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ROADWAYS AND INFRASTRUCTURE

Life cycle assessment of the construction of an unpaved road in an undisturbed tropical rainforest area in the vicinity of Manu National Park, Peru

Gustavo Larrea-Gallegos[1] **· Ian Vázquez-Rowe**[1,2] **· Geoffrey Gallice**[3]

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Abstract
Purpose The main goal of this study is to provide a thorough environmental sustainability analysis of the construction, traffic, and maintenance of a 45.6-km section of the 'Manu Road', an unpaved tropical road that is currently being built in the vicinity of Manu National Park, in the region of Madre de Dios, Peru.
Methods Life cycle assessment (LCA) using a set of 18 different impact categories was selected to conduct the environmental analysis. Modelling of machinery and vehicle emissions, as well as dust emissions, was performed to account for site-specific characteristics in terms of road construction and traffic. Similarly, direct land use changes were modelled with a particular emphasis on the decay of deforested biomass during construction. A set of different scenarios for the production system were considered to account for uncertainty regarding vehicle transit, amount of deforested biomass, and emission standards.
Results and discussion Construction, maintenance, and traffic of the Manu Road varied considerably depending on methodological assumptions. Deforestation due to direct land use changes appears to be the main environmental hotspot in terms of climate change, whereas in the remaining impact categories, traffic was the main carrier of environmental burdens.
Conclusions To the best of our knowledge, this study is the first LCA that focuses on the construction, maintenance, and traffic in a tropical rainforest environment. Despite the low requirements in terms of materials and technology to build this road, its derived environmental impacts are relevant in terms of climate change and particulate matter formation due to deforestation and dust emissions, respectively. Unpaved roads represent a relevant proportion of the entire road network worldwide, especially in developing tropical countries, playing a crucial role in the transportation of raw materials. Furthermore, road infrastructure is expected to expand explosively in the decades to come. Therefore, we suggest that LCA studies can and should improve the planning of road infrastructure in terms of life cycle inventories.

Keywords Amazon · Climate change · GHG emissions · Industrial ecology · Land use changes · LCA · Madre de Dios · Road construction

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✉ Gustavo Larrea-Gallegos
glarrea@pucp.pe

[1] Peruvian LCA Network, Department of Engineering, Pontificia Universidad Católica del Perú, 1801 Avenida Universitaria, San Miguel 32, Lima, Peru

[2] Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain

[3] Florida Museum of Natural History, University of Florida, Gainesville, FL, USA

1 Introduction

Roads, beyond their socio-economic benefits, also provide interesting environmental advantages in terms of managing forests, fire suppression, or creating recreational access to natural areas (Reid et al. 1994). However, roads are also known to damage wildlife habitat and alter ecosystems by acting as agents of vegetation change or by fostering deforestation through direct and indirect land use changes, especially in

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the tropics (Laurance et al. 2009, 2011). Furthermore, new roads may also have unanticipated, negative consequences for local and indigenous communities, particularly in developing tropical countries where colonization and illicit extractive activities are generally uncontrolled (Oliveira et al. 2007).

All of these social and environmental impacts are heightened whenever roads are built in sensitive natural environments, where biodiversity is yet to be strongly affected by the presence of human activities. For instance, road building in the Amazon rainforest has become a ubiquitous phenomenon that has gradually yet dramatically transformed the region's primary forests through massive land use changes (Godar et al. 2012). Roads have allowed the spread of subsistence farming (e.g. cattle ranching) and plantation agriculture (e.g. banana, coffee, soy, tea, or coca), especially in areas with rich soils, driving a large-scale conversion of forest and an associated reduction in biodiversity that has also been linked to a critical disruption of the functioning of existing forest ecosystems (Myers 1988).

Nevertheless, assessing the impacts of roads on the environment is complex due to the existence of a series of unique conditions that determine the nature of each project, including location, length, climate, traffic intensity, the selection of materials used in construction, or the wide range of policies that steer the way in which the road and the landscape through which it passes are managed. Consequently, the assessment of the environmental impacts of roads goes beyond static modelling (Stripple 2001).

Given the impacts of roads and the complexity of their assessment, the use of life cycle assessment (LCA), an environmental management tool used to monitor the environmental impacts engendered by a product or service, has been applied on numerous occasions to road design, construction, and maintenance with the aim of improving the sustainability of these infrastructures (Carlson 2011). For instance, the use of new, more sustainable materials rather than existing ones (Hakkinen and Mäkelä 1996; Mroueh et al. 2000; Park et al. 2003; Huang et al. 2009a; Yu and Lu 2012), the appropriateness of illuminating roads (Tähkämö and Halonen 2015), the modelling of mobility policies and traffic behaviour (Huang et al. 2009b; Querini and Benetto 2015), and the establishment of green procurement strategies (Butt et al. 2015) are just some examples of how LCA has been applied to the road sector (Santero 2011; Carlson 2011; Azari-Jafari et al. 2016). In fact, an LCA review performed by Muench (2010) reveals that in the construction phase of roads, the production of materials represents 60 to 90% of the total CO_2eq emissions. However, the GHG emissions linked to the traffic operating along the road will tend to widely surpass those generated by the construction phase (Muench 2010).

Interestingly, however, we found no evidence of the use of LCA to analyse the environmental impacts of road construction in the Amazon region. Despite the existence of numerous studies that identify key environmental disruptions linked to the intrusion of roads in primary and secondary rainforest areas (Naughton-Treves et al. 2003a, b; Delgado 2008; Laurance et al. 2009, 2011; Godar et al. 2012; Aguilar-Amuchastegui et al. 2014), LCA studies in Latin America have focused mainly on the agri-food sector, as well as bioenergy and building (Quispe et al. 2016). More specifically, a total of eight scientific articles in the past 6 years have been published linked to application of LCA in Peru, all linked either to the energy or agri-food sectors (Scopus 2016). Hence, the main objective of this study is to provide a thorough environmental sustainability analysis, using LCA, of the construction, operation, and maintenance of an unpaved tropical rainforest road that is currently being built to communicate the village of Boca Manu in Peru (S 12°15′53″, W 70° 54′37″; 295 m.a.s.l.), allowing the completion of a trade route between the capital cities of the Peruvian regions of Cusco and Madre de Dios (see Fig. 1).

The importance of this case study resides in the fact that this infrastructure is currently being built in the vicinity of two important protected areas in Peru: Manu National Park and the Amarakaeri Communal Reserve. Manu National Park forms the core area of the Manu Biosphere Reserve, a UNESCO World Heritage Site, which is considered one of the most biodiverse and culturally sensitive places on Earth (e.g. Catenazzi et al. 2013; Shepard et al. 2010). Road construction represents an important potential threat to the park and its indigenous inhabitants, since road accessibility could trigger increased human activity in the area, such as mining, slash and burn agriculture, logging, or uncontrolled colonization. These threats have already devastated vast areas of tropical forest in the Amazon (e.g. Asner et al. 2009). Although the construction of the road began in the 1960s, increasing the number of tourists and outside settlers in the area, certain local communities and economic interests are pushing for further road construction to extend the road to the village of Boca Manu, at the mouth of the Manu River and the entrance to the National Park and the core area of the Manu Biosphere Reserve. If the road were to be completed to Boca Manu, colonization, deforestation, and forest degradation would increase pressure on the area's biotic and abiotic resources and boost conflicts with local indigenous groups, some of which still live in voluntary isolation in the Manu region and are extremely sensitive to outside influences (Shepard et al. 2010).

The use of LCA in this particular case study is justified in several spheres. First of all, as described earlier, the construction of a road in the vicinity of one of the most emblematic and biodiverse national parks in the world, as well as within the protected buffer zone of an indigenous communal reserve, has fostered great interest in this otherwise minor infrastructure, due to the complex environmental impacts that it could cause once finalized and in operation. This has led to an intense debate among different authorities, conservationists, and the

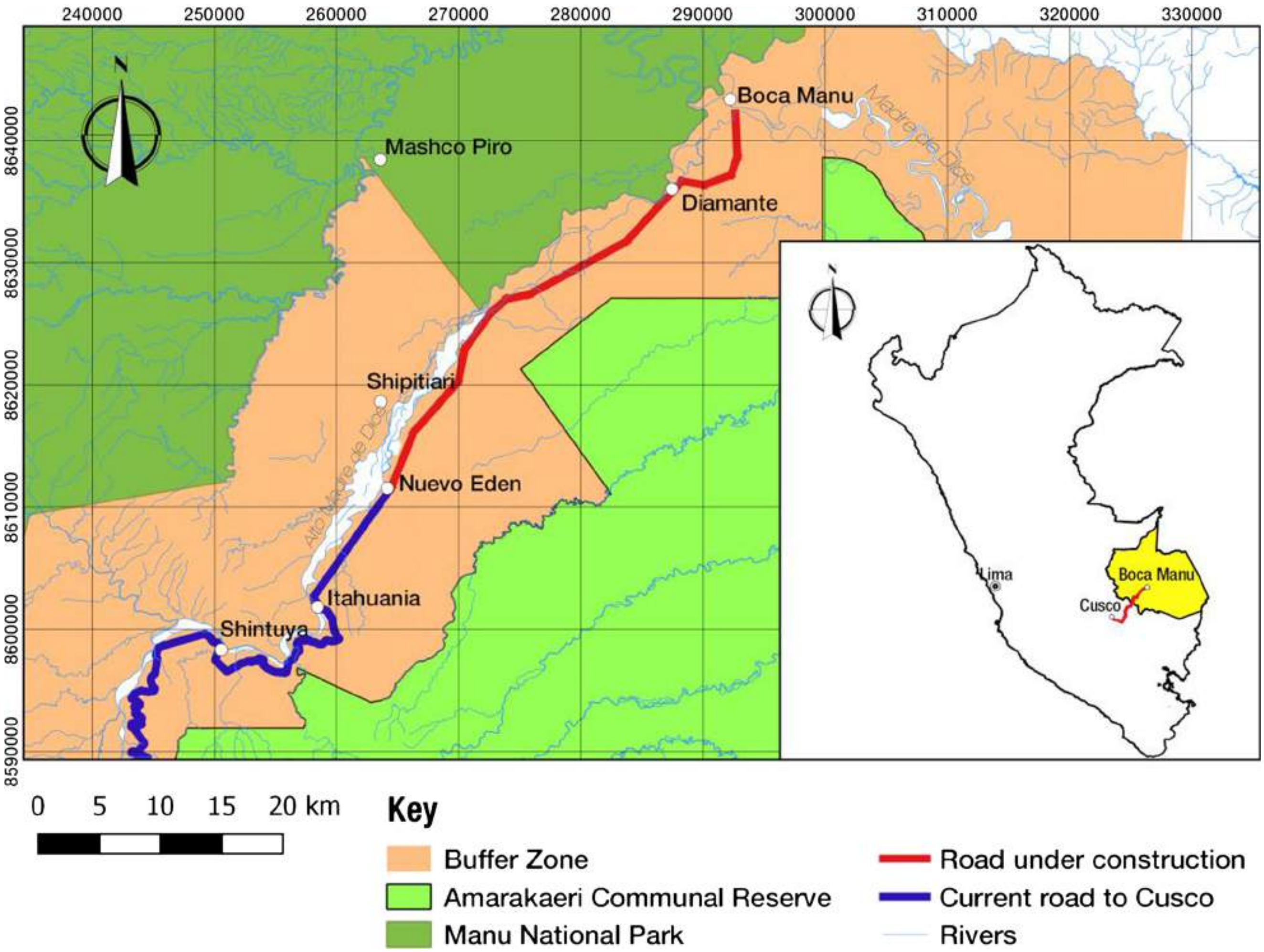

Fig. 1 Manu road project layout

general public in Peru, both in the Manu area and at the national level (MINAM 2016). The possibility of assessing a wide range of impact categories through LCA, as well as quantifying these impacts, constitutes an important milestone that could be of utility to the stakeholders mentioned above. Secondly, the use of life cycle tools in this context has not been previously explored in a rainforest environment, although road development in the world's tropics has proceeded, and will continue to proceed, rapidly. Therefore, the use of LCA in this study is pioneering for the region, for Peru, and for the Amazon region in general, and has the potential to stimulate future research and applied utility in the field. Finally, we show the utility of life cycle inventories that are adapted to the local road networks existing in remote tropical areas, where the extraction of raw resources (e.g. timber, minerals, tropical fruits, and other agricultural products) warrants improvement in most of the consulted databases. Therefore, the results derived from this study will be available for practitioners interested in developing similar analyses in other tropical, developing regions.

This study is intended to be of interest for the LCA community, as a way to describe current trends in terms of road infrastructure planning and design in remote tropical areas. In addition, policy-makers at the local, regional, and national level, as well as policy-makers in other tropical areas, could benefit from the results here presented. These may be of value to drive future legislation in road planning towards increased environmental sustainability and to consider additional environmental impacts beyond biodiversity when managing the conservation of protected areas in the tropics.

2 Materials and methods

2.1 Goal and scope

The main goal of this manuscript is to deliver an environmental assessment of the construction, maintenance, and operation of 45.596 km of unpaved road that are currently been completed to communicate the village of Boca Manu in the socalled Manu Road (see Fig. 1). LCA, as described in the ISO 14040 and 14044 standards, was the methodology selected to conduct the analysis (ISO 2006a, b). Nevertheless, we note that this study is part of a broader project in which the threats of road construction to the conservation of biological and cultural diversity, as well as carbon storage, in this part of the Amazon basin will be analysed in depth.

Based on the function of the production system, which is to construct and maintain this final stretch of unpaved road to the village of Boca Manu, a functional unit (FU) of 1 km of unpaved road in 1 year of operation was considered. This FU is in line with similar studies of road systems that have been modelled using LCA (e.g. Stripple 2001; Treloar et al. 2004). Its choice combines a simple computation of a section of the road, with a temporal allocation (1 year) that is justified by the fact that tropical forest roads generally require annual maintenance once the rainy season is over.

The system boundaries, which are depicted in Fig. 2, include all the phases of road construction, from provisional works and clearing of the forested area up to the final steps to compact the final unpaved road. In addition, the maintenance corresponding to 1 year of operation, as well as the use of the road during a 1-year period, was included within the system boundaries. Minor drainage structures have been omitted from the analysis due to the lack of information and their expected minimal contribution to the final results, representing less than 1% of the total length of the road. Indirect land use changes (iLUCs) due to better access to the area were excluded from these boundaries, but will be explored in a subsequent study. No additional functions were identified for the production system, which is considered to deliver one single final product; therefore, no allocation was needed.

A total lifetime of 15 years was considered for the road (i.e. 2016–2030), based on the assumption that in 2030, the unpaved road would need an upgrade due to increased traffic intensity. Direct land use changes (dLUCs) due to clearing for construction were allocated evenly throughout the specified lifetime. Lifetime selection is linked to the fact that 2030 is not only an important reference year in terms of re-evaluating the infrastructure conditions, but also considering that the Treaty of Paris obliges Peru to reduce its GHG emissions by 31% in 2030 (MINAM 2015).

2.2 Description of the unpaved road section

The portion of the analysed road already in existence begins in the city of Cusco and extends to the village of Nuevo Edén (S 12°37′16″, W 71°12′43″; 387 m.a.s.l.); the road section here considered extends from Nuevo Edén to the village of Boca

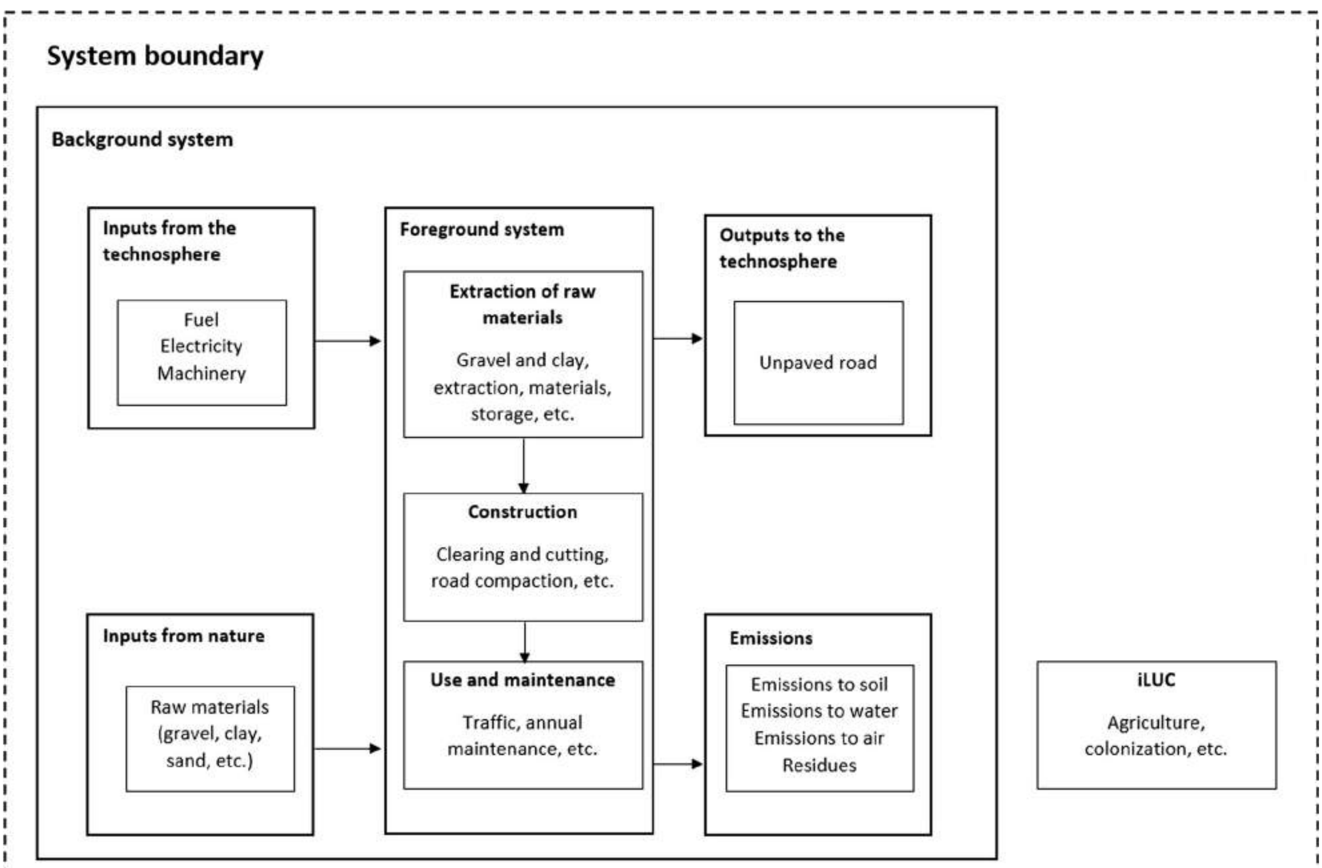

Fig. 2 Graphical representation of the system boundaries of the production system analysed

Manu, connecting other small native communities such as those of Shipiteari and Diamante (see Fig. 1). The road layout crosses the buffer zone of the Amarakaeri communal reserve, an area in which agricultural, forestry, and other commercial activities occur but are controlled.

According to accessed legal information, the construction of the Nuevo Edén-Boca Manu road will be executed in two different phases (MEF 2008). The first phase was under construction during the months of June–November 2015 (see Fig. 3). The procedures that have been defined for the construction of the first phase of the road (8.500 km) are the same as those for the second phase (37.096 km). This assumption was validated by the technical staff in charge of the project on the basis of homogeneous topographic and climatic conditions, as well as minor variations in terms of vegetation (Daniel Limachi, Eng., personal communication, September 2015). Hence, it was assumed that the primary data that were provided for the first 3.24 km of the road are representative of its entire length.

The road is classified by the Peruvian Ministry of Transport as an unpaved road with an estimated average annual daily traffic (AADT) below 200 vehicles (MTC 2014). The material used to build the road is comprised mainly of a variety of small boulders of varying size, granular material (mainly gravel), and to a lesser extent, clay. Most of the material to build the road is obtained directly from the adjacent Alto Madre de Dios River.

Fig. 3 Progress in the construction of the Manu Road (September 2015). The photograph represents a typical section of the Manu Road, which is made up of a gravel road surface extracted from the nearby riverbed. The cleared areas can be distinguished from the surrounding undisturbed rainforest

Although the description of the project provided by the site engineers suggests a 3-m road width, measurements performed on-site indicate that the actual width is 5 m, at least along part of the planned trajectory. Similarly, the average thickness of the road was fixed at 65 cm, based also on a sample of measurements along the first section. No significant cuttings in the land were performed throughout the length of the road, which implies that excavation volumes were very limited. Due to the low budget of the project, as well as heavy rainfall and adverse soil conditions, different construction procedures have been implemented with respect to national guidelines (MTC 2014). Finally, the road is not lit or marked and does not have any traffic signs.

2.3 Data acquisition and life cycle inventory

Several data sources linked to the environmental burden of road components were identified in the literature (Hakkinen and Mäkelä 1996; Mroueh et al. 2000). However, geographical and temporal differences necessitated a modified inventory analysis.

Primary data were obtained mainly in two field trips organized in August and September 2015, in which a series of local actors, mainly the engineers leading construction of the road, provided substantial information that permitted modelling the characteristics and maintenance of the machinery and fuel consumption associated with construction (Daniel Limachi, Eng., personal communication, September 2015). These data, which are related to the construction of the first 3.24 km of the road, were extracted from the daily logbooks of the engineers, in which the use and maintenance of machinery, fuel consumption, and progress of the road were recorded.

Machinery used for construction of the road is listed in Table S1 of the Electronic Supplementary Material. A lifetime of 15 years was assumed for heavy-duty vehicles (HDVs), while 5 years were assumed in the case of pick-up trucks. Therefore, taking into consideration that the construction of the first 3.24 km of the road was performed in a 2-month period, machinery use, and maintenance allocation was limited to this length of time.

The production of diesel, used by the machinery, was obtained by the combination of ecoinvent® data and national regulations that stipulate a 5% ethanol content (i.e. diesel B5). Emissions linked to machinery fuel combustion were modelled based on chapter 1.A.3.b of the EMEP/EEA Air Pollution Emission Inventory Guidebook 2013 (EMEP-Corinair 2014). In the case of HDVs, Tier 1 diesel emission standards were used, assuming that the 2005 European average HDV fleet, prior to the introduction of EURO 4 vehicles, was a valid proxy for Peru in 2015.[1] For the transport of the engineers to the construction site, a large size passenger pick-

[1] The introduction of EURO 4 standards in Peru was expected on January 1st, 2016.

up diesel vehicle was modelled, following the same steps as for computing emissions. Sulphur emissions due to gasoline and diesel combustion were corrected based on data obtained from PetroPeru (2016a, b), assuming the maximum allowed content of sulphur for the different types of fuel.

Material for the road was modelled according to the data provided by the road technicians. A total of 6096 t of unbound granular material were estimated per kilometre of constructed road. The density assumed for this material was 2850 kg/m^3, given the fact that the raw data provided by the technicians was volumetric.

Data for the maintenance of the road was obtained from the previous stretch of road which is already constructed between Río Carbón and Nuevo Edén (approximately 79 km). Based on the information from this part of the road, the inventory was adapted to the FU of the production system. The identical climatic conditions, as well as the similarity in the characteristics of the two projects, permitted the assumption of these data as a solid reference for the road currently under construction. It should be noted that no weed control is performed for roads of this type in this region, according to Daniel Limachi (personal communication, September 2015).

Finally, data linked to the use of the road were modelled taking into consideration the predicted AADT (MTC 2014). Large gasoline pick-up passenger cars were assumed to transit the road. Hence, EURO 3 vehicles were assumed and their emissions were calculated using the Tier 2 standard for gasoline for light commercial vehicles (LCV). Dust emissions engendered by road transit were modelled using the AP-42 EPA standards (EPA 2006), as described in section 2.3.2. All inventory data shown in Table 1 refer to the FU, whereas Table 2 shows all the background system inventories that were modified from the ecoinvent® database to adapt these to the local conditions (Ecoinvent 2016).

Table 1 List of the main life cycle inventory items for the production system under analysis. Data referred to the functional unit: 1 km in 1 year of operation

Forest clearing		
Inputs		
Occupation, traffic area, road network	ha	0.133
Transformation, from tropical rain forest	ha	0.133
Transformation, to traffic area, road network	ha	0.133
Emissions to air (biogenic)		
Carbon dioxide—CO_2 (aboveground)	t	48.84
Carbon dioxide—CO_2 (belowground)	t	0.88
Methane—CH_4 (aboveground)	kg	1.30
Construction phase		
Inputs		
Gravel	kg	6095.8
Diesel B5	kg	212.7
Emissions to air		
Carbon dioxide (fuel emissions)	kg	668.32
PM > 10 (unpaved emissions)	kg	145.7
PM10 (unpaved emissions)	kg	47.92
PM2.5 (unpaved emissions)	kg	4.79
Maintenance phase		
Inputs		
Gravel	t	167.43
Diesel B5	kg	272.43
Emissions to air		
Carbon dioxide (fuel emissions)	kg	855.99
PM > 10 (unpaved emissions)	kg	2185.8
PM10 (unpaved emissions)	kg	718.87
PM2.5 (unpaved emissions)	kg	71.82
Traffic		
Inputs		
Number of vehicles	p	12,045
Gasoline	kg	843.15
Emissions to air		
Carbon dioxide—CO_2 (fuel emissions)		2686.2
PM > 10 (unpaved emissions)	t	6.14
PM10 (unpaved emissions)	t	3.12
PM2.5 (unpaved emissions)	kg	310.52

ha hectare, *t* metric ton, *kg* kilogramme, *p* piece

2.3.1 Modelling of GHG emissions from aboveground and belowground carbon stocks in the deforested area

The land on which the road is being built is densely vegetated, with the rainforest canopy reaching heights of up to 50 m. Asner et al. (2014) created a map of aboveground carbon density using Light Detection and Ranging (LiDAR) technology with a resolution of 1 ha for all regions in Peru. Data from this report were used to model the aboveground carbon removed from the area occupied by the road using data specific to the Madre de Dios region.

Belowground carbon storage was modelled following the recommendations of Saatchi et al. (2011). More specifically, belowground biomass (BGB) was modelled as a function of aboveground biomass (AGB), using the following equation:

$$BGB = 0.489 \times AGB^{0.89} \quad (1)$$

It should be noted that estimated total carbon was set at 50% of total biomass, following Mokany et al. (2006).

Once the amounts of above- and belowground carbon storage were estimated, it was assumed that all cleared vegetation is left as slash, without any removal of timber products, since marketable timber has already been removed from the area, or without any burning. The decay rate for the timber and slash left on-site was assumed at 0.1 year^{-1}, based on the data provided by Houghton et al. (2000). Hence, it was assumed that

Table 2 List and description of the main dataset modifications that were performed to be included in the life cycle inventory

Dataset	Database (D) or guidelines (G)	Action taken
Electricity, high voltage, production mix (Peru)	ecoinvent® 3 (D)	The electricity grid for Peru was adapted to that of year 2014 based on the methodology described in Vázquez-Rowe et al. (2015)
Diesel, production	ecoinvent® 3 (D)	Diesel B5 is the main type of diesel used in Peru. The use of sugarcane biomass to produce the 5% of biofuel in the blend was assumed
Unpaved road dust emissions	EPA (G)	Unpaved emissions for road machinery and passenger vehicles in the use phase (i.e. traffic)
Diesel, emissions—heavy-duty vehicles	EMEP/EEA (G)	Tier 1 emissions for heavy-duty vehicles (HDV) were modelled for the machinery used to construct and maintain the road. EURO3 emission standards were taken into consideration taking into account Peruvian legislation and the fact that machinery was recently purchased
Diesel, emissions—passenger cars	EMEP/EEA (G)	Tier 2 emissions for light commercial vehicles (LCV) were modelled for passenger pick-up cars. EURO3 and EURO4 emission standards were selected depending on the scenario considered
Transport, passenger pick-up, large size, gasoline, EURO 3	ecoinvent® 3 (D)	Transport for passenger cars was obtained based on ecoinvent® to account for car maintenance, as well as tyre and brake ware emissions. Road ware emissions and gasoline emissions were fixed as zero, given the fact that they were modelled elsewhere in the inventory using other guidelines. The amount of unleaded petrol used per kilometre was adjusted
Machinery	ecoinvent® 3 (D)	Transport for machinery was obtained based on ecoinvent® to account for car maintenance, as well as tyre and brake ware emissions. Road ware emissions and gasoline emissions were fixed as zero, given the fact that they were modelled elsewhere in the inventory using other guidelines. The amount of unleaded petrol used was obtained from primary data provided by the road technicians

by the end of the 15-year period under analysis, the pre-existing aboveground carbon stock in the area will have been completely transferred into the atmosphere. For belowground carbon stock, several studies point out that in areas were slash is left to decay on-site, there is actually an increase in carbon content in the soil for an initial period of approximately 2 years and, thereafter, a downward trend commences (Fearnside 1996). However, in this particular case, it should be considered that the initial deforested width was 20 m due to required machinery manoeuvres, but that subsequently the road will be only 5 m in width. Given the fact that roughly the first 65 cm of soil are removed in this 5-m area, it was assumed that all soil carbon is lost, whereas in the remaining 15 m, the regeneration of the vegetation implied that soil carbon stocks would keep relatively stable throughout the period assessed. Finally, an annual regeneration rate of 3.25 Mg C/ha following initial deforestation was considered for these 15 m on each side of the road, as shown in Fig. 4 (Houghton and Hackler 1999).

Emissions of GHGs due to deforestation were estimated following Fearnside (2000). Methane (CH_4) emissions due to the action of termites were assumed for 2.97% of the aboveground carbon being oxidized, whereas the remaining carbon was assumed to be emitted in the form of CO_2 (Martius et al. 1993, 1996). Emission factors for CH_4 were set at 653 g CH_4 per ton of aboveground oxidized carbon, whereas 3.8 t of CO_2 were considered per metric ton of total oxidized carbon (above- and belowground).

2.3.2 Modelling particulate matter formation due to vehicle transit

When machinery and vehicles travel through unpaved roads, the force of the wheels on the road surface causes the pulverization of the surface material (i.e. mainly gravel and sand). Most of this pulverization ultimately leads to the emission of particles to air, mainly PM-2.5 and PM-10. Therefore, we included modelled emissions of these particles using the emission factors provided by EPA (EPA 2006). Two different equations were used to model the emissions during road construction (see Eq. (2)) and due to traffic (see Eq.(3)):

$$E = k\left(\frac{s}{12}\right)^a \left(\frac{W}{3}\right)^b \quad (2)$$

$$E = k\,\frac{\left(\frac{s}{12}\right)^a \left(\frac{S}{30}\right)^d}{\left(\frac{M}{0.5}\right)^c} - C \quad (3)$$

where E is the emission factor for a specific size; s represents the percentage of surface material silt content; W constitutes the average weight of the vehicle; S represents the mean vehicle speed; M refers to the surface material moisture content; and C, the emission factor for 1980s vehicle fleet exhaust, brake wear, and tyre wear in the USA.

For the case of road construction, the data available were global and did not detail the distance travelled by trucks. In order to be able to use the calculated emission factors (see

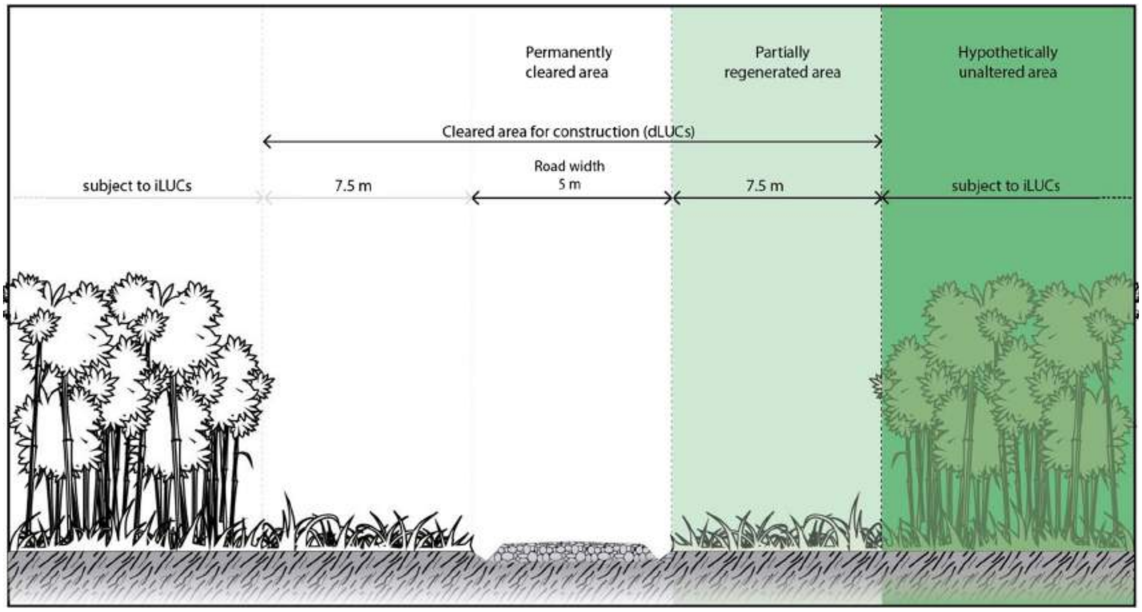

Fig. 4 Geographical representation of the width of the road, including dLUCs and plant growth recovery (Vector Open Stock 2016)

Tables S2-S4 in the Electronic Supplementary Material), it was necessary to assume for each trip the distance from the quarry to the road plus the average distance that was travelled to the construction site along the road. The total transport capacity of the trucks was used to determine the number of trucks needed to transport the road materials. This number was thereafter multiplied by the average distance described above, assuming round trips in all cases.

2.4 Life cycle impact assessment

The impact categories selected to perform the assessment were chosen to cover the widest range of categories possible (see Table 3). Firstly, given the importance of carbon storage and deforestation in tropical areas, the climate change (CC) impact category recommended by Hauschild et al. (2013) was used. To quantify this category, we follow the recently published IPCC guidelines (IPCC 2013), rather than the previous version (i.e. IPCC 2007). For the remaining impact categories, the ReCiPe method was used for a total of 17 different categories (Goedkoop et al. 2009).

2.5 Limitations of the study

The assumed road construction technique was based on a 3.24-km sample and the suggestions of local engineers. However, reality demonstrates that infrastructure projects tend to vary during the construction process. Additional limitations to the study are linked to assumptions made when building the background processes to support the foreground system. For instance, modelling of fuel production was not adapted to national refining conditions in Peru due to the lack of bibliography. However, diesel production was adapted to the B5 blend used in Peru and emissions were modelled accordingly following the EMEP/EEA guidelines (EMEP-Corinair 2014). Particulate matter emissions caused by pulverization were calculated using an empirical model developed by EPA

Table 3 List of impact categories used in the life cycle impact assessment phase

Impact categories		Assessment method
Abbreviation	Name	
CC	Climate change	IPCC 2013
OD	Ozone depletion	ReCiPe
TA	Terrestrial acidification	
FE	Freshwater eutrophication	
ME	Marine eutrophication	
HT	Human toxicity	
POF	Photochemical oxidant formation	
PMF	Particulate matter formation	
TET	Terrestrial ecotoxicity	
FET	Freshwater ecotoxicity	
MET	Marine ecotoxicity	
IR	Ionizing radiation	
ALO	Agricultural land occupation	
ULO	Urban land occupation	
NLT	Natural land transformation	
WD	Water depletion	
MD	Metal depletion	
FD	Fossil depletion	

(EPA 2006). It is possible that real soil and moisture content may differ from selected modelled values.

Despite these limitations, we note that this study does not intend to predict with exactitude the proposed case study, but to establish a benchmark to motivate further research in Peru and other tropical regions.

2.6 Sensitivity analysis

Uncertainty was observed in some of the methodological assumptions that were considered during the modelling of the production system. Hence, additional scenarios were created beyond the baseline scenario (A1), as shown in Table 4. Firstly, the baseline aboveground carbon storage that was assumed in the deforested land for the construction of the road was 96.4 Mg of C/ha. This value, which represents the average storage of carbon in the Madre de Dios region as determined in Asner et al. (2014), contains a level of uncertainty given the inclusion of urban and water bodies in its calculation. Consequently, three additional scenarios were considered: (i) the upper standard deviation (119.4 Mg of C/ha); (ii) the lower standard deviation (73.4 Mg of C/ha); and (iii) the average carbon storage in Madre de Dios without considering water bodies and urban land (99.3 Mg of C/ha). Belowground carbon was modelled in the sensitivity analysis following Eq. (1).

Secondly, the number of vehicles that will potentially circulate along the finalized road is another important source of uncertainty. Therefore, beyond the estimated traffic of approximately 33 vehicles per day, three additional scenarios were modelled, including 16, 50, and 200 vehicles per day. These estimates, as mentioned above, were justified based on the AADT. The Ministry of Transport in Peru assumes a range between 16 and 50 daily vehicles circulating along an unpaved road. Hence, an intermediate value of 33 vehicles per day, as well as the minimum and maximum forecasts, was assumed, as well as an additional scenario in which vehicles reach 200 on daily basis (MTC 2014).

Finally, an additional source was taken into account in terms of the emissions of vehicle transit. The baseline scenario assumed that all these vehicles corresponded to EURO 3 emission standards. However, scenario E1 models vehicle transit assuming that all vehicles will follow the EURO 4 emissions standards.

3 Results

3.1 Life cycle impact assessment linked to road construction

When analysing the environmental impacts following the A1 baseline scenario, the main impacts linked to road construction are attributable to machinery in most impact categories. Firstly, in the case of GHG emissions, 96% were due to the use of machinery throughout the construction of the road, whereas only 4% of the impacts were related to the transportation of staff and personnel to and from the construction site. More specifically, in terms of machinery, it appears that in the

Table 4 List of scenarios modelled for the computation of the results

Scenarios	Number of vehicles	Carbon stock in rainforest[a] (Mg of C per ha)
A1	33	96.4
A2	16	96.4
A3	50	96.4
A4	200	96.4
B1	33	119.4
B2	16	119.4
B3	50	119.4
B4	200	119.4
C1	33	73.4
C2	16	73.4
C3	50	73.4
C4	200	73.4
D1	33	99.3
D2	16	99.3
D3	50	99.3
D4	200	99.3
E1	33	96.4

Emission standards for all scenarios are EURO 3, except for scenario E1 which use EURO 4 standards

[a] Data obtained from Asner et al. (2014)

particular case of CC, diesel production and combustion are responsible for approximately 95% of GHG emissions, while only 5% can be linked to machinery production. Secondly, the remaining impact categories, with the exception of particulate matter formation (PMF), show a very similar trend, with over 90% of the impacts linked to machinery for the construction of the road. However, in the particular cases of metal depletion (70%), freshwater eutrophication (59%), and most toxicity categories (roughly 50%), these impacts are linked to the production of the machinery, rather than to the production and combustion of diesel. Finally, for the case of PMF, 96% of environmental impacts were attributable to unpaved road emissions in the form of PM-2.5 and PM-10, while the remaining impacts were linked mainly to the combustion of fuel (see Table 5).

3.2 Life cycle impact assessment linked to road maintenance

Road maintenance environmental impacts, not only in terms of GHG emissions but also across the remaining categories, showed very similar trends in relative terms to those for the construction phase due to the identical machinery and transport conditions modelled in both subsystems. However, in absolute values, the impacts in terms of maintenance were substantially higher given its annual periodicity. Hence, the maintenance of the road in 1 year of operation implied a net emission of 2.33 t CO_2eq per FU (127% higher than for the construction phase) and approximately 0.8 t PM1 0 eq in terms of PMF, representing a 14-fold increase with respect to the construction phase (see Table 5).

3.3 Life cycle impact assessment linked to traffic

Environmental impacts linked to traffic along the road are attributable exclusively to the traffic circulating along its length. Given the uncertainty behind the AADT calculation, several different scenarios (see section 2.6) were taken into consideration to account for this circumstance. Needless to say, the environmental impacts in this phase will be linear to the AADT as long as we assume a ceteris paribus situation. The selection of EURO 3 gasoline large passenger trucks as the only type of vehicle circulating through the road may be a proxy that reflects reality to a certain extent, considering that smaller vehicles will most likely not circulate along this infrastructure unless it becomes a paved network. However, the recent enforcement of importing EURO 4 newly purchased vehicles was modelled in scenario E1, assuming that all

Table 5 Environmental impact results per impact category and subsystem. Data referred to the functional unit: 1 km in 1 year of operation

Impact category	Unit	dLUCs	Construction phase	Maintenance phase	Traffic	Total
CC	kg CO_2 eq	31,898	1024	2333	3649	38,904
OD	mg CFC-11 eq	0.00	151.4	308.3	615.0	1075
TA	kg SO_2 eq	0.00	7.01	15.03	9.76	31.80
FE	g P eq	0.00	43.8	440.4	106.4	590.5
ME	g N eq	0.00	438.9	1428	564.8	2431
HT	kg 1,4-DB eq	0.00	77.1	706.7	318.1	1102
POF	kg NMVOC	0.01	7.73	15.15	10.90	33.80
PMF	kg PM10 eq	0.00	54.93	795.5	3429	4279
TET	kg 1,4-DB eq	0.00	0.78	1.27	0.43	2.47
FET	kg 1,4-DB eq	0.00	2.54	21.76	16.74	41.05
MET	kg 1,4-DB eq	0.00	2.34	20.29	16.95	39.57
IR	kBq U235 eq	0.00	61.0	168.1	251.3	480.4
ALO	ha*a	0.00E+00	2.73E−03	8.99E−03	1.39E−03	1.31E−02
ULO	ha*a	1.33E−01	4.98E−04	1.58E−03	6.93E−04	1.36E−01
NLT	ha	1.33E−01	2.96E−05	6.05E−05	1.20E−04	1.34E−01
WD	m^3	0.00	3.90	5.36	3.03	12.29
MD	kg Fe eq	0.00	25.87	317.6	35.68	379.2
FD	kg oil eq	0.00	292.5	689.7	1208	2190

CC climate change, *OD* ozone depletion, *TA* terrestrial acidification, *FE* freshwater eutrophication, *ME* marine eutrophication, *HT* human toxicity, *POF* photochemical oxidant formation, *PMF* particulate matter formation, *TET* terrestrial ecotoxicity, *FET* freshwater ecotoxicity, *MET* marine ecotoxicity, *IR* ionizing radiation, *ALO* agricultural land occupation, *ULO* urban land occupation, *NLT* natural land transformation, *WD* water depletion, *MD* metal depletion, *FD* fossil depletion, *ha* hectare, *kg* kilogramme, *g* gramme, *mg* milligramme, *a* year, m^3 cubic meter passenger cars would comply with this emission standard. While this scenario achieved substantial improvements in terms of photochemical oxidant formation (30%), these are minimal for CC (2%) and non-existent for PMF when compared to A1.

Finally, an additional aspect that must be considered is the fact that Tier 2 modelling for LCVs was used to model the emission of these vehicles. Although no scenarios were considered to reflect the modelling with Tier 1 or Tier 3 perspectives, it should be noted that the level of detail that can be accomplished in Tier 2, but especially Tier 3, guarantees increased precision as compared to Tier 1.

3.4 Life cycle impact assessment of the entire road system

When the baseline scenario (A1) is followed to monitor the environmental impacts of the road, 82% of total CC impacts are a consequence of dLUCs due to clearing for road construction. These impacts are linked to the emission of CO_2 from above- and belowground biomass, although these are partially attenuated thanks to the regeneration of vegetation along the edge of the road (see Fig. 3 for a graphical representation).

Figure 5 shows how different assumptions may enhance or diminish the importance of dLUCs in the CC impact category, with relative contributions ranging from 43.1% (scenario C4) to 89.3% (scenario B2). These variations are due mainly to the sensitivity analysis described in section 2.6. Nevertheless, despite the remarkable variation observed between scenarios, only a very high AADT, assuming the lower SD of carbon stock in the deforested area, would imply that dLUCs are not the main contributing process to GHG emissions, whereas in 11 out of 17 scenarios, their contribution is above 75% of total impacts.

For the remaining subsystems, the construction phase represents 2.6% of the total GHG emissions in the A1 baseline scenario, whereas maintenance reaches a value of 6%. It should be noted that the absolute values for these two subsystems do not vary given the fact that these were not subject to sensitivity analysis. Therefore, the variation in their relative contributions across the remaining scenarios is due to absolute changes in dLUCs and traffic. Finally, the CC contribution of traffic is directly dependent on the AADT modelled in each scenario. In A1 (i.e. 33 vehicles per day), this contribution represents 9.4% (3600 kg of CO_2eq per FU), whereas in scenario C4 (i.e. 200 vehicles per day), it represents 49.4% (22,400 kg of CO_2eq per FU).

For impact categories other than CC, traffic had the highest environmental impacts across most of them, especially in terms of PMF (80.1%), ozone (57.2%), and fossil (55.2%) depletion and ionizing radiation (52.3%) when the A1 baseline scenario was used as the reference. In contrast, machinery used in the construction and maintenance phases had high contributions in terms of metal depletion, eutrophication (marine and freshwater), and terrestrial acidification. When comparing these results to other scenarios proposed, C4 presented the highest relative contributions for traffic in PMF (96.1%), ozone (89%), and fossil (88.2%) depletion. In fact, traffic in this scenario constitutes the main impact in all categories (including CC), except for land occupation and transformation categories, and metal depletion.

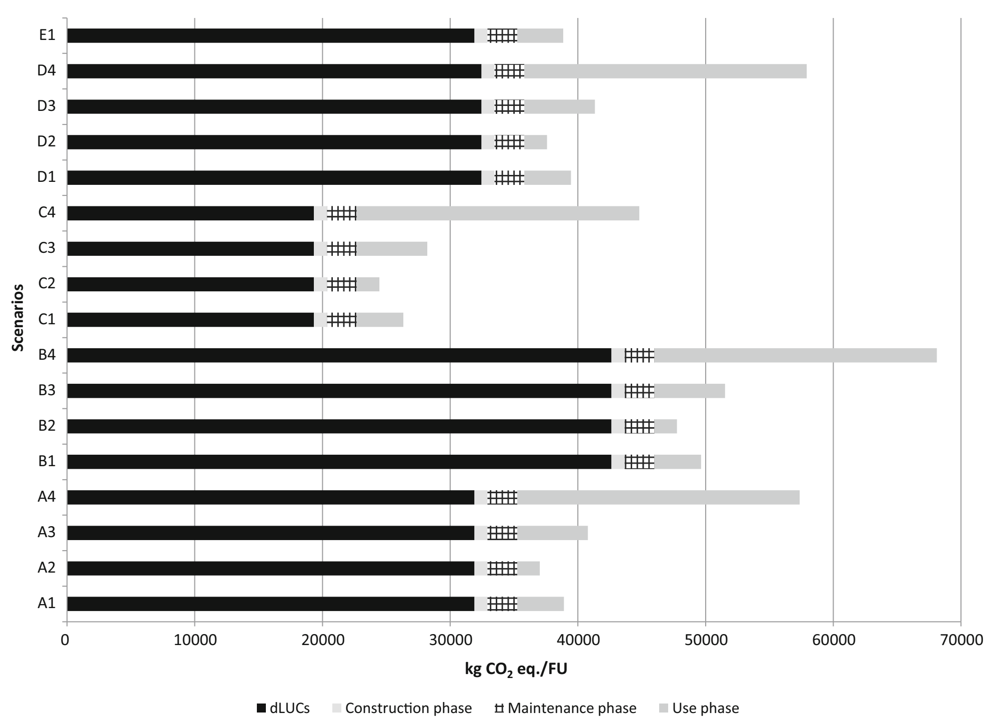

Fig. 5 GHG emissions per subsystem for the different scenarios. Results computed using the IPCC assessment method (IPCC 2013)

4 Discussion

4.1 Comparison with previous LCA studies of road construction projects

Although a number of studies have applied LCA to transportation infrastructure (e.g. Lundström 1998; Mroueh et al. 2000; Stripple 2001; Birgisdóttir et al. 2007), apparently, none have considered an unpaved road through similar, tropical rainforest conditions, making our results difficult to compare. This difficulty is due firstly to the specific parameters considered for in the designation of each FU, secondly to the stages of the whole life cycle considered in the system boundaries, and finally to the difference between the scope and goals set according to each study objective.

Despite these drawbacks, inventory data from two previous road LCA studies allowed us to estimate GHG emissions to perform a rough comparison. On the one hand, an asphalt road model in Sweden was considered (Stripple 2001). On the other, a natural mineral aggregated road in Finland, analysed by Muench (2010), was selected. The comparison was limited to CC given the fact that it is the most repeatedly used impact category in the literature and, therefore, it is relatively simple to reproduce. The two studies selected (see Table 6) utilize similar FU dimensions and the results were interpolated to match the FU used for the Manu Road.

Unlike the studies included in Table 6, construction and maintenance of the Manu Road accounted for almost 90% of net GHG emissions, whereas in the other two, over 89% of total emissions were attributable to traffic. This reflects the fact that the local conditions of the road under consideration here—unpaved and built through carbon-rich yet sparsely populated tropical forest—are very different from those of roads built in temperate areas of the world, which generally support heavier traffic volumes, greater use of processed materials in construction (e.g. asphalt and tarmac), and lower impacts in terms of LUCs.

An interesting finding was the fact that the life cycle inventories that are available in commonly used databases use standard paved roads as background processes for most datasets, without considering the fact that in tropical rainforest areas numerous raw materials are extracted and transported for hundreds of miles along underdeveloped road networks. For instance, in the case of ecoinvent® v3, the only road construction process available refers to a standard road in which a series of inputs, such as bitumen, steel, and concrete materials, or gravel crushing processes, are included as proxies (Ecoinvent 2016). While this process may constitute a representative reference for this type of infrastructure in most European and U.S. road network systems, we argue that in the case of Peru (and most nations globally), in which approximately 86.7% of the network is comprised of unpaved roads (CIA 2016), this inventory dataset is far off from average Peruvian transport conditions.

Our results highlight the importance of modelling unpaved roads in the tropics that have been largely overlooked to date. However, other unpaved roads should be analysed in the future in order to determine whether the environmental burden carriers identified in this study are also the main contributors in other contexts. For instance, it seems reasonable to assume that GHG emissions would tend to decrease substantially in areas where the carbon stock is lower or deforestation is not necessary to build a road, while PMF impacts would increase in areas with higher projected transit.

4.2 Utility of applying life cycle assessment to the analysed production system

It may seem evident that the impacts linked to climate change attributable to the global road system will probably draw the most attention from stakeholders and readers given the intense

Table 6 Comparison of environmental impact results with two other studies available in the literature

CO_2eq (t) emissions per year of operation for 1 km of road			
Author	Stage	CO_2eq emissions (t)	Percentage from total
Stripple[a,b]	Construction and maintenance	4.93E+01	10.4
	Traffic	4.93E+01	89.6
Mroueh[c]	Construction and maintenance	7.60E+00	1.2
	Traffic	6.30E+02	98.8
Current study[d]	Construction and maintenance	3.53E+01	89.9
	Traffic	3.65E+00	10.1

[a] 13-m width section, 50-year period, 5000AADT, operation stage excluded

[b] CO_2eq emissions for traffic were modelled using 0.1 l of petrol/km and 3.18 kg of CO_2 per kg of petrol, emissions factor obtained from EMEP-Corinair (2014)

[c] 17-m width section, 50-year period, 7000 AADT

[d] 5-m width section, 15-year period, 200 AADT

ongoing debate surrounding this specific environmental impact (MINAM 2015). Based on predictions that 90% of the 25 million km of new roads projected to be built by 2050 will be in developing countries (Dulac 2013; Laurance et al. 2014), it can be assumed that most of this global network will suffer limitations in terms of planning. Hence, the removal of enormous amounts of above- and belowground carbon across vast areas of tropical rainforest could become a major problem (Laurance et al. 2015).

Beyond carbon stock removal and CC, other categories should also be analysed in depth in order to determine their local or regional impacts. For instance, in the case of PMF, it should be noted that more than 95% of these are due to the traffic (fuel and dust emissions) along the road, introducing new health hazards to local indigenous communities.

Extraction of gravel and other material from the nearby river was not quantified. The rationale behind this decision lies in the fact that these materials are depleted at a rate that we consider overwhelmingly inferior to the dragging effect of the river, which guarantees the replenishment of this type of material as long as extraction activities do not increase exponentially (Eddy and Gergel 2015). The seasonal growth of the river in terms of volume also has an important landscaping effect, implying that human-induced changes to the landscape in the flooding area of the fluvial course will tend to disappear after the wet season.

Nevertheless, it should be noted that, despite the thoroughness of the current assessment that considers 18 different impact categories, there remains a series of non-quantified environmental impacts that might potentially derive from the execution of the Manu Road. Immediate and long-term edge effects, including desiccation of the rainforest surrounding the road and ecophysiological effects on bordering trees (Kunert et al. 2015), road-induced mortality of local fauna (Beebee 2013), the withdrawal of fauna from adjacent areas to the road or barrier effects in which populations are split (Suárez et al. 2013), and reduced gene flow threatening the long-term viability of species (Bonaudo et al. 2005), are just some examples of environmental impacts that are bound to occur when constructing roads in the rainforest (Goosem 2002). These, however, are not directly quantifiable through life cycle-oriented studies in their current state of development (Reap et al. 2008a, b).

The lack of life cycle methods to analyse some of these impacts justifies our decision to limit the life cycle impact assessment to the midpoint level, while excluding the environmental damage that is monitored through endpoints, since these endpoints would be substantially underrepresented and results would have a very high degree of uncertainty (Weidema 2015). In fact, this observation is in line with that identified by Hauschild et al. (2013), in which the authors point out that very few endpoint characterization models have developed to a level in which their recommendations are meaningful enough to be used in decision-making. Having said this, it should be noted that some of the midpoint impact categories used in the current study also have certain limitations when implemented in South America, since the characterization factors may not be completely adapted to regional characteristics. This may be the case for ozone formation, eutrophication and, most importantly for the discussion of this paper, particulate matter formation. Nevertheless, it is often mentioned that the heterogeneity of the European continent implies that European-based assessment methods (i.e. ReCiPe) can usually be used as a good proxy in other, also highly heterogeneous continents (EC-JRC 2012).

Therefore, we suggest that the inclusion of at least some of the life cycle indicators considered in this study could be a valuable contribution to the Environmental Impact Assessment (EIA) of roads in ecologically fragile areas, especially in the tropics. Although the implementation of an LCA within the EIA may be costly and time consuming, the method described in this paper could be part of a group of tools to aid stakeholders involved in planning, promoting, and evaluating road projects, to ultimately determine if a specific project should be implemented or discarded (Laurance et al. 2014).

5 Conclusions

Our study is, to the best of our knowledge, the first to use LCA to analyse the construction, maintenance, and operation of an unpaved road through tropical rainforest. The depletion of raw materials for the construction and maintenance of the road under study was low in comparison with other, more sophisticated roads studied elsewhere. However, the derived environmental impacts due to construction of the road are significant in terms of CC and PMF due to deforestation and dust emissions, respectively. In fact, an outstanding finding reveals that unpaved roads built in the Amazon rainforest have a completely different behaviour than those available in the literature. For instance, as shown by Muench (2010), traffic is the dominant energy user and, consequently, the main cause of GHG emissions in conventional paved roads. Although traffic is still the main energy carrier, this causality does not stand in unpaved roads in the Amazon, since most GHG emissions are linked to rainforest clearing in the construction phase.

Unpaved roads represent a large proportion of the entire road network worldwide, especially in developing tropical countries, playing a crucial role in the transportation of raw materials. Furthermore, it is expected that road infrastructure will expand explosively in decades to come (Laurance et al. 2014). Therefore, we suggest that LCA studies can and should improve the modelling of roads in terms of life cycle inventories, especially in tropical environments. The use of the methodology presented in this study could serve as a proxy for future studies.

Anthropogenic threats to remote rainforest regions may escalate due to increased human activity and iLUCs associated with the projected increase in road density, as recent oil spills, a dramatic increase in illegal gold mining, and deforestation in the Peruvian Amazon associated with new road and other infrastructure projects in the region demonstrate (The Guardian 2016). In fact, according to Oliveira et al. (2007), 75% of the degradation and/or clearing of Peruvian rainforest have occurred in areas that were within 20 km of a road.

Furthermore, these same authors state that the creation of new protected areas in Peru in recent decades, as well as the inherent remoteness of many Amazon areas in Peru, including the region surrounding the Manu Road—in other words, road-less areas—constitutes a barrier to further deforestation and forest degradation. Further research should monitor the environmental consequences, especially in terms of biodiversity loss and GHG emissions that iLUCs may engender (Foley et al. 2005; Vázquez-Rowe et al. 2014).

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