Status of Road Ecology Research in Africa: Do We Understand the Impacts of Roads, and How to Successfully Mitigate Them?

Wendy Collinson[1]*, Harriet Davies-Mostert[1,2], Lizanne Roxburgh[1] and Rodney van der Ree[3,4]

[1] Endangered Wildlife Trust, Johannesburg, South Africa, [2] Eugène Marais Chair of Wildlife Management, Mammal Research Institute, University of Pretoria, Pretoria, South Africa, [3] Ecology and Infrastructure International, Wantirna, VIC, Australia, [4] School of BioSciences, The University of Melbourne, Melbourne, VIC, Australia

Across Africa, transport infrastructure, including roads, is being built in over 30 planned development corridors that are likely to have major impacts on remaining natural habitats and associated biodiversity. Linked to this is the projected increase in human population size, which is predicted to grow by 1.3 billion people by 2050. Road ecology is the study of the ecological effects (both positive and negative) of roads and traffic but is perceived to be under-researched in Africa. In this context, we undertook a systematic review of road ecology research in Africa to understand the geographic and taxonomic scope of work undertaken to date, as well as recommendations for reducing the impacts of roads. We discovered 210 road ecology publications from Africa (published between 1954 and 2016), with most publications from the more affluent and politically stable regions (e.g., southern and East Africa). We found more publications than expected, with relevant research concealed within studies whose primary focus was on other topics. Most publications (1) focused on single species, and in particular on mammals (where chimpanzees and forest elephants were most studied); (2) were from southern Africa; and 3) were conducted in the grassland and savannah biome and the tropical and subtropical forest biome. Most publications examined the direct impacts of roads, in particular wildlife-vehicle collisions. Only one-third of the publications provided some form of recommendation for intervention to reduce or mitigate the impacts of roads, based on evidence from the publication. Most recommended interventions related to ecosystem or natural process recreation, as well as site and area stewardship. Gaps and future directions for research include rigorous testing of measures to mitigate the impacts of roads, inclusion of traffic monitoring in studies, understanding the impacts of upgrading roads, and exploring livelihood, economic and moral incentives and education and training as potential interventions for reducing the impacts of roads. Our review has highlighted the need for accelerating the study of the impacts of roads on natural habitats and biodiversity, in light of planned large-scale infrastructure development, and especially the study of appropriate mitigation measures that can be rigorously assessed and implemented before and during construction and upgrading of roads in Africa.

Keywords: Africa, conservation actions, linear infrastructure, road ecology, systematic review

INTRODUCTION

Roads are a critical element of human economic development and society, and global rates of road construction will likely rise for the foreseeable future, particularly in Africa, Asia and South America (Dulac, 2013; Laurance et al., 2014a). Roads and traffic have numerous, diverse—and mostly negative—consequences for biodiversity and ecosystem functioning. These impacts include the destruction and degradation of habitat (Laurance et al., 2015a; Ware et al., 2015), fragmentation of wildlife populations and their dynamics (Forman and Alexander, 1998; Ascensão et al., 2016; Chen and Koprowski, 2016), direct impacts through collisions with wildlife (Collinson et al., 2014; Seo et al., 2015; Son et al., 2016), and secondary impacts through increased access by people to previously unattainable natural resources (Wilkie et al., 2000; Vanthomme et al., 2013; Laurance et al., 2014b). The science of road ecology is well-developed in North America, Europe and Australia (Van Der Ree et al., 2015; Bennett, 2017), but is in its infancy in Africa (Bennett, 2017).

Across Africa, much of the major transport infrastructure is being built as part of "development corridors" (Laurance et al., 2014b, 2015a), comprising networks of roads, railways, pipelines, and ports, that facilitate the movement of people and commodities. There are over 30 development corridors planned across Africa, spanning over 53,000 km in length, and potentially affecting protected areas with high conservation value (Laurance et al., 2015b; Sloan et al., 2017). For instance, the proposed Cross River Calabar-Ikom-Kastina Ala Superhighway in Nigeria will effectively bisect some of Nigeria's last remaining intact forests (Mahmoud et al., 2017), and a proposed road to the gold fields near Lake Victoria in Tanzania could bisect the Serengeti National Park and disrupt one of the world's greatest remaining migrations of terrestrial wildlife (Haas, 2011). That these developments are being considered within areas of such high conservation and cultural value reflects a broader, concerning trend across Africa as a whole, whereby natural-resource extraction and related transportation-infrastructure development are often seen as the priority land-use, regardless of other factors (Mahmoud et al., 2017). Successful movement of individual organisms is critical to a species' survival and facilitating these movements by promoting ecological connectivity has become a central theme in ecology and conservation (LaPoint et al., 2015).

In this context, we systematically reviewed the scale, scope, and geographic extent of road ecology research in Africa to quantify the current knowledge and identify gaps and priorities for future research, management and policy formulation.

MATERIALS AND METHODS

Study Area and History

With 1.3 billion people (United Nations Statistics Division, 2017), Africa accounts for ~17% of the world's human population, making it the second largest and second most-populous continent (behind Asia in both categories). More than half of the anticipated growth in global population of ~2.2 billion people by 2050 (United Nations Statistics Division, 2017), is expected to occur in Africa, with a projected increase of 1.3 billion people (United Nations Statistics Division, 2017). With 41% of sub-Saharan Africans living in extreme poverty (United Nations Statistics Division, 2017; Oluwatayo and Ojo, 2018), this is coming at a time that the Sustainable Development Goals (SDGs) are gaining global traction, with economic growth and poverty reduction taking centre stage in most global policy discourse.

Driven largely by their abundant natural resources, several African economies are among the world's fastest growing as of 2014 (Taylor, 2014), and this is reflected in expansion plans for road, rail and energy transmission lines, with high concentrations of such projects slated to occur in environmentally sensitive areas (The African Development Bank, the African Union and the United Nations Economic Commission for Africa, 2016). The Programme for Infrastructure Development in Africa (PIDA; The African Development Bank Group, 2010), which was launched in 2010, Agenda 2063 (launched in 2015; African Union Commission, 2015), and a joint Memorandum of Understanding (MoU) signed by the World Bank, the Fédération Internationale de l'Automobile (FIA), and the International Transport Forum (ITF) in 2018 (World Bank, 2018a), all provide specific frameworks and funds to improve and support Africa's infrastructure networks and services over the next 50 years. China alone is currently investing ~US$100 billion annually in Africa for extractive mineral industries and associated transportation and energy infrastructure (Edwards et al., 2014), and while Agenda 2063 recognises that there will be "environmental challenges" associated with growth, there is little evidence in place to plan or implement mitigation of these impacts (Politzer, 2008; Laurance and Arrea, 2017).

Literature Search Methodology

We undertook a systematic literature search to investigate the scale, scope and geographic extent of road ecology research in Africa. Three searches were carried out by topic via the "sci-expandable" collection of journals in the ISI Web of Science Database (accessed 18 November 2015, 16 November 2016, and 29 April 2017). We used a formulaic search equation (e.g., = statutory region AND infrastructure type AND ecology impact or intervention), where "statutory region" referred to Africa or any official country in Africa; "infrastructure type" was road, rail, railway, train, vehicle, or transport; and ecological impact or mitigation was ecology, environment, barrier, roadkill, road-kill, wildlife vehicle collision, WVC, wildlife, biodiversity, fragmentation, road effect zone, or mitigation. We reviewed publications that included the most recent developments that were related to some aspect of roads, either solely, or in combination with other linear infrastructure. Publications whose sole focus was other linear infrastructure (e.g., rail or power lines) were excluded.

We elected to include only peer-reviewed papers, post-graduate university theses, conference proceedings, book chapters and reports, all written in English. We first removed duplicate records of those accessed on 18 November 2015, and then vetted the remaining publications ($n = 4,257$) for relevance based on title, abstract and key words, resulting in 150 relevant publications, relating to roads. These were divided equally

amongst the four authors for review. We also each reviewed four publications assigned to other co-authors (i.e., a total of 16) to ensure consistency in the interpretation of the study details.

We reviewed the citations in each of the 150 publications to identify additional publications that met our search criteria. Secondary publications with keywords such as "anthropogenic," "human-wildlife conflict," "vehicles," and "traffic" were also included, as it was probable, based on our experience with the first literature search process, that they may be related to roads or traffic. We excluded publications about "deforestation," "mining" and "spatial organisation of wildlife" unless their title also specifically included words to suggest some aspect of linear-infrastructure-development that may have been an explanatory variable. This process revealed a further 32 publications (from a total of 231; accessed 16 November 2016). We undertook a final search to account for literature published in 2016 (accessed 29 April 2017), with 28 publications out of a possible 1,356 deemed relevant, bringing the total final database to 237 publications. Of these, we excluded 27 from the final review, either because we could not locate a physical or electronic copy of the publication, or because the citation was incorrect. In such cases, we attempted to contact the primary author and obtain the publication directly from them, all without success (**Supplementary Material 1**).

We categorised the remaining 210 against criteria to describe the scope, scale and geographic extent of road ecology research in Africa (**Supplementary Material 2**). This included the country and geographic region of study, species and ecosystem(s) of focus, type of linear infrastructure, study design and type of impact, and whether they examined specific interventions aimed at mitigating impacts. Ten publications had a global or continental focus and were excluded from this analysis. The remaining 200 publications were classified according to the biome in which they occurred (Olson et al., 2001) (**Figure 4**). The biome of each study was assigned using that given by the author, or if absent, based on the location of the study.

We examined which variables could be related to the number of publications from each country. We hypothesised that the road density [in km of road/100 km^2, calculated using the Global Roads Open Access Data Set; CIESIN (Center for International Earth Science Information Network, Columbia University), and ITOS (Information Technology Outreach Services, University of Georgia), 2013] in that country or the Human Development Index (HDI; UNDP, 2018) or the Gross Domestic Product per capita (GDP in purchasing power parity; World Bank, 2018b) (**Figure 4**) could predict the number of publications produced per country. GDP and the HDI were highly correlated variables (Kendall's rank correlation $z = 7.00$, $p < 0.001$). Therefore, we excluded GDP from the analysis. To test for a relationship between the number of publications (corrected for population size, World Bank 2017) and HDI or road density, we fitted a negative binomial regression to the data, as the variance was significantly larger than the mean.

Publications that provided management recommendations that were based on evidence produced during the study were categorised using The Open Standards Conservation Actions Classification v 2.0 (CMP: Conservation Measures Partnership, 2016a,b). This is a standard classification of the conservation actions that managers can take to counter direct threats and was jointly developed by the International Union for Conservation of Nature (IUCN) and the Conservation Measures Partnership. The CMP provides systematic guidance about planning, implementing, and monitoring conservation initiatives to understand what works, what does not work, and why, and ultimately adapt and improve conservation efforts. In the context of our review, it served as a tool to measure the recommendations of each publication, based on evidence produced during the study, and highlight critical knowledge gaps. The classification consists of four hierarchical levels of action, with level 0 being the broadest overarching level with three categories, and level 3 containing the most detail (**Supplementary Material 3**).

Once classified, we assessed each recommendation against seven categories based on the Quality of Evidence (Salafsky et al., 2002), allowing for comparison across studies through quality control criteria. We recorded the categorisation results in a simple database to identify any trends (**Supplementary Material 2**).

We used R 3.5.0 (R Core Team, 2018), with the MASS, ggplot2, and ggpubr packages, for statistical analyses.

RESULTS

Study Type

Of the 210 publications, most focused on gathering empirical field data (166 or 79%). Of the remaining 21%, 14 were reviews of published literature, 13 presented conceptual ideas, and the remaining 17 were a combination of the three study types.

Publication Type

Most publications were from peer-reviewed journals (88.6%), followed by theses (5.7%), book chapters (4.3%), reports to government agencies (1%) and conference proceedings (0.5%). The 185 peer-reviewed publications were published in 95 different journals, of which 12 were specific to Africa. The most frequent source journals were *African Journal of Ecology* ($n = 12$), *Biodiversity and Conservation* ($n = 11$), *PloS One* ($n = 10$), *Ostrich—Journal of African Ornithology* ($n = 9$), and *Ecology* ($n = 7$).

Of the 12 theses, most were from a Bachelor of Science (Honours) degree ($n = 7$), followed by Master of Science or Philosophy ($n = 2$) and a Doctorate ($n = 3$). Most theses were undertaken at African universities, with nine from South Africa and one from Tanzania. Two theses came from universities outside of Africa (Norway and the United States). We found nine chapters from three different books, with the *Handbook of Road Ecology* (Van Der Ree et al., 2015) containing seven of the nine chapters. The three reports were from two countries, South Africa ($n = 2$) and Tanzania ($n = 1$), whilst the conference proceedings were from a conference in the Czech Republic in 2016 regarding photogrammetry, remote sensing and spatial information sciences.

Temporal Patterns

Publications were published between 1954 and 2016, with 169 published in the past decade (2006–2016), and just over half
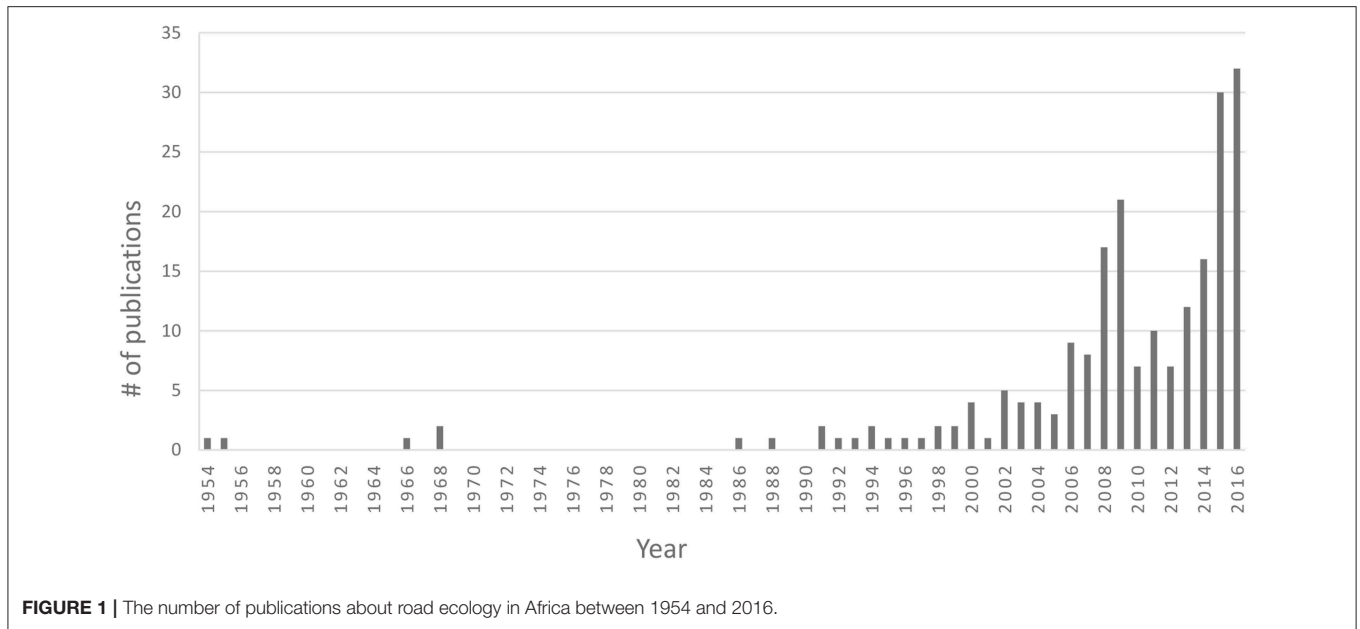
FIGURE 1 | The number of publications about road ecology in Africa between 1954 and 2016.
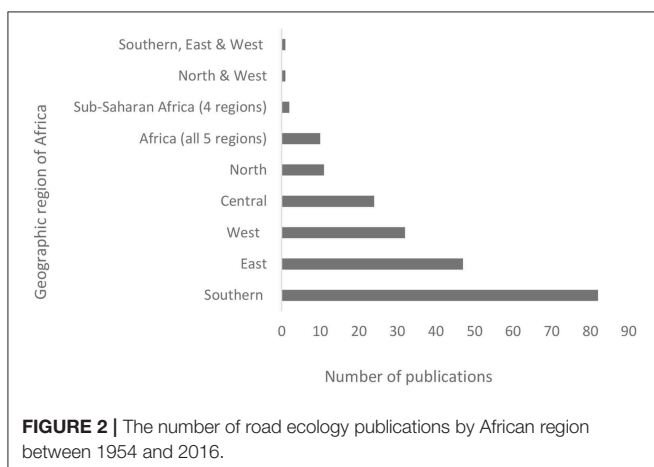

FIGURE 2 | The number of road ecology publications by African region between 1954 and 2016.

($n = 114$) published in the past 6 years (2010–2016; **Figure 1**). Only 20 (9.5%) publications were published over the 45-year period between 1954 and 1999.

Spatial Patterns in Published Road Ecology Research

Almost all publications ($n = 196$) were conducted entirely in one of the five sub-regions of Africa (**Supplementary Material 4**), whilst 14 publications were more generic and covered Africa as a whole (4.8%; **Figure 2**). Southern Africa was the most studied region (37.1%), followed by East Africa (24.2%), West Africa (18.8%) and Central Africa (14.8%). North Africa was the least represented of all the regions in Africa, with just 5.1% of the publications. Most studies ($n = 173$; 82.4%) were conducted in only one country, although two studies spanned seven African countries.

Approximately two-thirds (**Figure 3**; **Supplementary Material 4**) of the publications were conducted in just seven countries, namely South Africa ($n = 66$), Tanzania ($n = 21$), Cameroon ($n = 17$), Gabon and Kenya ($n = 16$ each), - Democratic Republic of Congo ($n = 15$), and Central African Republic ($n = 14$).

The earliest publications were conducted in Zimbabwe in the 1950s (**Supplementary Material 5**), with little further research anywhere in Africa being undertaken until the 1980s (again in southern Africa). It was only in the late 1990s that publications in the other geographic regions were published (**Supplementary Material 5**).
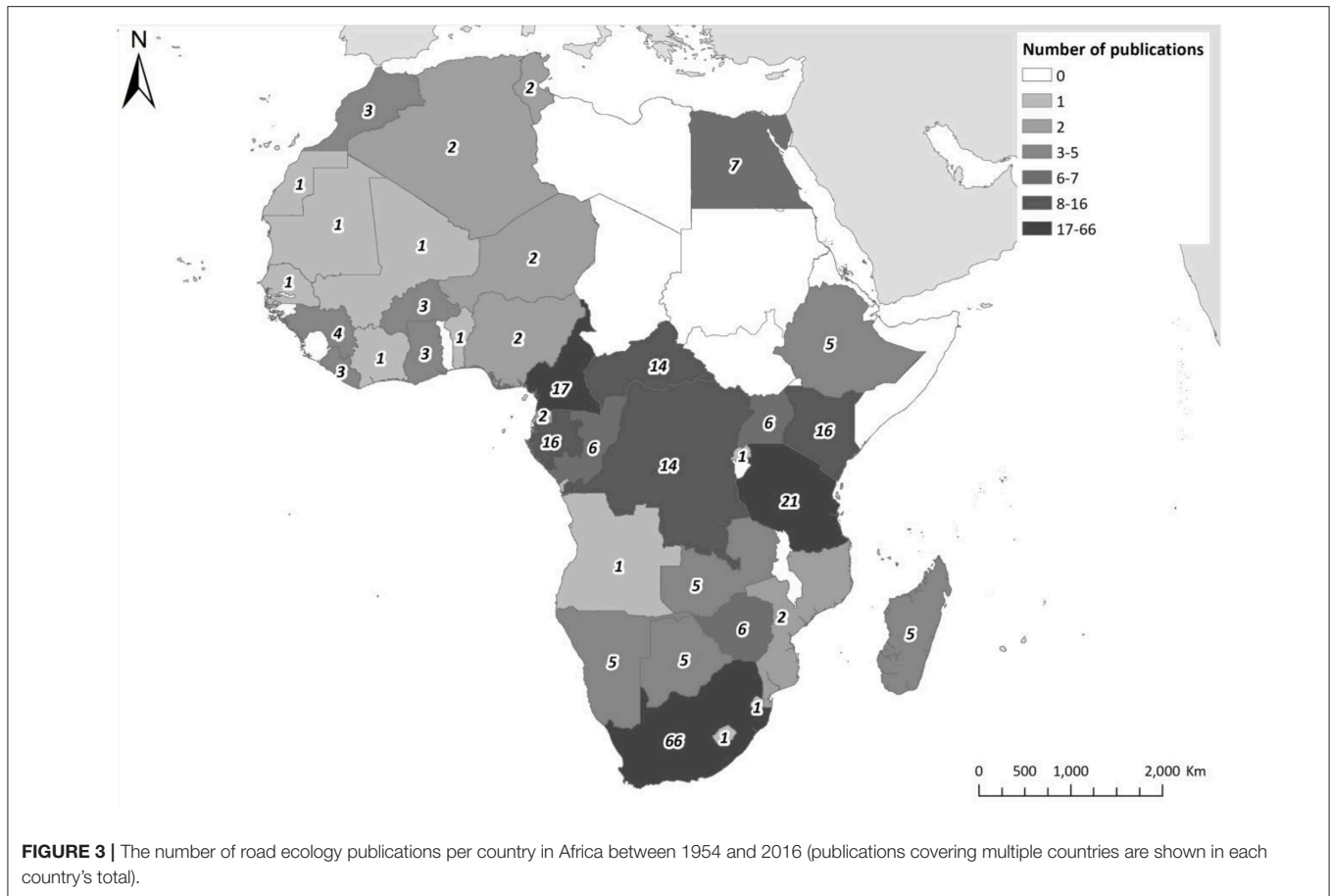
We found that there was no relationship between the number of publications per country and road density ($p = 0.76$), but that countries with a higher HDI had published a larger number of studies ($p = 0.01$; **Figure 4**).

Biome

Of the 200 publications that we could assign to a biome (i.e., that were not continent-wide studies), 21 covered two biomes, while seven covered three biomes. The remaining 172 publications covered a single biome.

Most publications were conducted in tropical and subtropical grasslands, savannas and shrublands (**Table 1**). This biome is the largest in Africa, covering ~14 million km^2. Although 35 publications were conducted within the deserts and xeric shrublands biome, relative to its total area, this was the least studied biome, with only 3.58 publications per million km^2 (**Table 1**).

Tropical and Subtropical Grasslands and Savannas, and Moist Broadleaf Forests were relatively more studied in relation to their road density than Mediterranean, Dry Broadleaf and Conifer Forests, and Montane Grasslands (**Figure 5**).

FIGURE 3 | The number of road ecology publications per country in Africa between 1954 and 2016 (publications covering multiple countries are shown in each country's total).

Dominant Land-Use

Most publications were from rural areas, which we defined as including natural areas and agricultural landscapes ($n = 144$; 68.6%), with 33 (15.2%) being undertaken in both rural and urban areas. Just 10 publications were from urban areas (4.8%), with land-use information not provided for the remaining 14 (6.7%). Furthermore, our initial search revealed that studies undertaken in urban areas were more likely to consider human wellbeing rather than the environment *per se.*

Just under half of the publications were from outside of protected areas (42.9%), followed by inside of protected areas (32.4%) or a combination of both (16.7%), with the remaining 8.1% unspecified. The estimated percentage of terrestrial protected areas in sub-Saharan Africa is 16.43% (World Bank, 2018b). Thus, the percentage of road ecology studies that were conducted inside protected areas is significantly higher, relative to land area than outside (Chi-squared single variable goodness of fit text, $\chi^2 = 81.5$, $p < 0.01$).

Most publications from within protected areas were undertaken in East Africa (38.4%), followed by southern Africa (34.2%), West Africa (15.1%), Central Africa (9.6%), and North Africa (1.4%). The remaining 1.4% accounted for generic studies encompassing the entire continent.

Ecological Focus of Study

Of the 210 publications, 60.5% focused on animals (vertebrates and invertebrates), followed by ecosystems (21.0%), plants (16.7%), and a combination of animals and plants (1.0%). Most animal publications were conducted on vertebrates ($n = 116$) with five publications on invertebrates and four on a combination of the two (**Supplementary Material 6**). Six publications focused on a combination of animals and plants with 35 publications focusing solely on plants. The remaining 44 publications focused on ecosystems, of which land-use change was the most studied topic ($n = 21$) (**Figure 6**).

More publications focused on individual species ($n = 112$) than multiple species ($n = 53$) for both the animal and plant Kingdoms. Mammals were the most studied terrestrial ($n = 43$) vertebrate group ($n = 98$), while amphibians were the least studied ($n = 1$) (**Supplementary Material 6**).

Most plant-focused publications centered on indigenous forest (both individual-species and communities; $n = 16$), with most being in Central Africa ($n = 11$), followed by alien and invasive plants ($n = 10$), with the remaining nine focusing on general plant communities, such as grasses (Rahlao et al., 2010) and roadside vegetation cover (O'Farrell and Milton, 2006).

We found that the chimpanzee (*Pan troglodytes veru; n = 10*) was the single most studied species, followed by the Forest
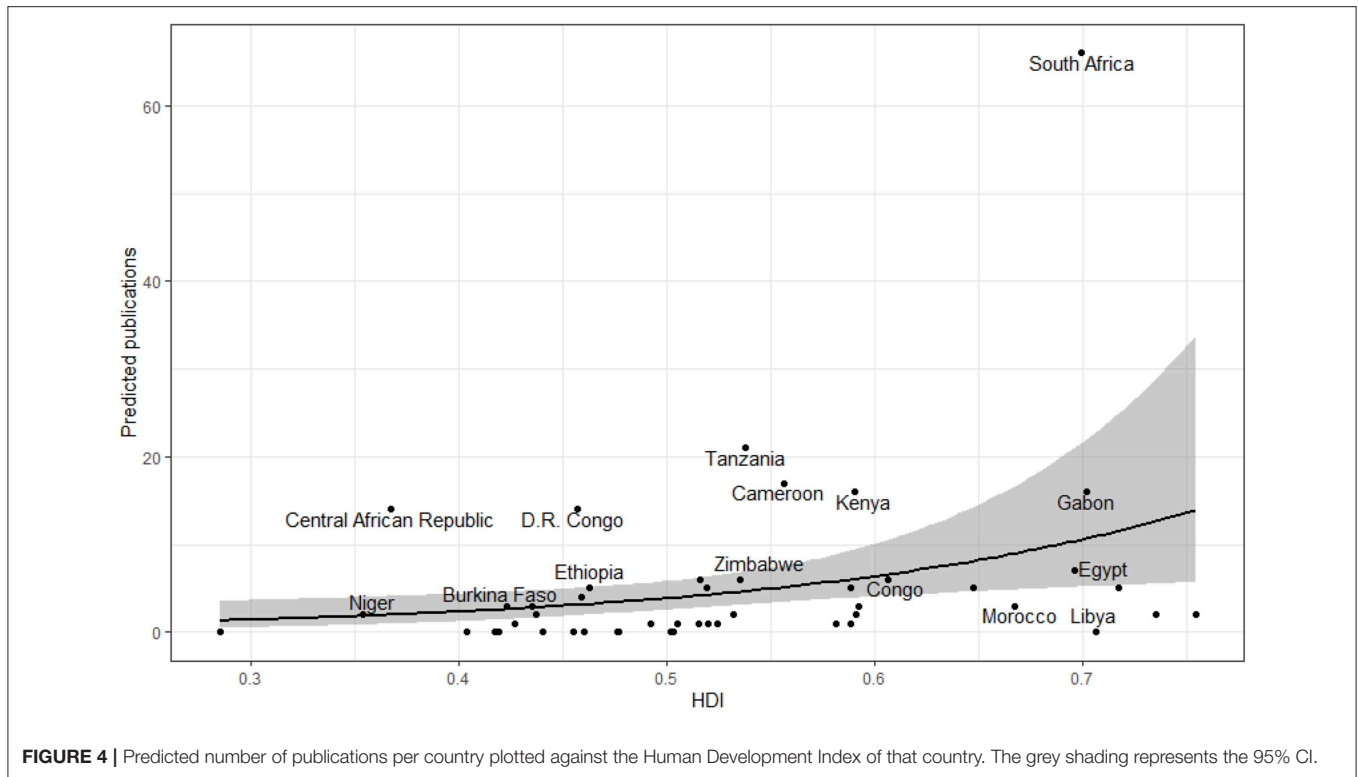
FIGURE 4 | Predicted number of publications per country plotted against the Human Development Index of that country. The grey shading represents the 95% CI.

TABLE 1 | Distribution of road ecology publications in the 10 biomes within Africa.

Biome	Biome area in km²	Total number of publications	Rank of biome area	Rank of the number of publications	Number of publications/million km²
Tropical and subtropical grasslands, Savannas and Shrublands	13,927,538	84	1	1	6.03
Deserts and xeric shrublands	9,785,552	35	2	3	3.58
Tropical and subtropical moist broadleaf forests	3,465,811	72	3	2	20.77
Montane grasslands and shrublands	866,317	16	4	4	18.47
Mediterranean forests, woodlands and scrub	845 914	16	5	4	18.91
Flooded grasslands and Savannas	560,903	5	6	6	8.91
Tropical and subtropical dry broadleaf forests	194,208	3	7	7	15.45
Inland water	154,944	1	8	9	6.45
Mangroves/estuaries	76,412	2	9	8	26.17*
Temperate conifer forests	23,091	1	10	10	43.31*

*The sizes of these biomes are small relative to the other biomes, and only one to two studies in each make them appear overstudied relative to other biomes.

Elephant (*Loxodonta africana cyclotis*; $n = 8$) (**Table 2**), both of which are resident in Central African countries.

Type of Infrastructure

Most publications ($n = 173$) focused solely on the impact of roads only, while 37 also included the impacts of other types of linear infrastructure. These included roads and fencing ($n = 18$), roads and rail ($n = 8$), roads and power lines ($n = 6$) and roads and pipelines ($n = 5$).

Ninety-two of the publications did not specify the purpose of the road, while 54 stated it was for general (i.e., day-to-day) usage, followed by primarily industrial (e.g., mining and logging) ($n = 25$), tourism ($n = 19$), and agricultural ($n = 2$) uses. Three publications stated that the road was also used by pedestrians. The remaining 15 publications were a combination of the three types: general and industrial ($n = 8$), general, industrial and tourism ($n = 4$), industrial and tourism ($n = 2$), and general and tourism ($n = 1$).

Only 39% of the publications provided data about the road surface, with 11.9% of these focussing solely on unpaved roads, 10.5% focussing on paved roads, and 15.2% conducted on a combination of the two surfaces. The remaining 1.4%
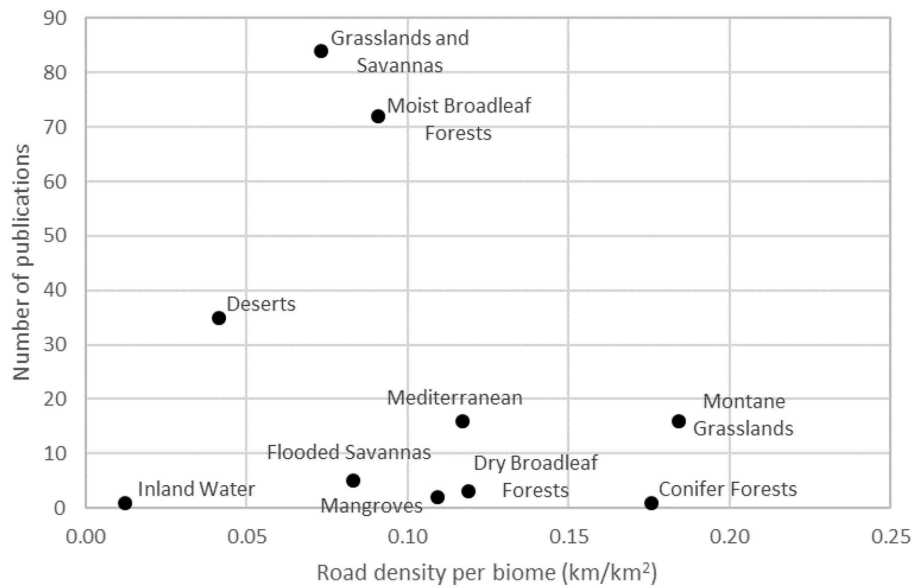
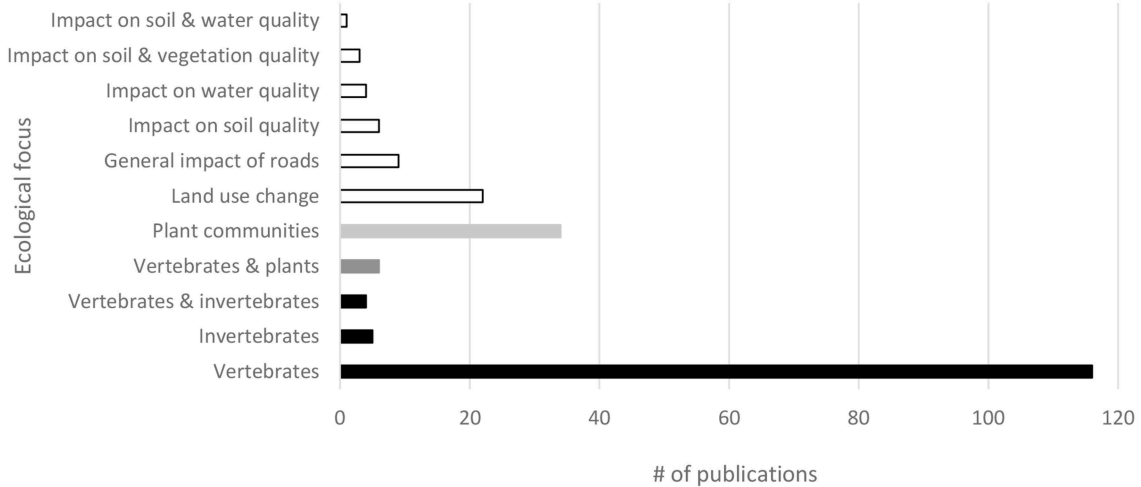**FIGURE 5 |** Number of publications per biome relative to road density (km of road/km²) in each biome.

FIGURE 6 | The ecological focus of 210 road ecology publications, according to broad ecological groupings (black bars represent animals, dark grey bars represent animals and plants, light grey bars represent plants and white bars represent ecosystems).

($n = 3$) were for other surfaces (e.g., sand and off-road). Only 20% ($n = 42$) of publications measured traffic volume and/or vehicle speed.

Study Design
Study Focus on Linear Infrastructure and Explanatory Variables
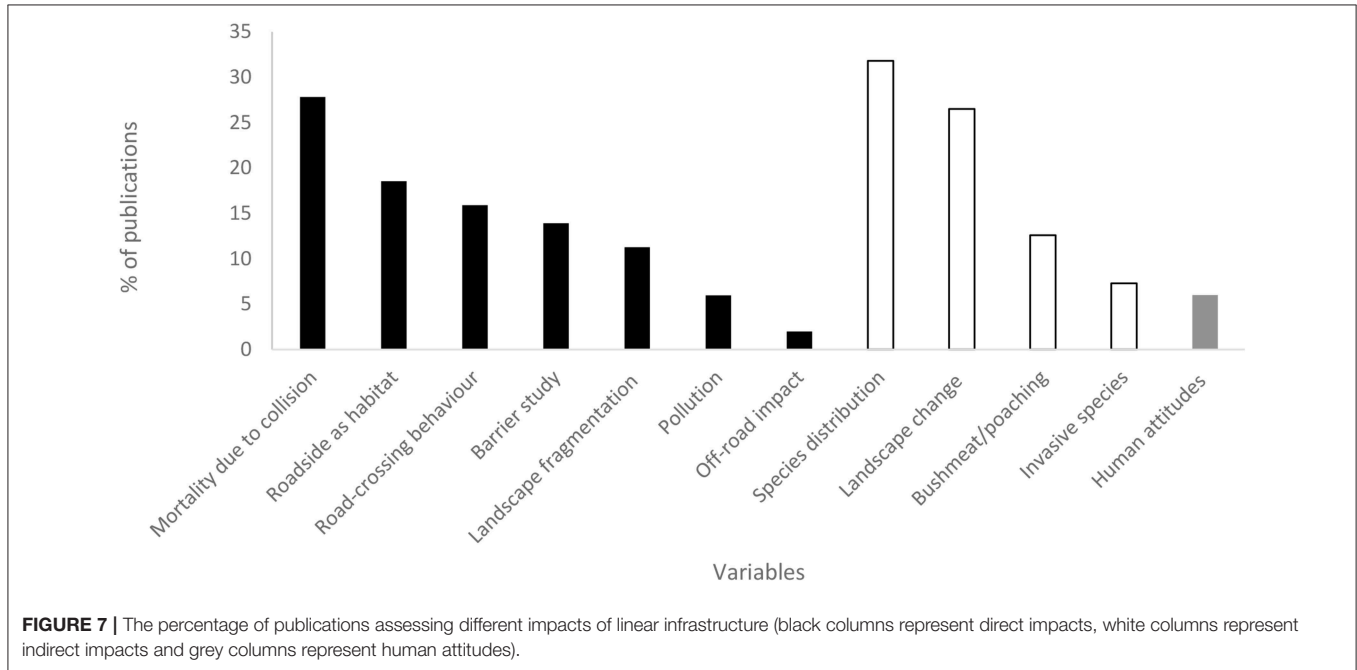
Linear infrastructure itself was the primary focus of just under half (44.8%) of the publications we reviewed. In most publications (71.4%) the linear infrastructure was used as an explanatory variable, showing causes or impacts of linear infrastructure on other (i.e., dependent) variables.

Among those publications that measured direct impacts on biodiversity ($n = 190$), those that examined wildlife mortality due to collision with vehicles were the most numerous ($n = 58$). Thirty-seven publications investigated the impact of roads on roadside vegetation and/or habitat, and 30 examined the impact of roads on the behaviour of animals near or crossing roads (**Figure 7**).

For publications addressing the indirect impacts of roads and traffic ($n = 161$), most used a measure of road length or density to explain the distribution of species ($n = 67$; 31.8%). Of the remaining publications, 54 examined changes in the landscape due to the presence of roads (**Figure 7**), such as changes caused by

TABLE 2 | The species most commonly the focus of road ecology publications with five or more studies from the 210 reviewed publications for road ecology in Africa.

Common name	Scientific name	Countries	Number of publications
Chimpanzee	*Pan troglodytes verus*	Democratic Republic of Congo, Republic of Guinea, Liberia, Uganda	10
Forest elephant	*Loxodonta africana cyclotis*	Cameroon, Central African Republic, Democratic Republic of Congo, Gabon	8
Western lowland gorilla	*Gorilla gorilla*	Central African Republic, Congo, Democratic Republic of Congo, Republic of Guinea	7
African elephant	*Loxodonta africana*	Burkina Faso, Cameroon, Kenya	7
Impala	*Aepyceros melampus*	South Africa, Tanzania, Zambia	5
Nightjars	*Caprimulgidae* spp.	South Africa, Niger, Zimbabwe	5

FIGURE 7 | The percentage of publications assessing different impacts of linear infrastructure (black columns represent direct impacts, white columns represent indirect impacts and grey columns represent human attitudes).
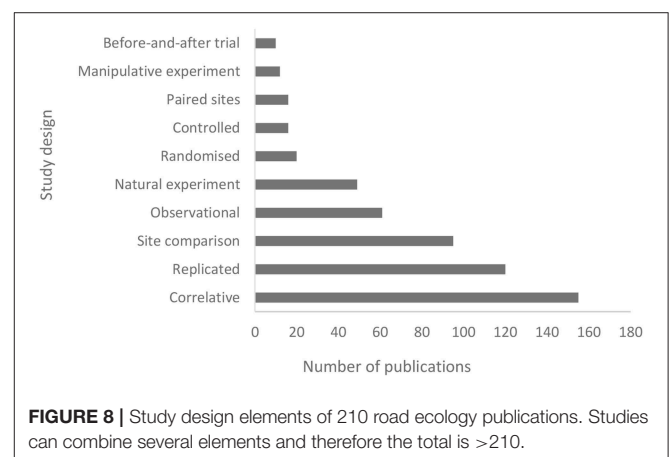
fire (Archibald et al., 2009) or clearance of forests due to logging (Christie et al., 2007).

Nine of the 210 publications studied human attitudes and their behaviour in relation to roads (**Figure 7**). These were all undertaken during the last 16 years, with four undertaken in southern Africa, two each in East and Central Africa, and one in West Africa. Five of these publications examined public perceptions of how linear infrastructure changes a landscape, three studied human attitudes to wildlife on roads and the possible causes of roadkill, and one addressed public opinions of methods to mitigate roadkill. The remaining publication focused on factors that increase a visitor's game-viewing experience in a protected area, with well-designed roads being a factor.
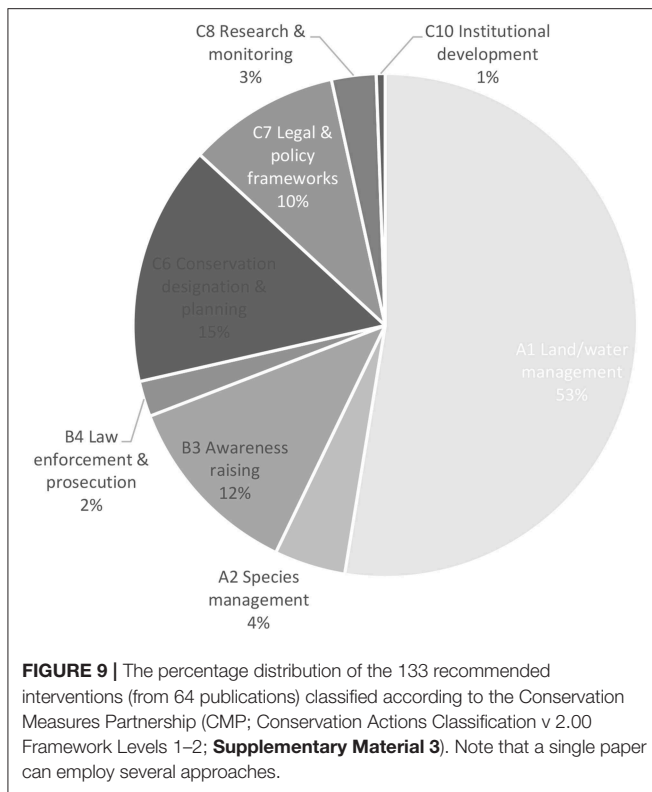
Study Design and Methods of Analysis Employed
More than half of the publications ($n = 120$) adopted study site replicates as their main method of study design, followed by site comparisons ($n = 95$), with only ten publications conducting a before-and-after-trial (**Figure 8**). Most studies analysed the data using correlations (**Figure 8**; $n = 155$) compared to simply reporting results or observational data without any formal analysis ($n = 61$), whilst 16 used both correlative and observational approaches (a single publication can employ several approaches).

FIGURE 8 | Study design elements of 210 road ecology publications. Studies can combine several elements and therefore the total is >210.

Recommendations and Associated Quality of Evidence
Only seven of the 210 publications evaluated the effectiveness of interventions, such as measuring rates of use of an elephant underpass in Kenya (Weeks, 2015). Four of these seven studies were in East Africa (Kenya, $n = 3$; Tanzania, $n = 1$) and three in South Africa.

FIGURE 9 | The percentage distribution of the 133 recommended interventions (from 64 publications) classified according to the Conservation Measures Partnership (CMP; Conservation Actions Classification v 2.00 Framework Levels 1–2; **Supplementary Material 3**). Note that a single paper can employ several approaches.

Three quarters of publications provided some form of recommendation for intervention, although only 30.5% of these ($n = 64$) contained recommendations that were based on any evidence from the published study itself, amounting to 133 evidence-based recommendations overall. The remaining publications with recommendations contained general or "conventional wisdom" recommendations that could *a priori* have been applied to almost any road ecology study anywhere in the world. Most recommendations (based on evidence from within the publications) came from studies from southern Africa (40.6%), followed by East Africa (24.6%), Central and West Africa (both 14.5%), and 5.8% for Africa, as a whole. No recommendations were found from North Africa.

We classified 133 different evidence-based recommendations for intervention from 64 publications according to the Open Standards Conservation Actions Classification v 2.0. Most of the recommendations proposed target restoration or stress reduction actions (CMP, Level A; **Figure 9**) followed by enabling conditions (CMP, Level C), and behavioural change or threat reduction actions (CMP, Level B). Within these primary levels, the category A1 (land/water management) had the most recommendations (37.6%; **Figure 9**), followed by the category C6 (conservation designation and planning; 20.3%; **Figure 9**) and B3 (awareness raising; 15.8%; **Figure 8**).

Level 2 categories of the CMP shows ecosystem and natural process recreation (A1.2) having the most recommendations for intervention (37.6%; **Figure 10**) followed by site/area stewardship (A1.1; 31.6%), outreach and communications (15.8%; B3.1) and site infrastructure (11.3%; C6.5). Four

publications within category B3 did not provide details of how the intervention should be undertaken and could not therefore be categorised further than Level 1.

Whilst there were many recommendations spanning the three broad CMP categories, there were also gaps for recommendations from many of the CMP classification levels, such as CMP Level B5 (*Livelihood, Economic and Moral Incentives*) and CMP Level C9 (*Education and Training*) (**Figure 10**).

The final level of the CMP Framework (Level 3) categorises recommendations for intervention, with visitor management (A1.1.8) having the highest number of recommendations (14.7%). Examples of CMP category A1.1.8 include restricting vehicular road usage (Ndibalema et al., 2008; Nortjé et al., 2012), and diverting future roads or locating roads away from protected areas (Ansara, 2008; Van Vliet and Nasi, 2008). This category was followed by mechanical actions (12.4%; A1.1.1;) including better management of roadside verges (Rahlao et al., 2010; Mkanda and Chansa, 2011), and cleaning of vehicles prior to entry and use within areas of high conservation values such as national parks, to avoid spreading alien and invasive plants (Ansong and Pickering, 2013). Transport was the third most common category (11.6%; C6.5.4) with examples including the installation of traffic-calming devices (such as speed bumps) at identified roadkill "hotspots" Drews, 1995; Hayward, 2009 and limiting future road upgrades through maintaining the unpaved road surface (Caro, 2015).

Our assessment of the quality of evidence showed that most recommendations (93.3%) were based on quality of evidence of levels I to III (**Table 3**), but <10% of the recommendations were based on studies that conducted a controlled trial (level I). Most recommendations were from publications that compared sites (level II-2; 44.8%) or temporal patterns (level II-3; 19.4%) and 15.7% of recommendations were based on expert opinions or descriptive studies (level III). We deemed the evidence in the remaining 6.7% of recommendations to be inadequate (level IV) or we were unable to assess the quality of evidence (NC) (**Table 3**).

DISCUSSION

Summary

Our review revealed many more road ecology publications from Africa than we expected, with a significant increase in the number of publications since 2006. Most of the publications were from the more affluent and politically stable regions (e.g., southern and East Africa), particularly pre-2006 publications (Drews, 1995; Dean and Milton, 2000), whilst post-2006 publications saw an increase in the number of papers from Central Africa (Hicks et al., 2012; Tompkins et al., 2015; Cameron et al., 2016).

A recent global review of road ecology papers published between 2011 and 2015 (Bennett, 2017) found that <10 studies ($n = 215$) were conducted in Africa. Consequently, there is a perception that few road ecology studies have been undertaken in Africa (Collinson et al., 2014, 2015; Kioko et al., 2015) possibly because earlier literature searches have been too narrow or too specific in the focus. We used broad search terms in our review, and thus discovered many more publications than Bennett
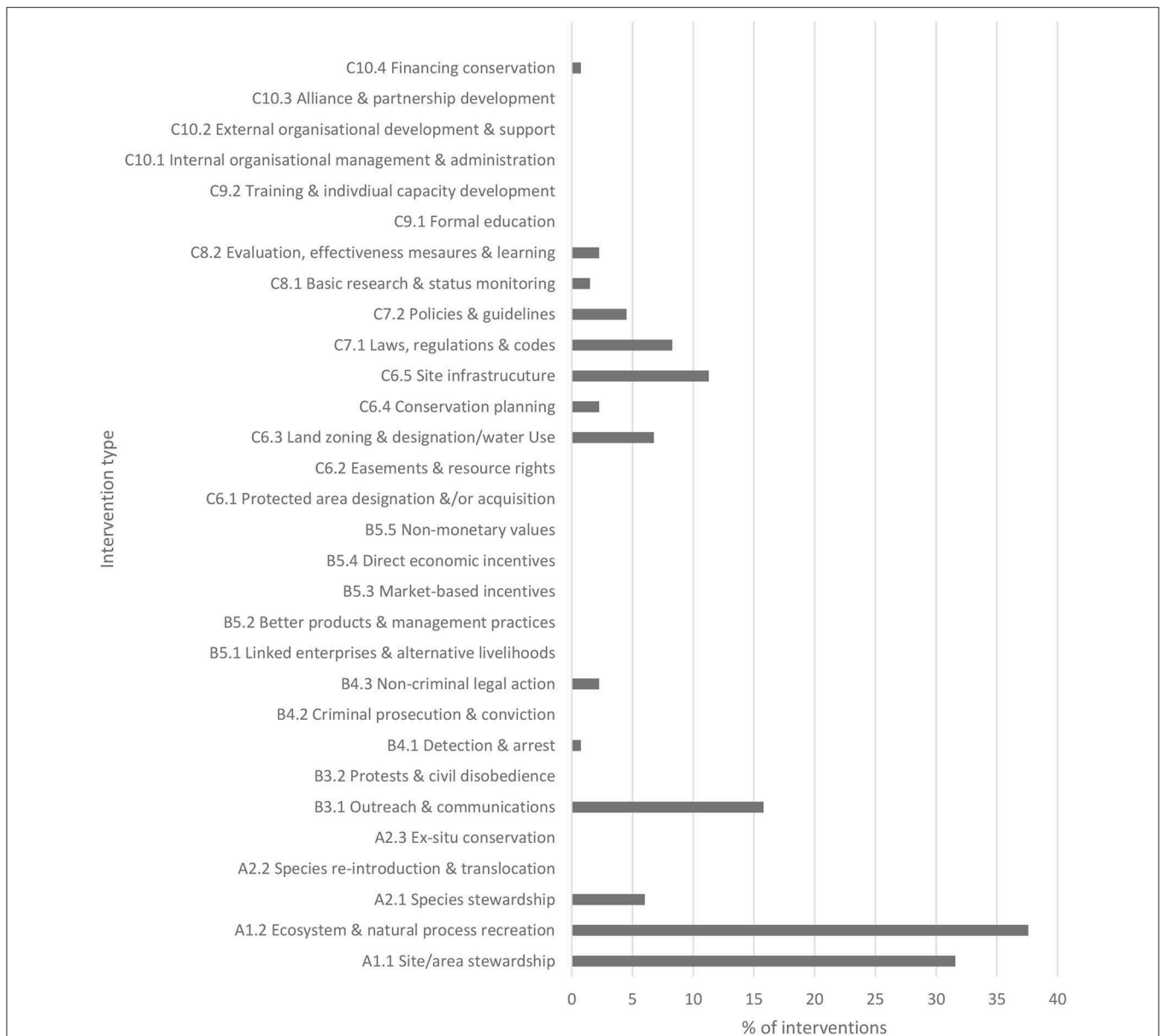
FIGURE 10 | The distribution of the 133 recommended interventions (from 64 publications) for Level 2 of CMP A (Target Restoration/Stress Reduction Actions), CMP B (Behavioural Change/Threat Reduction Actions), and CMP C (Enabling Condition Actions), classified according to the Conservation Measures Partnership (CMP; Conservation Actions Classification v 2.00 Framework Level 3; **Supplementary Material 3**). Note that a single publication can recommend several approaches.

(2017). We also found that many road ecology studies were hidden or buried in studies that were ostensibly on other topics, for example, where road density was an explanatory factor to help understand the distribution or abundance of a certain species, and not the primary focus (e.g., Blom et al., 2005; Aubréville, 2015; Bortolamiol et al., 2016).

We outline below some key points drawn from the literature that highlight future research priorities.

Threats to Habitats and Species

By definition, all of the publications we reviewed focused solely on roads (e.g., Collinson et al., 2014; Kleinschroth et al., 2016) or

jointly on roads with another type of linear infrastructure (e.g., roads and fencing, Van Niekerk and Eloff, 2005; roads and rail, Watson et al., 2015; roads and power lines, Laurance et al., 2009; roads and pipelines, Akert, 2015). We found limited research comparing paved vs. unpaved roads (but see, Awange and Obera, 2007; Collinson et al., 2014), and most publications (∼two-thirds) gave no indication of the surface of the roads they studied. This highlights a critical gap in the research, given the extensive unpaved road network in Africa. The global road network is ∼64 million km, with ∼2.7 million km in Africa, three-quarters of which are unpaved [Central Intelligence Agency (CIA), 2013]. Globally, 12 million km of paved roads have been built since

TABLE 3 | The quality of evidence for the 133 evidence-based recommendations from the 64 publications that provided recommendations for interventions (Salafsky et al., 2002).

Quality of evidence		% of recommendations (n = 133)
I	Strong evidence obtained from at least one properly designed, randomised controlled trial of appropriate size	8.9
II-1	Evidence from well-designed controlled trials, no randomisation	4.5
II-2	Evidence from comparison of differences between sites, with and without (controls) a desired species or community	44.8
II-3	Evidence obtained from multiple time series or from dramatic results in uncontrolled experiments	19.4
III	Opinions of respected authorities based on qualitative field evidence, descriptive studies, or reports of expert committees	15.7
IV	Evidence inadequate owing to problems of methodology, e.g., sample size, length or comprehensiveness of monitoring, or conflicts of evidence	3.7
NC	Unable to tell the quality of evidence from the paper	3.0

2000 with another 25 million lane-km projected to be built by 2050 (Dulac, 2013), many of which are planned for Africa. It would therefore be logical to devote resources to examining before-and-after studies in light of many of these unpaved roads targeted for upgrade (Dulac, 2013), while accounting for other changes associated with paving, such as increased traffic volume and vehicle speeds. We found few studies that measured traffic volume and/or vehicle speed (but see Mouhoub Sayah et al., 2009; Collinson et al., 2014) and, in light of increased road expansion and the resulting increase in traffic volumes, we recommend that future research incorporates traffic monitoring surveys to obtain baseline estimates and track changes over time.

We found a shift in study focus across the continent in the last decade, from species distributions to that of landscape change (e.g., Maeda et al., 2010; Nortjé et al., 2016), specifically in Central Africa (e.g., Laporte et al., 2007; Kleinschroth et al., 2016). This is unsurprising given that this region of Africa has been recognised in recent years as a "conflict zone" (Laurance et al., 2014a), with high environmental costs accorded to infrastructure development or future impacts of climate change (Laurance et al., 2014a). Furthermore, recognition of the spread of alien and invasive plants, particularly on roadside verges (e.g., Kalwij et al., 2008; Foxcroft et al., 2011) has emerged in latter years as an indirect threat of roads, particularly in South Africa.

Wildlife crime has gained momentum as a topic of international attention and concern in the last few decades (Wilson-Wilde, 2010), with roads facilitating illegal activities such as poaching (Laurance et al., 2014b). We found that 18% of the publications showed evidence of roads facilitating poaching (e.g., Maisels et al., 2013; Shaffer and Bishop, 2016). These studies were specifically in East (e.g., Jones et al., 2009; Kimanzi et al., 2015) and Central Africa (e.g., Wilkie et al., 2000; Haurez et al., 2013), and they primarily focused on mammals, such as

the African elephant (Maingi et al., 2012; Shaffer and Bishop, 2016), forest elephant (Blake et al., 2007; Maisels et al., 2013), Western Lowland gorilla (Stokes et al., 2010; Haurez et al., 2013) and Temminck's ground pangolin (*Smutsia temminckii*, Pietersen et al., 2011). With many of these species classified as threatened (IUCN, 2018a), and with annual estimates of the cost of wildlife crime ranging from US$10–20 billion globally (Wilson-Wilde, 2010), the effort of research undertaken, specifically in these regions, supports the need for an understanding of both habitat and species of concern.

Addressing the Threats

One-third of the publications provided some form of recommendation for intervention, based solely on evidence from the paper, with the remaining publications either making no recommendations, or making recommendations that were too broad, and which neglected to provide evidence directly gleaned from the research. Intervention strategies were often poorly described, lacked operational guidelines and theoretical justification, as well as measurement of data quality, which is common in many disciplines (Salafsky et al., 2002; Becker, 2005; Proctor et al., 2013). The population of some of the conceptual ideas presented in the papers, whilst beyond the scope of this paper is an opportunity for further investigation.

It was apparent that there has either been little or no mitigation of the impacts of roads in Africa, or it has yet to be studied and published (but see Le Brun, 2013; Donaldson and Cunneyworth, 2015; Weeks, 2015). This is in stark contrast to more developed countries in North America (e.g., Clevenger et al., 2001; Sielecki, 2001) and Europe (e.g., Seiler, 2003; van Vuurde and van der Grift, 2005), where literally thousands of interventions have been tested and published since the 1980s (Rytwinski et al., 2016). There are numerous measures for mitigating the negative impacts of roads globally, some of which use existing infrastructure, such as storm drains and culverts beneath roads to assist animals with safer crossings of roads, and thus reducing roadkill (Rytwinski et al., 2016). There are only three African road ecology publications where mitigation has been tested, and therefore provide case studies about wildlife-crossing structures, two in East Africa (Donaldson and Cunneyworth, 2015; Weeks, 2015) and one in South Africa (Le Brun, 2013) although data for the effectiveness of these measures was not measured. A further study in South Africa, which was outside the period of inclusion in our literature search, is the only study in South Africa, that we are aware of, that has assessed the effectiveness of a mitigation measure (Collinson et al., 2017).

Despite the paucity of evidence-based recommendations, most recommendations came from publications within South Africa where most of the empirical and conceptual data was collected. This then begs the question as to why no mitigation has yet been applied, or if it has, when will the results be published? These limitations are not unique to Africa, since Rytwinski et al. (2016) state that there is a paucity, in general, of scientifically rigorous studies on mitigation effectiveness. Furthermore, notwithstanding the evidence of the emerging threats to the Central African forests from industrial logging (Laporte et al., 2007), and therefore, declared a "conflict zone"

(Laurance et al., 2014b), the proposed recommendations from the nine publications (Malcolm and Ray, 2000; Blom et al., 2004; Blake et al., 2007, 2008; Clark et al., 2009; Laurance et al., 2009; Epps et al., 2015; Kleinschroth et al., 2015, 2016) should be given urgent priority for implementation and assessment.

Identifying the Gaps

Most of the studies collected basic enumeration roadkill rates (e.g., Dean et al., 2006; Perony and Townsend, 2013) or presented conceptual ideas (e.g., Zhang et al., 2006; Müller and Mburu, 2009). This is often a common feature when undertaking new research within countries and was observed historically in more developed countries such as Britain (Philcox et al., 1999) and North America (Caro et al., 2000), where studies in the field of road ecology first commenced with gathering road mortality data. This is apparent in developing countries beyond the African continent that seek to first gather empirical data (e.g., India, Selvan et al., 2012; China, Yun et al., 2013), and then expand to applying and assessing mitigation measures, as is the case with more developed countries (e.g., USA, Langen et al., 2009; Australia, Taylor and Goldingay, 2010).

With <20% of the papers undertaking a study on human attitudes, it is globally recognised that the integration of the social sciences into long-term ecological research is an urgent priority (Redman et al., 2004; Ingold and Palsson, 2013), none more so when it comes to understanding driver behaviour. Africa is not alone in this limited understanding, and it is only in the last decade that global studies have been undertaken to address this integration (Lester, 2015; Grace, 2017).

Whilst there were many recommendations spanning the three broad CMP categories, there were also gaps for recommendations from many of the CMP classification levels that should be considered for future study, provided they are appropriate. CMP Level B5 (*Livelihood, Economic and Moral Incentives*) received no recommendations and, as a factor that seeks to provide better products and management practices (B5.2), market-based incentives (B5.3), as well as direct economic incentives (B5.4), this would be a critical area in gaining "local buy-in" and sustainability for environmental work as well as supporting local livelihoods. Likewise, CMP Level C9 (*Education and Training*) also received no recommendations. Whilst Awareness raising (CMP B3) "touched" on education, it was not specified as formal instruction through school learners or providing technical assistance to project teams (McKinney, 2002).

Not all recommendations are always feasible to implement, based on budget constraints or inadequate environmental impact assessments (EIAs) undertaken during the planning and design stage (Langan, 2015). This, therefore, requires that relevant experts are involved in EIA processes (Fischer, 2007). It also requires governments to recognise the negative impacts of roads on biodiversity, and the benefits to addressing these. It is also critical to be pragmatic in our understanding of which impacts can be successfully mitigated, and those that cannot, and therefore should always be avoided during planning and design stages of projects. This is not an easy task in a continent that is battling to improve its socio-economic circumstances, and where conservation often takes a back seat (Sayre, 1999). Developing

centralised repositories of road ecology data, working groups such as the IUCN's Transport Working Group (IUCN, 2018b), and engagement platforms with African infrastructure investors would provide a foundation to addressing critical threats.

CONCLUSIONS

Despite the widespread perception that there is a paucity of African road ecology publications (Collinson, 2013; Collinson et al., 2015; Kioko et al., 2015; Bennett, 2017), our literature search revealed a surprisingly large number of studies. Global attention and concern has shifted toward Africa in the last decade since improved stability, abundant resources and increased foreign investment into many African nations have spurred economic growth (Taylor, 2014) and road expansion (The African Development Bank, the African Union and the United Nations Economic Commission for Africa, 2016).

The European Commission has committed to providing African countries with financial support to facilitate poverty eradication and the broader achievement of the United Nations SDGs. According to Laurance et al. (2015b), expanding and upgrading Africa's road network may well improve the continent's socio-economic situation, but negative environmental outcomes could provoke an environmental crisis. EIAs are intended to identify potential risks and liabilities of infrastructure projects, and to minimise such risks with suitable mitigation and offset measures. However, EIAs are often widely seen as too transient to determine the actual environmental costs of new infrastructure projects (Laurance and Arrea, 2017), and the cumulative impacts of roads can lead to negative indirect effects, such as habitat fragmentation (Jaeger, 2015).

Despite our search findings demonstrating more studies than expected, this does not mean that enough has been done. There is still a pressing need for well-designed, basic road ecology studies to be undertaken in Africa, on a wide range of topics. The number and type of recommendations outlined in the studies through using the Open Standards Conservation Actions Classification highlights many areas that were either not studied or had limited study. For example, far more papers alluded to wildlife with few considering areas such as pollution (Inchaouh et al., 2017; Megido et al., 2017), biological invasions or off-roading (see **Figures 6**, **7**). Furthermore, whilst some of the papers described animal behaviour around roads (e.g., road avoidance, foraging near roads; Bortolamiol et al., 2016), a broader search that includes additional terms, specifically "behaviour" will likely source further road ecology-related studies (for example, Shepard et al., 2008; Neumann et al., 2012). Our study has highlighted the need for the accelerated study of the impacts of roads and appropriate mitigation measures, and adoption of recommendations made in the African road ecology publications, so that mitigation be applied and rigorously assessed. We further advocate for a detailed review of the EIA process be undertaken for different African countries focusing on the quality of proposed linear infrastructure projects, with project investors devoting more resources to more robust environmental assessments, with tangible recommendations and solutions.

AUTHOR CONTRIBUTIONS

WC, HD-M, LR, and RR: project conceptualisation, data analysis and manuscript writing. WC and LR: data collation and cleaning.

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SUPPLEMENTARY MATERIAL

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