Title

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OVERCOMING THE BARRIER EFFECT OF ROADS – HOW EFFECTIVE ARE MITIGATION STRATEGIES?

An international review of the use and effectiveness of underpasses and overpasses designed to increase the permeability of roads for wildlife.

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Abstract: Roads, railways and other linear infrastructure are pervasive components of most landscapes throughout the world. Combined with the effect of vehicles, they have the potential to cause mortality in wildlife, severely disrupt animal movement and increase the risk of local extinction. Management agencies and conservation organisations currently spend considerable amounts of money annually on engineering solutions to increase the permeability of roads for wildlife. We evaluated the use and effectiveness of wildlife crossing structures (e.g. tunnels, culverts, overpasses) by reviewing studies published in the refereed scientific literature, conference proceedings and consultant reports. We evaluated the scientific rigour and methodology of studies, the extent to which studies demonstrated an increase in permeability, the detail included in the reporting and the extent to which population, community and ecosystem effects were shown. One hundred and twenty three studies were reviewed and all except two found an effect at the level of the individual animal. Two studies demonstrated a positive effect for the population and thus overall, the effectiveness of mitigation measures at reducing the risk of population extinction remains unclear. The level of scientific rigour, amount of replication and description of adjacent habitat and animal populations varied considerably among studies, in many cases limiting the level of inference that could be made. In the context of evaluation, we propose that a clear distinction be made between "use" and "effectiveness" of a wildlife crossing structure. The use of a structure may be broadly defined as the rate of detections of individuals or species, while effectiveness relates to a specific question or the goal of mitigation. A large amount of effort has conclusively shown that crossing structures are used by many species of wildlife. The long-term success of mitigation will ultimately depend on their effectiveness – i.e. to what extent have they mitigated the barrier effect of roads and has this prevented the local extinction of populations due to road effects? The next phase of research must focus more explicitly on quantifying their effectiveness, relative to location- and species-specific goals.

Introduction

Roads and traffic are pervasive components of landscapes throughout the world. There is a growing recognition of their deleterious impacts on the natural environment and the need to quantify and mitigate these impacts (Spellerberg 1998; Forman *et al*. 2002; Donaldson and Bennett 2004; Davenport and Davenport 2006). The effects are diverse including many direct and indirect impacts, such as the loss and degradation of habitat; incursion of weeds, disease and feral animals; direct mortality of wildlife due to collision with vehicles; disruption of movements due to the creation of barriers; altered microclimatic conditions; and changes to the acoustic environment.

Road construction and management agencies around the world are currently investing large amounts of money quantifying the ecological effects of roads and traffic and investigating numerous mitigation techniques. Within the field of road ecology, the role of roads as barriers to the movement of wildlife and the effectiveness of measures to facilitate wildlife crossings have received considerable recent attention. This research has primarily focussed on quantifying the number and locations of road-killed animals (e.g. Rosen and Lowe 1994; Groot Bruinderink and Hazebroek 1996; Huber *et al*. 1998; Haxton 2000; Shuttleworth 2001; Malo *et al*. 2004) and the rate of use of tunnels, culverts, and overpasses by wildlife (e.g. Foster and Humphrey 1995; Yanes *et al*. 1995; Clevenger and Waltho 2000; Ng et al. 2004; Clevenger and Waltho 2005). Prompted by human-safety issues, the highly visible nature of road-kill carcasses and the potential conservation implications, agencies responsible for road construction and management have attempted to reduce the number of roadkills by preventing animals from accessing the road and facilitating crossing by constructing tunnels, culverts and overpasses. There has been considerable effort to document the use of these crossing structures by wildlife, and studies have been conducted in Europe, North America and Australia (e.g. Mansergh and Scotts 1989; Rodriguez *et al*. 1996; Clevenger and Waltho 2000; Clevenger *et al*. 2001; Ng *et al*. 2004).

The broad aim of this review is to assess the use and effectiveness of mitigation measures intended to decrease the barrier effect of roads and other linear infrastructure. It is timely to review current practice and provide direction for future works and studies to ensure best-practice. The missed opportunity costs of installing ineffective or insufficient mitigation structures may be significant. We focus on distinguishing between the use of a structure and its overall, long-term effectiveness, and assess methodological approaches and issues. Our focus on methodology is because we wanted to assess the scientific basis of published results and attempt to identify strengths and weaknesses in current approaches.

How Effective Are Mitigation Strategies?

It is helpful to define various terms and concepts to help clarify the direction and intent of this review. The Oxford English Reference dictionary definition of **mitigate** is "to make milder or less intense or severe"; **effectiveness** is "having a definite or desired effect"; and **use** (as a noun) is the "act of using or the state of being used". Our working definition of a **wildlife crossing structure** is ‘a physical structure that increases the permeability of the road or other linear infrastructure by facilitating the safe passage of animals over or under it and in the case of roads and railways, preventing collision with vehicles’. Wildlife crossing structures may be purpose built for wildlife or may primarily serve other functions (e.g. water drainage or access by humans). In the literature there is considerable confusion and interchangeable use of terms when describing mitigation structures. We have developed the following terms and definitions (table 1) to reduce confusion and provide consistency when describing the mitigation structures. In essence, we propose that a mitigation measure be described according to its specific structure, rather than its intended use. We propose to use the terms “underpass” and “overpass” as general terms that describe a collection of structures. We invite comment from practitioners in other countries as to the appropriateness of these terms.

In this review we have classified all structures in the studies according to their dimension and form, irrespective of the names given them by the authors. When we were unable to classify mitigation structures into one of our specific categories based on structure and size, we used the terms given by the original authors, or given the general term of ‘underpass’ or ‘overpass’.

Table 1: Definition of engineering options to mitigate the fragmentation effects of linear infrastructure

Structure	Description
OVERPASS*	**Allows passage of animals above the road**
Land bridge	Also known as eco-duct or wildlife bridge. This is a (typically) wide (30 – 70 metres) bridge that extends over the road. The bridge has soil on it, and is planted with vegetation and enhanced with other habitat features (e.g. logs, rocks, water-body etc).
Overpass (small roads)	This bridge above the major linear infrastructure is typically to allow human/stock access across the road. This overpass is typically narrow and not hourglass shaped. The road on the overpass is typically a minor road – it may be unsealed, single lane etc
Canopy bridge	This is a rope or pole suspended above the traffic, either from vertical poles or from trees. Typically installed for arboreal and scansorial species.
Glider pole	These are vertical poles placed in the centre median or on the road verge, and provide species that glide intermediate landing and launch opportunities.
Local traffic management	Devices to reduce the speed or volume of traffic – e.g. road closures, chicanes, crosswalks, lighting, signage.
UNDERPASS*	**Allows the passage of animals below the major linear infrastructure**
Culvert	Culverts are typically square, rectangular or half-circle in shape. They are typically pre-cast concrete cells or arches made of steel. They may be purpose built for fauna passage or drainage, or a combination of both.
Tunnel	Tunnels are typically round pipes of relatively small diameter (e.g. < 1.5 metres diameter). May also be termed “eco-pipe”.
Bridge	A bridge is a structure that maintains the grade of the road or elevates the traffic above the surrounding land, allowing animals the opportunity to pass under the road. When used to mitigate the barrier effect of linear infrastructure, the primary function is often to facilitate water drainage or the movement of local human traffic, and secondarily to facilitate the passage of wildlife.

* There was considerable overlap in use of terms to describe crossing structures, particularly for underpasses. The definitions in this table are an attempt to reflect their design, rather than their potential use.

Literature Sources

The information for this critical review was sourced by searching the ISI Web of Science database in March 2007 using the terms ‘underpass, overpass, culvert, tunnel and barrier’ in combination with the terms ‘road, wildlife and fauna’. Extensive reference lists from a number of general ‘road ecology’ reviews (Bennett 1990; 1999; Forman et al. 2002b; Davenport and Davenport 2006) and from each article we reviewed were also searched. Consultants reports were included when these were obtainable within the time constraints and conference presentations were included if published in a proceedings. There is a notable bias towards a comprehensive set of reports from Australia, Spain, France and The Netherlands, which reflects the geographic bias of the authors place of work and residence. We welcome the inclusion of reports from other regions of the world for future publications. Only studies that presented new data on the use or effectiveness of wildlife crossing structures were included in the critical review. Papers that summarised published data, gave an overview of projects within their jurisdiction, or discussed projects that were in the planning or construction stages were excluded from the review. Studies that included other aspects of road ecology and wildlife (e.g. rate or location of road-kill, effectiveness of exclusion fencing, animal behaviour or survival after translocation) were only included if they also included data on use of crossing structures.

Results

Number of Papers and Geographic Location of Study

One-hundred and twenty-three studies that fitted our search criteria for structures used as wildlife crossings by fauna were found and reviewed. These 123 studies included:

- all publications in English, Dutch, Spanish and French-language scientific refereed journals;
- all consultants reports from Australia, the majority of reports from The Netherlands, Spain and France, and some from the USA and Canada;
- a subset of papers published in the 1996, 1998 and 1999 ICOWET conferences, the 2001, 2003 and 2005 ICOET proceedings, and the proceedings from the Habitat Fragmentation and Infrastructure (1995) and Toads and Roads (1989) conferences.

The studies were conducted in Denmark, Brazil, Sweden, Finland, and Portugal (n = one study each), two in the United Kingdom, four in Germany, nine in Canada, 14 in Spain, 15 in the Netherlands, 16 in France, 29 in Australia and 30 in the United States of America.

Number and Types of Structures

A total of 1864 structures were reported on and the majority were underpasses (83%), and specifically culverts (40% of 1864). The underpasses included culverts (742 examples); bridges (130); underpasses of unknown type (333); and tunnels (340). Overpasses included land bridges (68); overpasses with small roads (112); canopy bridges (8); glider poles (1); and other devices such as crosswalks, and signage (35). The total number of crossing structures is not an accurate measure of the total number in existence because the same structures may have been reported on in two or more publications. Nevertheless, it gives an indication of the relative proportions of each type of structure.

The mean number of crossing structures investigated per study was 9.9 (range 1 – 186), with 41 of the studies focusing on one (n = 19), two (n = 14) or three (n = 8) structures.

Type of Linear Infrastructure

Structures to enhance connectivity have been constructed across a number of different types of linear infrastructure. The majority of the 122 studies focussed on mitigating the effects of roads and traffic (n = 113); railway lines (5); one on road and railway lines; one on an oil pipeline; and two on a water canal. We did not locate studies that attempted to measure the mitigation of the fragmentation effects of powerlines or other utility easements. The majority of the 114 road studies focused on mitigating the barrier effect of major roads (e.g. highway, freeway or motorway).

It was rare to find that the road and/or traffic were fully described. Road conditions were fully described in 13 studies (partially in 66) and traffic conditions were fully described in 24 (partially in 6). The road was typically described in terms of its classification and number of lanes (e.g. “major highway”, “4-lane interstate highway”, or “4-lane divided highway”). This is a potential source of confusion, especially when attempting international comparison. A full description of road and traffic conditions is important because it allows international readers to place the study (and indeed their own mitigation project) into context. For example, a species may be more willing to use a certain type of structure if the road is narrower and has fewer cars than if the same structure traverses a wide, multi-lane highway. Data on road width, number of lanes, presence, width and vegetation characteristics of a median strip are the minimum road features that should be described. It may be possible to infer road width to some extent from the length of the structure used in mitigation. However there was a pronounced variation in the length of structures, even on the same road or train-line, thus limiting the utility of this approach (e.g. Hunt *et al*. 1987; Clevenger and Waltho 2000; Ng *et al*. 2004).

Design, Timing and Duration of Study

The majority of studies measured the rate of use/frequency of detections of animals using crossing structures and came to conclusions about the factors influencing crossing rates. This was most rigorously achieved by relating the rate of use to habitat, landscape and physical characteristics of the mitigation structures by using a correlation and/or regression approach.

A 'before-after' comparison approach was evident in 15 of the 122 studies, which included rates of road-kill before and after mitigation (e.g. Dodd *et al*. 2004). Mansergh and Scotts (1989) conducted an assessment of population sex ratios and over-winter survival before and after mitigation. Other researchers assessed the effectiveness of fencing to funnel animals towards the structures (e.g. Rodriguez *et al*. 1997; Cain *et al*. 2003). Most studies commenced after the structures had been built and were therefore unable to include a rigorous assessment of the pre-mitigation scenario. Similarly many studies that investigated faunal use of existing non-wildlife passages (e.g. drainage culverts) did not include a pre-mitigation analysis. A number of studies implied that there were elements of a 'before and after' approach, but this was not conclusive or clear from their methods or results. Three sequential studies (Singer 1978; Singer and Doherty 1985; Pedevillano and Wright 1987) reported on the use of the same structures over time, and in combination the three studies provided a before and after approach. One study used a novel approach to test small mammal preferences by translocating animals across the road in the vicinity of different structures, and provided excellent replication by using many animals near multiple structures (McDonald and St Clair 2004). Controls were reported in 29 of the 122 studies, with approximately half of the controls acting in a before-after approach. A small number of studies had true controls, with some experimental treatments and other areas remaining untreated (e.g. Singer 1978; Lehnert and Bissonette 1997; McDonald and St Clair 2004).

Most studies were not explicit about the timing of their surveys in relation to structure or road completion. The earliest use of a structure after construction was recorded for the Mountain Pygmy Possum *Burramys parvus* which used a tunnel two weeks after completion (Mansergh and Scotts 1989). Similarly, Golden Lion Tamarins were reported to use a canopy bridge "as soon as it was assembled" (Valladares Padua *et al*. 1995).

The duration of monitoring varied across studies, ranging from 4 nights (Jackson and Tyning 1989) to 20 years (van der Ree *et al*. in preparation). Excluding this 20-year study (which utilised a 20-year census data set collected for other reasons) the mean duration of monitoring across the 121 studies was 1.7 years (range 4 nights – 8 years). The frequency of monitoring within each study was extremely variable, and included daily (Reed *et al*. 1975), once per week (Clevenger et al. 2001), and 15 – 22 days per month (Rodriguez *et al*. 1997). The frequency of monitoring depended in part on the survey technique selected.

Description of Populations of Wildlife and Habitats Adjacent to Roads

Most studies (78 of the 122) gave some description of the vegetation or landform in their study area. Description of the vegetation, landform and geography is important for readers unfamiliar with the study area to gain appreciation of the region. Furthermore, it is critical for readers who want to make an independent assessment of the likelihood of a certain species occurring in the area, and thus being potentially available to use the crossing structure.

Less than half of the studies (56 of 122) incorporated some assessment of the presence or abundance of their target species into their evaluations. The most comprehensive was a calculation of expected crossing rates based on relative animal abundance in adjacent habitats (Clevenger and Waltho 2000; Clevenger et al. 2001). Various methods were used to investigate occurrence or abundance in adjacent habitat, including radiotracking (e.g. Foster and Humphrey 1995, Australian Museum Business Services 2001e, Cain *et al*. 2003); track or camera counts (e.g. Gloyne and Clevenger 2001; Braden *et al*. in press); and studies that used detailed census data of their target species (Mansergh and Scotts 1989; Guyot and Clobert 1997, van der Ree *et al*. in preparation). Literature sources (e.g. previous studies) and museum databases were used in 20 studies to evaluate habitat preferences and seasonal fluctuations in abundance. An assessment of animals in adjacent habitat was not relevant in studies that focused primarily on the behaviour of animals using the tunnels (Reed et al. 1975; Singer 1978; Reed 1981; Singer and Doherty 1985; Pedevillano and Wright 1987) or in the single study that used a translocation approach (McDonald and St Clair 2004).

Survey Technique

A range of techniques was used to identify the use of crossing structures by wildlife. The most common technique was tracking pads (74 studies), where a substrate (e.g. sand, soot, ink) was used to record animal footprints, from which the species, direction of travel and number of crossings could be inferred. Thirty-six studies used video or remotely triggered infra-red still cameras; radiotracking (7 studies); direct observations (13); game counters or sensors (6); trapping (12); collection and identification of scats (16) or hair (8); and other techniques used included dusting with fluorescent pigment and pitfall traps.

Quantification of the Negative Impact of the Road and Traffic

The negative effect of the linear infrastructure or traffic on wildlife was evaluated in approximately 50% of the 122 studies. The majority of these referred to previous studies or used general ecological principles to predict that the linear infrastructure was likely to reduce connectivity.

Assessment of Factors Influencing Rate of Use

Most studies included an assessment of factors influencing rate of crossing (98 of 122). Of these 98 studies, 24 explicitly used a quantitative approach (e.g. regression modeling, correlations) to assess the influence of different parameters (e.g. dimensions of structure, rate of use by humans, traffic volume, and presence of vegetative cover at the structure entrance) on the rate of crossing by wildlife. The remaining studies that made conclusions about the factors influencing rate of use, typically including qualitative judgments and incorporated the results of other studies.

A range of variables was identified as influencing the rate of use of the mitigation structures by wildlife. Commonly cited variables that positively influenced rates of use include abundant and high-quality habitat near to the entrance of the structures; dirt or “natural” floors; large “openness” ratios (length x width x height of underpass); absence or low rate of use by humans; and presence of “furniture” such as logs, rocks and vegetation on or in the structure. However, it should be noted that the direction and magnitude of the effect of these and other variables are likely to be species or species-group specific, and were shown to vary from location to location. Furthermore, the effect of correcting for local abundance at each crossing structure (sensu Clevenger et al. 2001) will further refine the identification of important variables.

Extrapolation or Study of Effect at Population Level

Five publications reported on a population-level study or effect and an additional 23 studies implied or alluded to population-level effects such as increased viability or prevention of a population sink. Population-level effects were shown for the Mountain Pygmy-possum *Burramys parvus* in south-east Australia where the use of an under-road tunnel led to a measurable increase in the viability of the population (Mansergh and Scotts 1989; van der Ree et al. in preparation) and for Badgers *Meles meles* in The Netherlands (van der Grift *et al*. 2003).

Discussion

Aim and Effectiveness of Wildlife Crossing Structures

Forman et al. (2002b) proposed that the overall objective of wildlife crossing structures is to ‘increase the permeability of a road corridor’ (p. 161). They list a series of six criteria against which to measure effectiveness, namely: i) reduce rates of road-kill; ii) maintain habitat connectivity; iii) maintain genetic interchange; iv) ensure biological requirements are met; v) allow for dispersal and re-colonisation; and vi) maintain meta-population processes and ecosystem services. We propose that an explicit and fundamental measure of the effectiveness of wildlife crossing structures is the long-term viability of local populations or prevention of likely reduction in viability (in the case of a road widening or upgrade).

According to at least some of the six criteria proposed by Forman et al. (2002b), all of the studies we reviewed were likely to be considered successful at the level of the individual animal. The vast majority of wildlife crossing structures monitored increased the permeability of the road by allowing individual animals to move more safely across the road. In this sense, the crossing structure was successful for the individual, at the time it was recorded using the structure. However, it has been noted that use of structures does not necessarily equate to conservation gain (Ng et al. 2004). In other words, have the negative effects of the road been reduced to the point where the risk of extinction is at a satisfactory level? Are road construction and management agencies actually doing enough to mitigate the negative effects of roads and traffic? Are populations declining in size due to road effects, even though we observe them using the crossing structures? The answer to these questions remains largely unanswered, despite an extensive body of work over the past two decades.

Study Design and Methods

The mitigation works must have a clearly defined and measurable goal. The six criteria proposed by Forman et al (2002) and our goal “to increase population viability” should be seen as guiding principles only, and not the actual goal against which success can be measured. The goal for each project must be specific to the location, species of concern and nature of the problem. We recommend use of the ‘SMART’ approach (Specific, Measurable, Achievable, Realistic, and Timeframed) to set a specific goal and thus facilitate more comprehensive evaluation of mitigation measures. An ecological goal for a road through habitat might be to “maintain the risk of extinction of a species to less than 5% over the next 100 years”. Alternatively the broad goal of maintaining connectivity could be made more specific such that “more than 90% of individuals within the population that approach the road successfully cross-over”. The identification of specific goals for each project is likely to alter the emphasis of the mitigation. In one area the focus may be on reducing road-kill, while for another species it may be on maintaining daily movements.

The design of a study is critical to the inferential strength or reliability that may be obtained. A rigorous scientific approach relies on clearly articulating a specific question, and then designing the study to answer that question with maximum efficiency and achieving maximum clarity of results. Most of the studies we reviewed were retrospective, in that they investigated the occurrence of crossing structures by wildlife after construction, typically without controls. Depending on the initial question posed, this approach may be satisfactory. However, we would argue that the next phase of research into the use and effectiveness of wildlife crossing structures should elucidate the probability of population persistence as a function of mitigation. Trade-offs exist between the perfectly-designed study and reality, and in the case of studying road effects it may not be possible to include the “before” situation, adequate replication and randomisation may not be feasible, and resources may be limited (Roedenbeck et al. 2007). Road agencies need to invest in manipulative and experimental studies that provide maximum inferential strength. Roedenbeck et al (2007) provide an excellent and thorough discussion of the various study designs, their strengths and weaknesses and financial cost in evaluating road effects. It is important to note that the relative cost to undertake a thorough evaluation of structure effectiveness is likely to be less than the costs to build the structure, and indeed significantly less than the overall costs of road construction and management.

One approach to evaluating wildlife crossing structures is to compare the effects of post-mitigation vital rates (e.g. dispersal, gene flow, birth rate, survival) with the pre-mitigation situation and the non-road situation using population viability analyses (van der Grift and Pouwels 2006). If the age or sex structure, survival, patterns of dispersal, and gene flow before mitigation are not known, then it is difficult to assess whether these parameters have improved after mitigation. We are not suggesting that a detailed field assessment of the actual impacts of every road for every species be undertaken prior to mitigation. However, the reliability of population viability models at predicting and assessing potential impacts and success of mitigation rely on thorough and realistic population parameters. It may be possible to substitute data from other locations or species in order to build population models.

There is a need to more fully identify and quantify the negative effect of roads and traffic. For example, the number of animals killed after collision with vehicles is clearly a major issue and a cause of concern for both human safety and conservation. Nevertheless, road-kill is just one aspect of the negative effect of roads and there are likely to be many others that need to be considered. Therefore, studies evaluating the effectiveness of mitigation measures should not rely solely on measuring the rate of road-kill as an index of crossing-structure success. Ironically, the absence of a species in the road-kill tally may be due to a lack of suitable habitat or that other effects of the road (e.g. noise, light or chemical pollution) are deterring animals from even reaching the road or that the local population has become sufficiently rare that it can no longer be detected, rather than a successful mitigation. This highlights the need for information on the status of populations in adjacent habitats.

A lack of statistical replication in many studies has likely limited the quantitative evaluation of factors influencing rates of use. Even Yanes et al. (1995) who investigated the rate of wildlife crossing within 17 tunnels in Spain lamented that their small sample size prevented them from drawing conclusions about the importance of particular design features for wildlife. Adequate replication is critical because the natural environment is variable and an unrepresentative picture may be obtained if all the structures are coincidentally placed in areas with high or low population sizes, with high or low densities of predators, with high or low density of geographic or landscape features that encourage or discourage use.

Numerous studies have shown an increase in the rate of use of mitigation structures over time as animals become accustomed to the structures, as disturbance due to construction is rehabilitated and as vegetation cover increases. Furthermore, seasonal variation in rate of use is also evident, and this is unlikely to be detected in short studies. There appears to be a trend for longer-term studies being undertaken in recent years, which include pre-mitigation studies to develop a baseline; monitoring during construction; and then post construction monitoring.

Survey Method

Remotely-triggered cameras and tracking pads were the most commonly used techniques to survey use of crossing structures. While these methods are effective at detecting large species and those with diagnostic tracks, they are less efficient at detecting smaller and more cryptic species. The method of survey will also influence the type of inference that can be made; however these biases were rarely acknowledged. For example, the number of tracks of a certain species does not necessarily equate to the total number of individuals using the structure. It may be that a dominant individual has established a territory and its frequent use of the structure prevents access by other individuals. Finally, recording the presence of an individual within a structure (e.g. recording footprints at one end of a structure) does not always equal a successful crossing. Therefore, the minimum standard for recording a successful crossing might be a set of tracks travelling in the same direction recorded at both entrances to the tunnel or overpass (e.g. Gloyne and Clevenger 2001; e.g. Ng et al. 2004). A combination of survey techniques should always be employed, and new techniques such as genetic techniques and the use of remote data-loggers with PIT tags offer potential new insights. Greater effort to detect smaller and less diagnostic species from tracking pads (perhaps using a finer substrate such as ink or marble dust) are also recommended.

Other survey techniques, although more labour-intensive, may allow the purpose of use of a tunnel or overpass to be elucidated. The type of use (e.g. occasional or dispersal passage, daily as movement within a home range or migration) is likely to have implications on population persistence. For example, a concurrent radiotracking study of tunnel crossings under Highway I-75 in Florida USA for the Florida Panther found that of the 10 reported crossing only two individuals were involved, and use was related to the home ranges of the panthers (Foster and Humphrey 1995). For some migratory species, the direction of travel and time of year is strong evidence that the crossing structure is used in migration. Similarly, the daily use of underpasses by mountain goats to access a salt lick (Singer 1978; Singer and Doherty 1985; Pedevillano and Wright 1987) is convincing evidence how the structure is being used. The use of crossing structures may be sex-specific, as there is some evidence that road-crossing ability may also be sex-dependent (van der Ree 2006). In most situations, it is unknown if animals dispersed across the road and established new territories, used the structure daily to access resources or used it for some other purpose.

Importance of Study of Animals in Adjacent Habitat

The rate of use of crossing structures is related to the abundance of animals in adjacent habitat (e.g. Yanes et al. 1995). Thus, studies that draw conclusions about the suitability of certain types of structures without considering animal abundance may give an incomplete assessment of suitability. One interesting approach calculated an expected rate of crossing based on animal abundance in adjacent habitat and compared the expected rate of use to that observed (Clevenger and Waltho 2000; Clevenger et al. 2001). At the very least museum and wildlife atlas records can provide a list of species that probably occur in the study area. However, this should be considered the very minimum at which the pool of potential species be estimated. Estimates of crossing rates relative to local abundance (with local abundance preferably estimated simultaneously) will more fully elucidate the effectiveness of certain structure types.

Improving Knowledge Transfer

In this review we assessed information published in the refereed scientific literature, consultants reports and conference proceedings. To our knowledge, we have the majority of Australian, Spanish, French and Dutch reports, but only a small proportion of reports from North America. This bias is due to our own geographic locations and we welcome the opportunity to include reports from North America and elsewhere in a more comprehensive review to be published in the future. The primary literature sources that are most accessible to road engineers and consultants around the world are likely to be international peer-reviewed journals and some recently completed agency reports. For example, three recently published studies that we reviewed (Cain et al. 2003; Taylor and Goldingay 2003; Ng et al. 2004) all cited three of the earliest papers published in journals on the use of underpasses (Reed et al. 1975; Reed 1981; Singer and Doherty 1985). Therefore, accessibility is enhanced when published in journals. The peer-review process will also potentially improve the scientific rigour and reliability of inferences and conclusions. The additional costs involved in writing up the findings for publication in a reputable journal would be relatively small compared with the cost of the research itself, and should be factored into commissioned studies. An alternative suggestion is that road agencies should stipulate that the findings of commissioned studies be prepared for submission to scientific journals.

To further improve the efficient and accurate transfer of knowledge, we suggest a series of minimum criteria be reported in all studies. This is critical for the reader to gain an understanding of the overall configuration of the linear infrastructure; the surrounding vegetation; road and traffic conditions and the mitigation structures. The overall configuration of the linear infrastructure includes the number and width of vehicle lanes, particulars on service and access lanes, and details of central median. The presence and type of vegetation adjacent to the road (and within the central median) may act as potential habitat and therefore should be described. The road traffic conditions require clarification. Pertinent factors include mean vehicle speed, and variations in vehicle speed, traffic volume, and times of peak traffic flow. The characteristics of each mitigation structure should be clearly described. We support a recent memo from the ICOET organising committee outlining a recommended terminology for structure dimensions (length, width, height); cross-sectional shape (e.g. round, rectangular); intended function (drainage, wildlife passage); and mode of construction and materials (e.g. pre fabricated concrete box culvert). This is important to avoid potential confusion due to inconsistent nomenclature across regions and studies. We suggest an international working party convene to present a final set of standard definitions of structures that can be adopted by the wider field.

Conclusions

Many agencies around the world are constructing and modifying roads to have less environmental impact. The amount of money spent on mitigating the barrier and other effects of roads and traffic are relatively small compared with the overall construction and maintenance budgets of state and national road agencies. Furthermore, the funds required to fully evaluate the effectiveness of mitigation actions is comparatively smaller. Given the recent surge in research and expenditure on minimising the ecological effects of roads and traffic it is pertinent and timely to evaluate the effectiveness of mitigation measures and comment on the direction that future research and monitoring should take. The studies we reviewed clearly demonstrate that most measures designed to increase the permeability of roads for wildlife were successful at the level of the individual animal. The detection of an animal in a tunnel or overpass indicated that on the occasion it was detected it may have made it safely to the other side. However, the extent to which the population has benefited from that successful crossing is unclear. There is insufficient information and analysis in the majority of studies to evaluate whether the viability of the population has increased to an acceptable level.

The rate of use of a wildlife crossing structure is an important and essential first step in evaluating effectiveness. After 20 years of such evaluations, it is apparent that research at the next level of complexity is required. The rate of detections of animals within a structure is information that must feed into an analysis of whether the population is likely to exist in 20, 50 or 100 years time. In other words, have the negative effects of the road been sufficiently mitigated that population persistence has been sufficiently enhanced to ensure long-term survival? This is a critical question that road agencies must be able to answer in the positive if they are to comply with strict legislation that aims to conserve biodiversity. Finally, the barrier effect of roads is just one potential impact on fauna, and mitigation that addresses this may only increase viability within the limits posed by other effects.

Biographical Sketches: Rodney van der Ree is an ecologist at The Australian Research Centre for Urban Ecology, a division of the Royal Botanic Gardens of Melbourne. He obtained his PhD in wildlife ecology by studying the influence of landscape geometry on arboreal marsupials. The effects of fragmentation and barriers were central to his thesis, sparking the interest in road ecology. Rodney is currently leading a collaborative research project with VicRoads (the Victorian State road agency) entitled “quantifying and mitigating the barrier effect of roads”.

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