Society (Amsterdam)* 12: 101–106.

Rascio, N., and Navari-Izzo, F. (2011) Heavy metal hyperaccumulating plants: How and why do they do it? And what makes them so interesting? *Plant Science* 180: 169–181.

Ries, L., Debinski, D. M., and Wieland, M. L. (2001) Conservation value of roadside prairie restoration to butterfly communities. *Conservation Biology* 15(2): 401–411.

Ruiz-Capillas, P., Mata, C., and Malo, J. E. (2013) Road verges are refuges for small mammal populations in extensively managed Mediterranean landscapes. *Biological Conservation* 158: 223–229.

Saarinen, K., Valtonen, A., Jantunen, J., and Saarnio, S. (2005) Butterflies and diurnal moths along road verges: Does road type affect diversity and abundance ? *Biological Conservation* 123: 403–412.

Schaffers, A. P., Raemakers, I., and Sýkorka, K. V (2012) Successful overwintering of arthropods in roadside verges. *Journal of Insect Conservation* 16: 511–522.

Senapathi, D., Goddard, M. A., Kunin, W. E., and Baldock, K. C. R. (2017) Landscape impacts on pollinator communities in temperate systems: evidence and knowledge gaps. *Functional Ecology* 31: 26–37.

Shu, Y., Zhou, J., Tang, W., Lu, K., Zhou, Q., and Zhang, G. (2009) Molecular characterization and expression pattern of Spodoptera litura (Lepidoptera: Noctuidae) vitellogenin, and its response to lead stress. *Journal of Insect Physiology* 55: 608–616.

Skórka, P., Lenda, M., Moron, D., Kalarus, K., and Tryjanowski, P. (2013) Factors affecting road mortality and the suitability of road verges for butterflies. *Biological Conservation* 159: 148–157.

Skórka, P., Lenda, M., Moron, D., Martyka, R., Tryjanowski, P., and Sutherland, W. J. (2015) Biodiversity collision blackspots in Poland: Separation causality from stochasticity in roadkills of butterflies. *Biological Conservation* 187: 154–163.

Suárez-Esteban, A., Fahrig, L., Delibes, M., and Fedriani, J. M. (2016) Can anthropogenic linear gaps increase plant abundance and diversity? *Landscape Ecology* 31(4): 721–729.

Sutcliffe, O. L., and Thomas, C. D. (1996) Open corridors appear to facilitate dispersal by Ringlet butterflies (Aphantopus hyperantus) between woodland clearings. *Conservation Biology* 10(5): 1359–1365.

Swaileh, K. M., Hussein, R. M., and Abu-Elhaj, S. (2004) Assesment of heavy metal contamination in roadside surface soil and vegetation from the West Bank. *Archives of Environmental Contamination and Toxicology* 47: 23–30.

Szentgyöryi, H., Blinov, A., Eremeeva, N., Luzyanin, S., Grześ, I. M., and Woyciechowski, M. (2011) Bumblebees (Bombidae) along pollution gradient - heavy metal accumulation, species diversity, and Nosema bombi infection levels. *Polish Journal of Ecology* 59(3): 599–610.

Szentgyöryi, H., Moroń, D., Grześ, I. M., Wantuch, M., Rożej, E., Settele, J., Potts, S. G., Laskowski, R., and Woyciechowski, M. (2010) The effect of heavy metal pollution on the development of wild bees.

In *Atlas of Biodiversity Risk*.

Tewksbury, J. J., Levey, D. J., Haddad, N. M., Sargent, S., Orrock, J. L., Weldon, A., Danielson, B. J., Brinkerhoff, J., Damschen, E. I., and Townsend, P. (2002) Corridors affect plants, animals, and their interactions in fragmented landscapes. *PNAS* 99(20): 12923–12926.

Valtonen, A., and Saarinen, K. (2005) A highway intersection as an alternative habitat for a meadow butterfly: effect of mowing, habitat geometry and roads on the ringlet (Aphantopus hyperantus). *Annales Zoologici Fennici* 42: 545–556.

Valtonen, A., Saarinen, K., and Jantunen, J. (2006) Effect of different mowing regimes on butterflies and diurnal moths on road verges. *Animal Biodiversity and Conservation* 29(2): 133–148.

Vanbergen, A. J., and Insect Pollinators Initiative, T. (2013) Threats to an ecosystem service: pressures on pollinators. *Frontiers in Ecology and the Environment* 11(5): 251–259.

Vermeulen, H. J. W. (1994) Corridor function of a road verge for dispersal of stenotopic heathland ground beetles Carabidae. *Biological Conservation* 69: 339–349.

Villemey, A., Jeusset, A., Vargac, M., Bertheau, Y., Coulon, A., Touroult, J., Vanpeene, S., Castagneyrol, B., Jactel, H., Witte, I., Deniaud, N., De Lachapelle, F. F., Jaslier, E., Roy, V., Guinard, E., Le Mitouard, E., Rauel, V., and Sordello, R. (2018) Can linear transportation infrastructure verges constitute a habitat and/or a corridor for insects in temperate landscapes? A systematic review. *Environmental Evidence* 7(5): 1–33.

Vinchesi, A. (2013) How did the alkali bee cross the road? Assessing transportation impacts to alfalfa seed production in the Walla Walla Valley. In *Proceedings of the 2013 International Conference on Ecology and Transportation*.

Wojcik, V. A., and Buchmann, S. (2012) Pollinator conservation and management on electrical transmission and roadside rights-of-way: a review. *Journal of Pollination Ecology* 7(3): 16–26.

Wynhoff, I., van Gestel, R., Van Swaay, C. A. M., and van Langevelde, F. (2011) Not only the butterflies: managing ants on road verges to benefit Phengaris (Maculinea) butterflies. *Journal of Insect Conservation* 15: 189–206.

Xun, E., Zhang, Y., Zhao, J., and Guo, J. (2018) Heavy metals in nectar modify behaviors of pollinators and nectar robbers: Consequences for plant fitness. *Environmental Pollution* 242: 1166–1175.

Contact us: Buglife, The Lindens, 86 Lincoln Road, Peterborough, PE1 2SN

www.buglife.org.uk

Tel: 01733 201210

Email: info@buglife.org.uk

@buzz_dont_tweet

Photo credits L-R; Ladybird spider *(Eresus sandaliatus)* © S. Dalton, Jellyfish © D. Huffman, Tansy beetle (*Chrysolina graminis*) © S. Falk and Large garden bumblebee (*Bombus ruderatus*) © S. Falk

Saving the small things that run the planet

Buglife - The Invertebrate Conservation Trust is a registered charity at
The Lindens, 86 Lincoln Road, Peterborough, PE1 2SN
Company no. 4132695, Registered charity no. 1092293, Scottish charity no. SC040004