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The impact of roads on sub-Saharan African ecosystems: a systematic review

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Abstract

New major road infrastructure projects are planned or underway across sub-Saharan Africa (SSA) and are expected to have complex, and often deleterious, impacts on natural ecosystems across the region. For this reason, it is necessary to review evidence of how and through which mechanisms, roads might affect these landscapes. We reviewed 137 peer reviewed articles and documented 271 reported effects of roads and their underlying mechanisms inside and outside protected areas across SSA.

Our findings show that (a) the study of the effects of roads on ecosystems in SSA is growing and not limited to the field of road ecology; (b) the negative effects of roads on species were reported at a similar frequency within and outside of protected areas; (c) the road-effect zone varied with effect but typically is between 1 and 7 km for larger mammals; (d) access to surrounding ecosystems through roads was the main mechanism driving effects; studies found accessibility influenced land use patterns and illegal hunting and harvesting; (e) other mechanisms by which roads affect (animal) species include, through functioning as a foraging site, and a habitat, and by acting as barriers to and corridors for movement; and (f) there was far more evidence on how roads can negatively impact ecosystems; in contrast, there was less certainty around mechanisms by which roads had no significant or a positive impact, since many of these were either speculated or unknown.

An understanding of the underlying mechanisms can assist researchers and environmental assessment practitioners to predict how and where future road development might drive changes in biodiversity and land cover. Moving forward, we suggest that future research build a better understanding of the cumulative effects on different mammal and non-mammal communities and ecosystems more broadly and examine the socioeconomic contexts that characterize different road impacts in SSA.

1. Introduction

The Programme for Infrastructure Development in Africa (PIDA) [1] expects many new road infrastructure projects to begin throughout sub-Saharan-Africa (SSA), adding to the large number that are already underway. Such large-scale developments are strategically designed to promote trade and economic development [1–3]. However, the development of new roads in SSA is causing concern in the conservation community [4–8], which believes that it may have a detrimental impact on natural ecosystems through enabling large-scale and long-term overexploitation of natural resources and thus biodiversity loss [7, 9–14]. Most of the impacts are thought to be deleterious and might be directly or indirectly related to many current threats to ecological integrity [10].

There is a large body of literature from across the world on the ecological effects of roads, mainly from the field of road ecology. Most of this literature has focused on identifying visible and quantifiable effects of roads on a single species [10, 14–16]. This is also seen in reviews, which focus on the effects of roads on wildlife [12, 15–17]. The Handbook for Road Ecology [10] identifies seven key effects of roads on wildlife: increasing wildlife mortality; acting as barriers to species movement; promoting avoidance by species; attracting species; acting as a habitat or passage for movement; promoting habitat loss and promoting habitat degradation. Road development not only affects wildlife, but can also disturb other plant and animal communities [12, 18], causes hydrological and geomorphological impacts [14, 19, 20] and changes the chemical characteristics of air [19, 21]. The shift in focus from assessing the impacts of roads on a single species to taking a landscape or ecosystem view is a recent one [17] and is still largely exploratory [5, 9]. The ecological effects of roads vary over time [14, 22] and have a multidimensional nature [9–11, 14, 17, 23], which makes them difficult to assess and quantify. Furthermore, the effects are heterogeneous and may vary with factors that are not frequently addressed, such as road quality and size [14, 23, 24], road construction and management [25–27], law enforcement [28], whether a road is in a protected area [29, 30] and the underlying mechanism of an effect.

In developing regions such as SSA, many factors may interact with roads to affect ecosystems. These include poaching [31, 32], other illegal activities such as harvesting [31, 33, 34], human–wildlife conflict [35–37], population growth, and climate variability and change [38]. These interactions have rarely been discussed in reviews and are largely understood at a theoretical level. The review by Collinson *et al* [39] is probably the most up-to-date compilation of information on the ecological effects of roads in Africa; however, this work mainly involved mapping the reported effects of a road, the taxa studied, and other information related to where and when these effects were identified. The indirect and cumulative development impacts of roads are less well understood [14, 16]. For instance, land use change is predicted to be among the largest drivers of biodiversity loss in Africa [40] and a major concern for future road development is its facilitation of land cover and land use changes [5]. However, these interacting effects of roads are rarely reported in reviews.

With the ambitious road developments that have been planned, countries across SSA will require carefully planned and well informed road infrastructure design in order to maximize the benefits and minimize the trade-offs associated with road development [8, 10]. Achieving balance between ecosystem conservation and infrastructure development will require an understanding of the interaction between roads and ecosystems in the SSA context. Thus, the overall goal of this systematic review is to synthesise current evidence and understanding of the specific ways in which roads interact with ecosystems in SSA and critically assess their effects. We are also interested in whether the interactions inside protected areas differ from those reported outside protected areas, as the management of protected areas, particularly the management of threats [29, 30, 41, 42], may play an important role in the potential effects of a road.

During the course of our review, it became apparent that the effects of roads on whole ecosystems was not well researched [14, 15, 17, 39]. Therefore, we chose to focus on identifying the effects of roads on various elements that exist within ecosystems. The specific aims of our review were as follows:

- To examine the distribution of the reported effects of roads. To do this, we conducted a systematic mapping exercise to describe the spatial and temporal variation of the reported effects of roads inside and outside protected areas across SSA regions.
- To identify key road impact pathways using a systematic review framework. First, we examined and summarized the effects of roads on a range of elements related to biodiversity (specifically species composition and distribution) and land cover. Then, we analysed the reported underlying mechanisms associated with each road effect. This allowed us to identify key road impact pathways across the range of cases studied.
- To identify the gaps in literature on the effects of roads by (a) assessing the reliability of available information (specifically the source of reported mechanisms) and (b) identifying important links between roads and ecosystem elements that require further research. We also reviewed the options suggested for management of impacts in relation to the reported effects.

2. Methods

2.1. Search strategy and string

We used the ROSES systematic review framework [43] to develop and structure our search strategy. To address the key elements of our research, we defined the scope according to population, intervention, comparator, and outcome (PICO). We developed a separate search string for each PICO component and included all relevant descriptions and synonyms (see supplementary information [SI] table 1 for details on the executed search available online at stacks.iop.org/ERL/16/113001/mmedia). The following points describe each component within the context of our review.

- *Population/Subject:* describes the geographical area of interest. Here we listed all countries in SSA as well as all World Wildlife Fund (WWF) [44] biome types across the region.

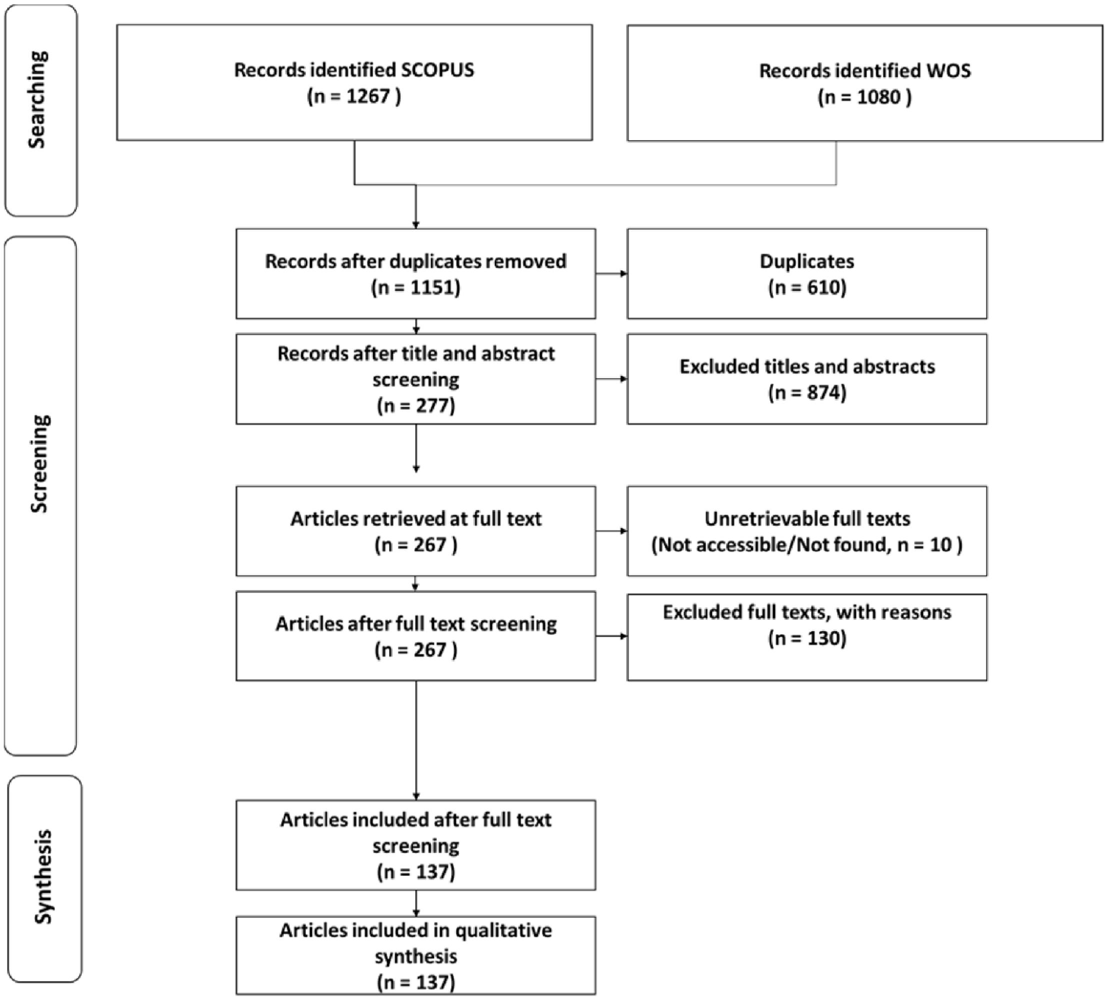

Figure 1. Flow diagram (after Haddaway *et al* [43]) showing the sequence of actions followed to accept articles. Scopus and Web of Science (WOS) databases were searched for peer-reviewed publications. The next step was the screening process. Titles and abstracts of publications were screened, following strict inclusion and exclusion criteria before being accepted for synthesis. Reproduced from [43]. CC BY 4.0.

- *Intervention*: describes the driving variable in which we were interested, in this case roads. We added variants of this term, such as highways, freeways and any other form of linear road infrastructure that describe a road but do not explicitly state this in the title or abstract.
- *Comparator*: describes the examination of comparisons, for instance comparing the effect of a road before and after construction. Few studies made comparisons between the effect of a road and no road. Hence, we excluded the comparator.
- *Outcome*: describes the expected and potential effect of roads on ecosystems. We developed a list of possible effects based on a large body of evidence that was mostly drawn from areas outside of SSA but were still applicable. We included synonyms, proxies and elements of the natural ecosystem.

2.2. Selection criteria

Using the PICO structure as a guideline, we created a list of inclusion and exclusion criteria to aid our selection process. For this search, we used both the Scopus and Web of Science databases. We did not review any grey literature or theses but focused only on peer-reviewed literature. Titles and abstracts of all detected articles were reviewed and assessed according to the inclusion and exclusion criteria presented in figure 1 and described below:

Abstracts reviewed had to meet the following criteria:

(a) the study described effects of a road or road-related variable on an impact related to an ecosystem element or biodiversity;
(b) the study area was in SSA; the effects of a road, highway, or freeway were quantified, and road-related variables such as distance to road, road density or road area were represented as independent variables in the study;
(c) the road-impact data source was primary or secondary. Primary refers to data generated from the study in question, while secondary data sources refer to data collection by credible

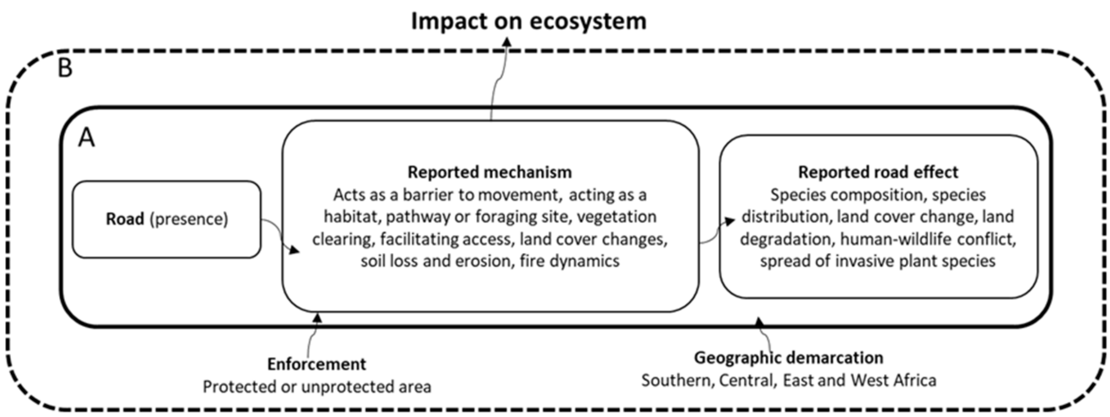

Figure 2. Depiction of the impact assessment process followed in this review. The focus of the review was to identify and understand the reported effects of roads and the underlying mechanisms by which roads interact with ecosystems. The information in the mechanism and road effect boxes show the relevant findings from this review (A). We investigated the role of enforcement and geographic demarcation on the existing relationships between roads and the factors affecting ecosystems (B). The overall impact of roads on ecosystems was not determined in this study.

external studies or sources. Authors must have also quantified any interaction between road presence and an ecosystem element in the study;
(d) the article was presented in English.

Abstracts meeting the inclusion criteria progressed to full text review. Articles were excluded if one or more of the following exclusion criteria were met:

(a) the road impact discussed in the study was purely proposed or predicted;
(b) the road impact was suggested or discussed but not investigated or studied (e.g. in a systematic review or perspective article);
(c) the impact of a road was derived from interviews only;
(d) the main study location was not in SSA, for example, global scale studies that did not isolate the impacts of roads in SSA countries or regions;
(e) the impact of a road could not be isolated or identified; one example of this scenario was when roads and buildings were classified as anthropogenic drivers, and we were not able to distinguish the road impact from the impact of the building; and
(f) the observed impact was between road traffic and any ecosystem element because the impact of traffic is highly variable with location, road type, and many other variables that lie outside the scope of this review.

2.3. Coding and analysis

We extracted information describing the effects of roads on various elements or facets of biodiversity and whole ecosystems. Below, we describe the data collection process used to examine the distribution of research across SSA, the effect of roads on various ecosystem elements, and the mechanisms through which roads affect these elements.

2.3.1. Distribution of research across SSA

To understand the spatiotemporal distribution of the reported effects, we extracted information on the study period, publication year, specific location of the study, the ecosystem type (using the WWF biome list [44]) in which the study was conducted, and whether the study was conducted inside a protected area. Thereafter, we mapped the distribution of information on the location of the main author, the inclusion of an African-based author, and the journal in which each article was published. We also analysed information related to the data-collection techniques and other input variables used in each study.

2.3.2. Effect of roads on ecosystem elements

To determine the effects of roads on ecosystems across SSA, we documented the impact pathway from road presence to the modification of an ecosystem element (figure 2(A)). Most studies investigated the effect of a road on more than a single ecosystem element, these were documented as separate, individual effects. In all cases, we used the road variable (road presence) as the independent factor potentially contributing to each reported effect. The assessment of the impact on entire ecosystems was beyond the scope of this review (figure 2(B)) as all papers focused on the interaction between a road and one or more specific ecosystem elements.

We collected information on the taxonomic group associated with each road effect, except in cases where an effect was associated only with natural land cover.We examined the effects of roads on various classified taxonomic groups and natural land covers. In addition, we were interested in the influence of protection status and geographic region on roads' direct effects on biodiversity (i.e. species composition and species distribution). Here we categorized reported effects on species abundance, and occasionally diversity and evenness as species composition and effects on species occurrence, avoidance, and attraction as species distribution. Where appropriate, we recorded the nature of each effect as either positive, negative, or none. Increases and decreases represented observed quantitative changes, for example an increase in species composition was positive, but a decrease was negative. We also extracted any available information that described a road effect zone, that is, the spatial area or distance extending outward from the road where the impact occurred [22].

2.3.3. Identifying the processes by which roads affect ecosystems

We extracted information on the underlying mechanisms through which roads affected ecosystems. We considered these mechanisms to be the processes that led to the reported effect. We then examined the evidence for each identified mechanism. These mechanisms were either speculative or evidence based. Speculative mechanisms were not quantified but rather discussed as a potential explanation for the observed effect. Evidence-based mechanisms were examined and quantified within studies. Several other reported effects had no known mechanism.

We then used a Sankey diagram to track the road impact pathway. This pathway described the link between each reported effect and its associated mechanism inside and outside of protected areas. For instance, roads in protected areas acted as barriers to movement (underlying mechanism), which reduced the distribution range of elephants in that area (effect).

2.3.4. Recommendations for management

Finally, we collated suggestions and recommendations within the studies for the management of road impacts. Based on the findings from our review and the suggestions provided by authors, we discuss options for managing effects of roads in SSA.

3. Results

3.1. Distribution of literature across SSA

There were 137 studies selected for this review (SI figure 2). More studies were conducted in Southern Africa (61), and South Africa was the country (37) with the highest number of study sites. Central Africa (38) had the second highest number, followed by East Africa (24) and West Africa (14) (figure 3). Although there were 137 studies conducted, 82 studies reported more than a single effect; across all studies 271 effects were reported (figure 3(A)). Studies conducted in Central Africa mainly reported on the effects of roads on species distribution range (25), species composition (53), and occasionally land use change (12). Studies from Southern Africa reported on interactions between roads and species composition (42), species distribution range (21), land degradation (13), and the spread of invasive plant species (11). Some studies from East Africa reported on the effects on species composition (19) and distribution (8). The studies from West Africa generally reported on the effects on land cover change (23). Reported effects were identified both inside (94) and outside (176) protected areas (figure 3(A)).

The mapping shows that there are a number of African-based authors investigating the role of roads in driving changes in ecosystems. Almost half (46%) of the lead authors were based in Africa, though the majority (59%) of these were in South Africa. Other African-based lead authors were mostly from Central Africa (SI figure 1).

The 137 selected articles were published between 1995 and 2019. The number of articles published, increased from 11 for the period 1995–2000 to 55 in 2016–2019. As shown in figure 4, the majority (63%) of all reported effects were from articles published after 2011. Since 1995, the effects of roads on species composition have been an ongoing focus. After 2011, there were several articles investigating the effects of roads on species distribution and land use changes. The interations between roads and invasive species were only reported in studies published after 2006 (figure 4).

Of the studies published after 2010, only about one-third (33%) used data that was collected in the period 2010–2019. In studies published from 2001 on, there was, on average, a 5 year interval between the data collection period and the year an article was published. We were only able to clearly identify data sources in 111 publications, the majority of which used field work (77). Thirty-two studies partly or only used remote sensing data, the use of which began to grow in popularity after 2011.

All the studies reviewed looked at multiple drivers of ecosystem change, where roads were only one of the drivers studied. We were able to collect information on specific drivers (other than roads) from 93 publications. Many studies focused on a combination of biophysical and socioeconomic (41) or only biophysical (31) drivers, while fewer looked at only socioeconomic drivers (21). There was little difference in the number of studies using either a combination of drivers or only natural drivers in each region. A similar number of studies used a combination of drivers (25) or only biophysical drivers (20) when investigating effects on species composition and distribution. Several other studies used either biophysical (5) or socio-economic drivers (8) to understand land cover change and land degradation. Common socio-economic drivers included the presence of and distance to settlements, population density, and distance to cities or towns.

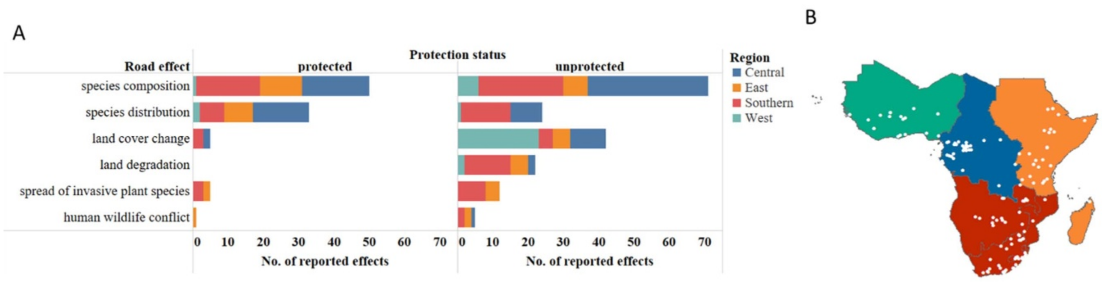

Figure 3. Frequency of reported effects (in protected and unprotected areas) from 137 peer-reviewed articles (A). Road effects refers to the ecosystem element impacted by the road. All known study sites (145) were mapped across SSA (B).

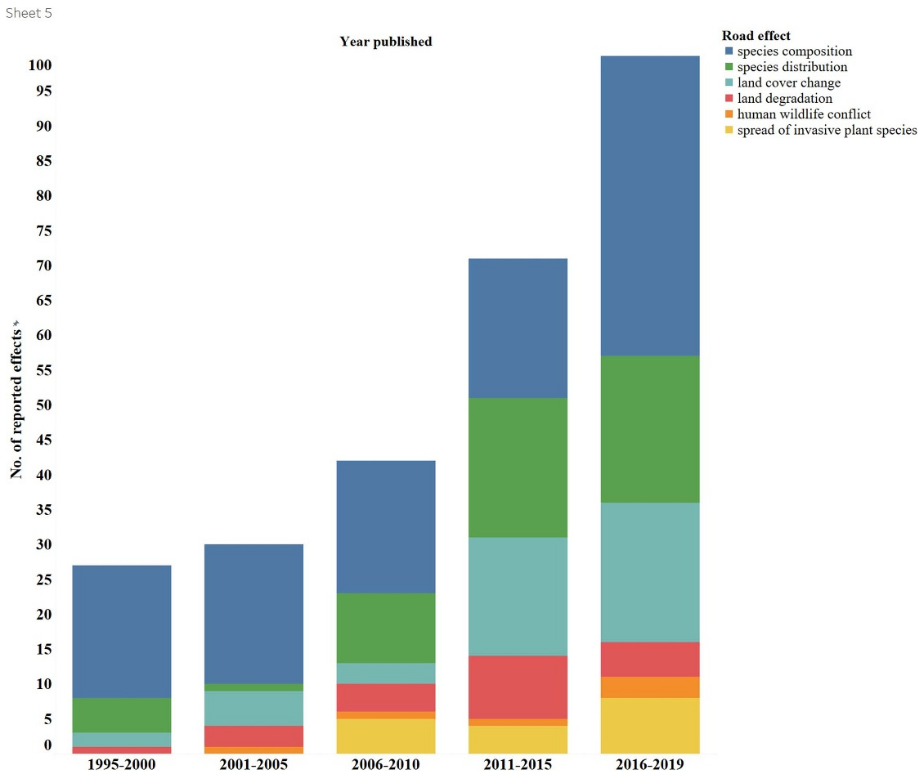

Figure 4. Reported road effects from all articles grouped according to the year each article was published and stacked by different main road effects.

3.2. Effects of roads on ecosystem elements

The reported effects of roads were either related to land cover (change in type or degradation) or biodiversity (impacts on species composition or distribution) (figure 5). Although authors sometimes discussed the effects of roads on the spread of invasive species, they rarely examined its cumulative impact on any ecosystem element. We found the effects on biodiversity were studied inside and outside protected areas while the effects on land cover were mainly from outside protected areas. Hence in the section below we examine only the reported effects on biodiversity, inside and outside protected areas in different regions.

Studies focused more on the effects of roads on species composition (121) than distribution (57) (figure 5). Inside protected areas, roads mainly increased or had no effect on species composition (31/50). Outside protected areas, roads were associated with both reduced (37) and increased (23) species composition. The effects on species distribution also varied with protection status. Inside protected areas, roads often limited species distribution (23/33). Outside protected areas, roads usually had no effect on species distribution (20/24).

In total, across SSA, the frequency of reported negative, no significant, or positive effects on biodiversity (species composition and distribution), were

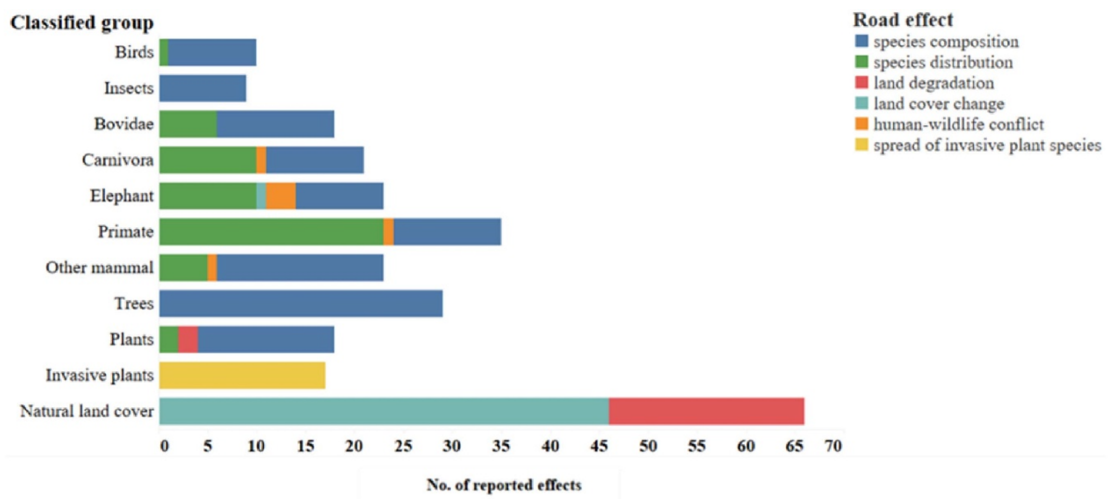

Figure 5. This graph is showing the number of reported effects in two dimensions: (i) the specific ecosystem element affected (classified taxonomic groups and natural land cover); (ii) the effect type (e.g. species composition or distribution, etc).

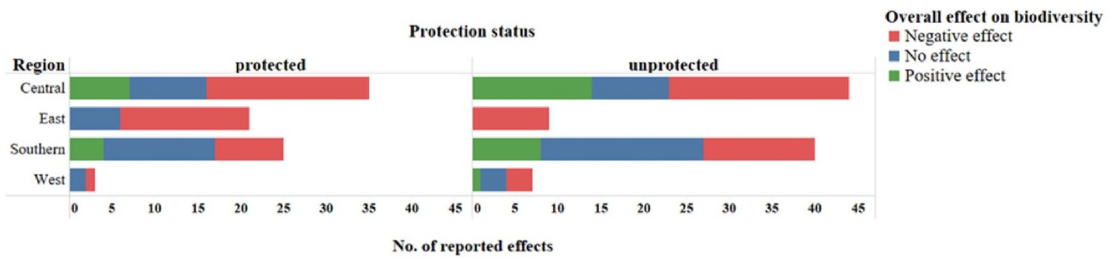

Figure 6. The total number of reported direct effects of roads on biodiversity (a combination of species composition, species distribution and, human-wildlife conflict) in protected and unprotected areas across SSA.

similar inside (51%, 36%, 13%) and outside protected (46%, 31%, 23%) areas (figure 6). Many studies reported negative effects both inside (19/35) and outside (21/44) protected areas in Central Africa. In East Africa, there were more reported effects for inside protected areas, the majority of which were negative (15/21). In Southern Africa, there were more reports of roads having no or a positive effect on biodiversity both inside (17/25) and outside (27/40) protected areas (figure 6). In terms of the effects on specific taxonomic groups, the effects on mammals were the most widely reported, mainly primates (35), elephants (24), carnivores (21), bovids (18) along with diverse other mammals (23). There were also several other reports of roads affecting indigenous plants (18) and trees (29).

Effects on primates were mainly studied in Central Africa (26) and occasionally in East Africa (4). There appeared to be little difference in the reported effects on primates inside and outside protected areas. Road presence, in both areas limited the distribution of chimpanzees (15) but not gorillas (8). Effects on elephants were also studied in Central Africa (12) and to a lesser extent East Africa (5). The effects on elephants varied inside protected areas, in some cases road presence limited elephant distribution (3) and reduced their composition (4) while in others, elephants were unaffected (5). Outside protected areas, effects on elephant distribution were mixed (5). The effects on carnivores were studied in Southern Africa (19). Inside protected areas, roads reportedly had no effect and occasionally a positive effect on carnivore composition (8). Outside protected areas, road presence had no influence on carnivore distribution (7). The effects on bovids were studied inside protected areas in Central (6), East (5) and Southern Africa (5). Roads reportedly limited bovid distribution (5) but had no significant effect on their composition (7). The effects of roads on the composition and distribution of all other mammals, both inside (8) and outside (14) protected areas were mixed.

Effects on birds were mostly studied outside protected areas in Southern Africa (8). In more cases (5), roads were associated with reduced bird composition. Studies from Southern Africa also examined how roads affected insect composition outside protected areas (8). Roads were associated with both increased and reduced insect composition. The effects on trees were studied in East (10) and Central Africa (14) and occasionally Southern Africa (5). In East Africa, roads were linked with reduced tree composition both inside (5) and outside (5) protected areas.

Figure 7. The road effect zone reported in studies, for main ecosystem elements.

In Central Africa, roads outside protected areas were associated with both reduced (14) and increased (7) tree composition. Effects on indigenous plant composition were mixed and usually studied outside protected areas (13) in Southern Africa (9).

Of the 271 effects identified, we were able to extract road effect zone information for 54 (figure 7). Occasionally, researchers reported that invasive species were present between 10 and 150 m (3) but absent beyond 1.5 km–50 km (2). The findings on mammal presence and absence were mixed. For instance, carnivores (4) were sighted within 1 km but not beyond 5 km from a road, while elephants (5) were usually sighted between 1 and 10 km from a road but not beyond the10 km zone. On the other hand, primates (8) were generally found away from roads (>7 km). The reports on bovid (8) distribution were mixed, with some studies finding them present and others absent within 1 km from a road. In terms of land use, agricultural activity (5) was reported from as little as 150 m but extended as far as 50 km from a road. Logging (6) reportedly occurred between 1 km and 5 km from a road, while increased urban cover (4) was reported in areas between 1 and 5 km from a road.

3.3. The processes by which roads affect ecosystems

3.3.1. Underlying mechanisms

Most reported effects (220) had an identified mechanism. Common mechanisms (SI figure 2) through which roads affected ecosystem elements included roads acting as both barriers to (28) and corridors for movement (15), as attractive habitats for species (25), through vegetation clearing (21), by providing access (89), or causing erosion and soil loss (24). While the mechanisms identified led to negative and occasionally positive effects on ecosystem elements, there were also examples where road presence had no significant effect on an element. For example, a study that compared the abundance of plants along roadsides and in adjacent habitats, found there was no significant difference in composition. In this case, road presence had no effect on plant abundance, perhaps because roadsides acted as habitats supporting their survival.

Mechanisms associated with each identified effect were either supported by empirical data and analysis (155), speculated (59), or not provided by authors (unknown) (55) (SI figure 2). Overall, mechanisms associated with negative effects on ecosystem elements (168) were largely evidence-based (117) while those having positive, or no effect (63) were more often speculated or unknown (102) (SI figure 2). Reports of roads supporting land cover changes were usually evidence-based (43). The effects of road induced access on species composition and distribution (36) were largely speculative (21). Reports of roads affecting biodiversity composition by acting as habitats (14) were mainly speculated (9). Reports of roads acting as habitats for invasive species (10) were almost always evidence based (7). There were also many evidence-based reports of roads affecting biodiversity composition through vegetation clearing (21) and by acting as barriers to movement (18). The reports of roads causing soil loss and erosion (20) were usually evidence based.

Road-induced access (for hunters, into natural habitats [28] and to markets [8]) was mainly reported in studies from Central (18) and East (10) Africa and rarely in Southern (3) or West (5) Africa. Others reported that access influenced logging, in Southern (7) and Central (6) Africa, urbanization in West (7) and East (2) Africa, and agricultural activity in (9) West and (5) East Africa. Studies looking into roads acting as barriers to movement were from Central, East and Southern Africa. There were reports of roads acting as habitats in Southern Africa (26) and, to a lesser extent, in all other regions (16). Vegetation clearing was reported in Central (9) and Southern Africa (10). Soil disturbance and erosion were reported in Southern (14) and East (5) Africa.

3.3.2. The road impact pathway

Of the identified mechanisms, the majority (8/9) were reported both inside and outside protected areas. In figure 8 we bring together earlier results to summarize the interactions between the effect mechanisms and the outcomes inside and outside protected areas.

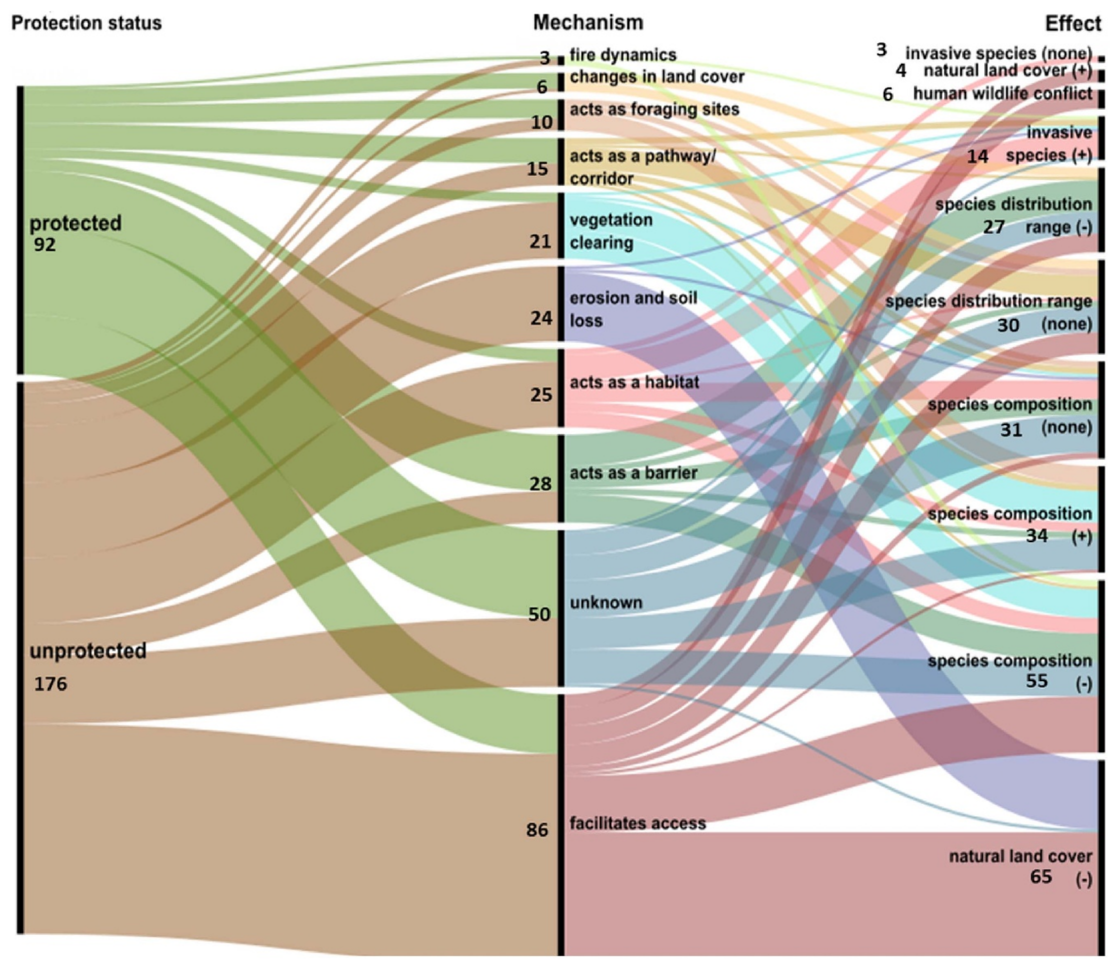

Figure 8. Sankey diagram illustrating the relationships between location of study site (protected or unprotected), identified mechanisms, and reported road effects. Each flow shows a unique road impact pathway; the thickness of each flow represents the frequency (values to the left of each category) at which each interaction was reported.

There were several reported effects, inside (28) and to a lesser extent outside (22) protected areas where the mechanisms causing these effects were unknown.

Of all the reported effects, 33% were attributed to road related access, the majority (76%) of which were identified outside protected areas. Authors found that by providing access to land and markets, roads had enabled agricultural expansion (17), urbanisation and increased rural settlement (9), and logging activity (18). As a result, roads had a significant influence on land cover changes in the region. Roads also supported hunting by facilitating access into natural habitats both inside and outside protected areas (36). Access for hunting mainly impacted larger animals (such as elephants and chimpanzees) by restricting their movement (25). Greater access also increased interaction between humans and elephants and humans and chimpanzees (8), which resulted in human-wildlife conflict outside protected areas (5).

There were more reports of roads acting as barriers by restricting the local movement of Studies reported that chimpanzees, and occasionally bovid and other mammals had avoided roads inside protected areas. Fewer studies reported on the effects of roads acting as barriers, on species composition (7), most of which were related to roadkill.

On the other hand, roads supported species in various ways. Animals were sometimes attracted to roads. This was because roadsides functioned as foraging sites (10), providing feeding resources (e.g. roadside herbaceous vegetation and roadkill) for mammals and occasionally birds; this mechanism was common both inside and outside protected areas. Roads also functioned as corridors that facilitated the movement of some animals (mainly carnivores) in both areas (15). When animals used roads as foraging sites and corridors, researchers found that overall, road presence had no effect on their local distribution. In some instances, there were reports of increased animal presence (a positive effect) in areas closer to roads. Outside protected areas, roadsides sometimes functioned as habitats, providing suitable conditions for growth and survival of some native plant and insect species (9). There were several other reports of roads supporting the spread of invasive plant species by acting as habitats (9).

Outside protected areas, road construction and maintenance resulted in vegetation clearing (18). Authors usually studied its effect on tree species in forested habitats. In general, clearing for logging roads had negative effects on tree composition but when roads were abandoned, there was evidence of regrowth of vegetation.

We also found evidence of roads increasing land degradation in its surroundings (24). This was due to road construction and presence causing soil disturbance and promoting gully erosion. This mechanism was only reported outside protected areas.

3.4. Recommendations for management

Most studies did not provide information or suggestions on actions and next steps for managing the effects of roads. Many studies (98) offered research recommendations (32%) or advised on management actions (40%) to address the state of ecosystem elements. Most research recommendations (77%) suggested a need for more research data as well as the importance of collecting monitoring data for management. Management suggestions were slightly more informative: common suggestions were (a) to take a more holistic management approach and include surrounding communities in decision making processes; (b) conduct integrated spatial planning when designing and constructing roads; and (c) to increase law enforcement to mitigate the effects of roads. Only a few authors proposed clear interventions and suggested that management develop strategies or initiatives to monitor activity and collect data. Vague recommendations were not included in the analyses.

4. Discussion and conclusions

We identified several important links between roads and (a) species composition and distribution, (b) the spread of invasive plant species, (c) land degradation and (d) land cover change (figure 3). Linking the effects with underlying mechanisms allowed us to identify key road impact pathways in SSA (figure 8). However, due to the uneven distribution of available information on road effects and the underlying mechanisms, our ability to distinguish whether these impact pathways might vary between taxonomic groups, geographic sub-regions and inside versus outside protected areas was limited. Moreover, only 57% of all reported effects were explained using evidence-based (as opposed to speculated) mechanisms. While both positive and negative effects on ecosystems were documented, we found more reliable information on how roads can negatively impact ecosystems; in contrast, there was less certainty around mechanisms that led to roads having no significant or a positive impact since many of these were either speculated or unknown. Despite this, most of the reported mechanisms are well known in the field of road ecology [10] and were most likely appropriate suggestions, albeit requiring evaluation with further empirical work.

4.1. Status and trends

The road effects identified (figure 3) were generally found during a wider field assessment of ecological status, which implies road ecology as a discrete field is not well-established in Africa, and that useful information on the ecological effects of roads can be expected outside of the subdiscipline of road ecology. However, there was a growing involvement of African-based researchers, as the proportion of studies with African authors increased from 56% in 1995–2005 to 74% in 2010–2019 (SI figure 1). Additionally, we found that the number of publications per 5 year period increased six-fold between 1995–1999 and 2015–2019 (figure 4). Our analysis also shows a geographical bias in the available literature, with just under half (45%) of all studies conducted in Southern Africa (figure 3), and especially South Africa. This relative dominance extends to biodiversity research in general and is most likely due to the long history of investment in research in Southern Africa [42].

Despite calls to examine the direct and indirect effects of roads at wider scales, such as the landscape level [14, 15, 17, 45], research to date has mostly focused on quantifying the impacts on individual species (figure 3). We found studies mostly focused on the abundant, charismatic, and easily identified species, such as elephants and chimpanzees (figure 5). Research on the role that roads play in determining land cover changes began to increase after 2011. We suspect this is largely due to increased use of open-source GIS and satellite remote sensing tools and techniques to generate landscape-scale ecological information. Nonetheless, as most of the articles that we reviewed focused on effects on wildlife distribution and composition, it was not surprising that field work was a major source of data for studies.

4.2. The road impact pathway

We bring together findings (figures 5, 6 and SI figure 2) to describe the ways by which roads interacted with ecosystem elements, to determine key road impact pathways in the SSA context. We found the outcomes of road-ecosystem interactions were influenced by the underlying mechanism (figure 8). Key mechanisms by which roads attracted and supported species include, through functioning as a foraging site, a pathway for movement, and as a habitat. In contrast, roads negatively impacted animals through acting as barriers to movement and facilitating access for hunters. The main mechanism by which roads affected land use was via accessibility, specifically access to previously inaccessible land, markets, cities, and economic opportunities. In several cases, studies speculated that observed patterns and changes were related to road access, but fewer studies provided evidence of this mechanism. Nevertheless, it was clear that major roads had a marked impact on the spatial patterns of land use.

Major roads also had a strong influence on the spatial patterns of urban growth in cities and towns across East and West Africa. Researchers identified a star shaped growth pattern, where urban cover increased along major roads that emanate from city centres. In SSA, this is a result of both planned and unplanned urban growth [46] and is usually attributed to rural-urban migration [42, 47]. Increases in urban cover can also trigger changes in land use patterns elsewhere. For instance, there was evidence of land abandonment in peri-urban areas that were further away (>5 km) from major roads [48] and land use transitions due emerging urban sprawl gulping up farmland communities [49]. Our understanding of roads in the rural context is limited, but it is likely that major road development will promote local economic activity [47] and transitions from farmland to more built environments [50].

Additionally, in West Africa, roads enabled cropland expansion, newly created agriculture plots, and transitions from shifting cultivation to more permanent agricultural practices [48, 51–54]. Roads, specifically paved ones [55] are expected to play an important role in agricultural expansion and intensification because they link farmers to markets and vice versa [55, 56]. In this way, roads act as indirect drivers because they incentivise agricultural activity. Other factors such as local demand, population growth, migration, and climate variability may affect agricultural expansion [37, 52]. The findings of this review also suggest that road-facilitated cropland expansion around wildlife habitats can increase human–wildlife interaction and thus conflict. This is because agricultural resources such as crops are known to attract some mammals (such as elephants and chimpanzees) and may even have a stronger influence on their distribution than wild food resources [57].

While some roads will have been legally constructed for a range of development purposes, including logging, they were often used by illegal loggers to access forests and woodlands. Informal trading of wood products has better prospects along roads [58] which might explain why areas close to roads, especially highways and main roads were depleted of standing tree biomass. An increased demand for illegal wood products may lead to a steady decline of timber species and an increase in less preferred or other exotic species [59–61]. Furthermore, as seen in other parts of the world (such as the Amazon) access may prompt the construction of illegal secondary roads [62, 63] and increase the rate and extent of logging. Given that a large proportion of SSA's remaining agroecologically suitable land falls within forest biomes [42], it is likely that with enough logging, transformation to agriculture can occur [51].

There was considerable evidence that proximity to roads is a major factor enabling poaching and hunting. Besides facilitating access for hunters, roads also provide market access and reduce transportation costs [35, 38], which may have sustained the trade of bushmeat and illegal wildlife trafficking. While those species closer to the road are targeted, hunting activity may stretch as far as 5 km from a road [28]. We found the intensity of a hunting threat varied with species and was dependent on its desirability. For instance, chimpanzees are consumed and sold in markets [35] while elephants are poached for their ivory [42] and are therefore more likely to be affected by road presence. Interestingly, the distribution of gorillas was less affected by road presence [57, 64, 65], presumably because they did not experience the same level of hunting pressure.

The findings of this review show that roads can act as movement barriers but suggests that animals may adapt by altering their behaviour in the short term. Many animals avoided crossing roads because they found it risky due to potential wildlife-vehicle collision. Surprisingly, studies on roadkill [66–69] were far fewer than those recording animal presence and crossing probability. We found the likelihood of a road being a barrier depended on several factors, including road type, road width, season, roadside vegetation, and canopy cover [41, 66, 67, 70]. More importantly, whether a road was a barrier depended on the species affected, suggesting species have different thresholds that may change with the factors mentioned above.

Roadsides and tarmac shoulders can be very productive (i.e. acting as foraging sites) and often attracted herbivores [57, 71]. Wild food resources (forest edge species and herbaceous vegetation along roads) had a strong influence on the distribution of some mammals, perhaps stronger than risk avoidance [57]. Other animals, such as carnivores preferred the use of low-activity roads because they facilitate easier movement, better visibility for hunting prey and roadkill to feed on. Other generalist species that mainly forage on the ground (such as the invasive Pied crow in Southern Africa) also benefitted from roadkill [69]. Although these findings suggest roads may support animals, these are probably short-term adaptations. It is widely known that roads can act as ecological traps that attract species and increase wildlife-vehicle collision [67, 72, 73].

Roadsides and verges sometimes functioned as habitats by providing suitable conditions for growth and survival of plant species [14, 74–76]. However, there was also evidence to suggest roads may indirectly threaten indigenous roadside plant populations. For instance, by disrupting the foraging patterns of birds, roads may adversely affect seed dispersal and pollination [77]. Roadside conditions also facilitated the spread of invasive plant species that are capable of colonizing and dominating an area [26, 78]. Whether roads act as a habitat for native or invasive plant populations can depend on the type of ecosystem, management of the surrounding area and road construction and maintenance methods [25, 26]. Roadside conditions and food resources also attracted other ground foraging species such as ants [79, 80]. Ants may have benefitted from available road kills and a favourable microclimate along verges. Given these findings on ants and that they are bio-indicators, road verges may play an important role in conservation, particularly in highly modified landscapes [10, 79].

Linear clearing was another way in which roads impacted ecosystems. The effects of clearing were noticeable in forests. Studies showed that clearing for logging roads can result in reduced standing tree biomass, loss of herb cover as well as destruction of the overhead tree canopy [81–83]. However, the abandonment of roads, specifically those enabling logging in forests, can result in regrowth of trees and other vegetation. Regeneration, over the long term (e.g. 30 years since abandonment) may not result in similar levels of vegetation but can assist with canopy closure and regrowth of herb cover [82].

Finally, during and after its construction, roads had increased the risk of land degradation in their surroundings [84–89]. Roads are known to alter the natural drainage network during construction and modify the processes that regulate water storage and distribution on landscapes. In many instances this resulted in increased overland flow which leads to higher run-off along roads [85, 90, 91] and eventually soil loss and erosion. It is likely that road runoff may be contaminated with chemicals which leads to pollution in surrounding areas [14]. Generally, the larger the road surface area the more likely there will be increased soil loss due to its increased runoff and therefore its erosive power [14]. In tropical regions, that receive heavy rainfall, this can cause flooding [63].

4.3. The way forward

4.3.1. Managing the impacts of roads

Many of the suggestions for management of the reported effects are well known and are already covered in road ecology research (see the relevant chapters in Handbook for Road Ecology [72, 92–95]). Other complex multidimensional road effects (such as illegal hunting and harvesting) still require more research, and it is therefore difficult to explore management options at this stage. Nevertheless, the reports of illegal hunting and harvesting and barrier effects (figure 8) highlight the challenges associated with roads inside protected areas. Based on our findings (figure 6), protection alone, may not be effective at mitigating the negative impacts of roads. While new road development in and around protected areas across SSA is problematic, they may pose the greatest risks in Central Africa. It is likely that resource constraints, civil unrest and potentially ineffective management influences the ways in which roads affect species inside protected areas in Central Africa.

Mitigating and managing the effects of future road development in SSA, will require researchers and environmental assessment practitioners to predict where interactions will happen and whether it is likely to affect ecosystem functionality. Information on the road effect zone can be useful when estimating the potential effects of future road development. Planners and practitioners can use road effect zone estimates to determine the extent of area that may be affected by existing and future roads [10]. The inconsistencies in reported road effect zones for the same species (figure 7) highlight the importance of understanding the context of an effect. Based on our results and the literature, we find the scope of an effect can be influenced by the size and quality of the road; the presence or proximity to natural resources, current and proposed protected areas, and existing natural habitats; the likelihood of further development around the road; the proximity to other roads or road networks; the proximity to markets and towns; and the topography of an area.

For future road development, sustainable infrastructure design and construction require collaboration among road agencies, government, researchers, and other relevant stakeholders. The recent edition of the Handbook of Road Ecology is a good starting point for researchers, practitioners and policy makers. It provides valuable insight into the ways in which we can assess the impacts of roads, mitigate their negative impacts, and improve and implement eco-friendly road design strategies [96–98]. As suggested, the impacts of roads can be minimized if there is intervention at the planning and design phase of road infrastructure [96–99].

4.3.2. Research opportunities

There are some noteworthy lacunae in this review which suggest areas for further research. First, we were unable to distinguish road type and size and it is likely that these influence the mechanisms and effects of a road [23]. Second, the frequency of reported effects was highly variable within and between taxa, geographic sub-regions and inside and outside protected areas, which made it difficult to assess its influence on road impact pathways. Third, a large majority of the findings related to species composition and distribution were derived from short term studies, hence these impact pathways may change over the long term. Finally, in some cases, we found it difficult to unpack underlying mechanism(s) that were speculated by authors (SI figure 2), as it involved thoroughly examining the authors explanation for the observed road effect. Therefore, we acknowledge that there may have been bias in our interpretation and thus categorising of reported mechanisms.

We found: (a) that the existing peer-reviewed literature was unable to provide sufficient insight into the effects on small mammals, insects, birds, reptiles and amphibians; (b) the cumulative impacts of reported interactions between roads and individual animals, on animal populations and ecological communities; (c) the cumulative effects of roads on biodiversity, specifically through land degradation, logging, agricultural expansion, and urbanization; (d) the effects of roads on ecological processes (such as pollination or fire); (e) the effects of roads on land degradation and human wildlife conflict in East and West Africa; and (f) the effects of roads on land cover change in Southern and East Africa. Given their role in altering species distribution and land use patterns, roads should be studied as a driver of change in biodiversity and land cover predictions. Furthermore, the impacts of future road development may extend far beyond its immediate area and thus overlap with areas designated as suitable for conservation under projected climate conditions. Therefore, it is critical that we investigate whether biodiversity refugia (areas suitable for conservation), in a changing climate, are threatened by future road development plans across SSA.

This review also highlights the importance of understanding how road-ecosystem impact pathways might vary under different biophysical and socio-economic contexts. Ideally, future research should be interdisciplinary and be able to inform and guide initiatives and policy that seek to address socio-economic development. It is important for there to be a balance of perspectives as ecological effects of roads can be related to their use that is centred around increasing trade and improving economic development. Natural scientists often report that roads are generally favored by economists and international donors and funders, but they view roads as detrimental due to their impact on the natural habitats [23]. Although the goals of natural scientists and economists should be similar, there appears to be much debate and disagreement between them. Achieving a balance of both environmental and development needs is a challenge that SSA had not fully addressed.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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