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Kouadio Assemien François Yao, Yao Blaise Koffi, Olivier Belcourt, David Salze, Lasm Théophile, et al.. Mining impacts assessment using the LCA methodology: case study of Afema gold mine in Ivory Coast. Integrated Environmental Assessment and Management, 2021, 17 (2), pp.465-479. 10.1002/ieam.4336 . hal-02952592

HAL Id: hal-02952592
https://imt-mines-ales.hal.science/hal-02952592

Submitted on 26 Jul 2023

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Mining Impacts Assessment Using the LCA Methodology: Case Study of Afema Gold Mine in Ivory Coast

Kouadio Assemien François Yao,†‡ Blaise Koffi Yao,‡ Olivier Belcourt,† David Salze,† Théophile Lasm,‡ Miguel Lopez-Ferber,† and Guillaume Junqua†*

†LGEI, IMT Mines Alès, Université de Montpellier, Alès Cedex, France
‡UFR STRM, Université Félix Houphouët-Boigny, Abidjan, Ivory Coast

ABSTRACT

Environmental impact assessment studies are mandatory for major industrial or infrastructure projects in most countries. These studies are usually limited to on-site impacts during exploitation but do not consider indirect impacts generated off-site or those concerning other steps of the project, including dismantling. National regulations in various countries have recently begun to include these neglected impacts to obtain a better appreciation of project trade-offs. Several scientists have highlighted the substantial potential of using the life cycle assessment methodology to increase the level of detail and completeness of environmental impact assessment (EIA) studies. Even if mining activities are known to produce significant local impacts, their consequences outside an extraction site have not yet been well documented. The implementation of the life cycle assessment (LCA) methodology in the EIA procedure has been carried out in a Au mining project by separating on-site and off-site impacts during the entire life cycle of the mine from prospection to site restoration following the end of exploitation. Mining projects occur over large time periods and require diverse materials and processes. The main difficulty of such analysis is the data collection that needs to be extrapolated for some of the activities. Even with these limitations, the Afema case study highlighted the significant share of off-site impacts (from a spatial perspective) and the major contribution of the exploitation phase of the mine (from a temporal perspective). Operating activities, especially excavation, ore, and waste rock transportation, blasting, ore processing, and tailing treatments, are the main impacts produced during the exploitation phase and are involved in climate change, particulate matter formation, and land destruction. Therefore, this standardized LCA method should be recommended by the regulatory authorities for use in EIA procedures.

Keywords: Mining industry   Life cycle assessment   Environmental impact assessment   On-site impacts   Off-site impacts

INTRODUCTION

An environmental impact assessment (EIA) is a widespread and legally required procedure used to support local decision making. The objective of an EIA is to evaluate the environmental impacts of a project and to reduce or compensate them. The EIAs rely on different tools involved in all stages of the procedure (screening, scoping, identifying impacts, assessing impacts, developing mitigation measures, reporting, etc.). Ogola (2009) argued that EIA practitioners are free to use the best available methods or models and their own expertise to obtain the most accurate estimate of the environmental impacts of a project. Such impacts may affect the place under study or other locations in a direct or an indirect way. However, in most EIAs, the approach taken does not allow us to consider impacts generated outside a study location, even if the impacts are caused by the activity under consideration.

A life cycle assessment (LCA) is a holistic approach that considers all potential environmental impacts generated by an activity. Although originally focused on products and services, its application domain has recently expanded to organizations, including specific sites (ISO 2014; Larrey-Lassalle et al. 2017). A LCA accounts for all potential impacts, direct or indirect, local or global. Several authors, such as Tukker (2000), Finnveden and Moberg (2005), Manuilova et al. (2009), Jeswani et al. (2010), Potting et al. (2012), Židonienė and Kruopienė (2014), and Bidstrup (2015), have thus suggested the use of the life cycle assessment approach to complement EIA studies, providing a larger scope. However, a classical LCA does not differentiate the impacts occurring at a given location from those occurring elsewhere. The development of site-dependent LCIA methodologies allows clustering of potential impacts as a function of location. Accordingly, Manuilova et al. (2009) believe that there is a high potential to apply these

* Address correspondence to kouadioyao.assemien@gmail.com

models to EIA to increase the level of detail and accuracy of environmental assessments. Tukker (2000) and Manuilova et al. (2009) considered that LCAs allow the consideration of emissions and effects related to upstream and downstream activities in a supply chain, not only at the location of the process itself. Such indirect impacts of projects can be higher than direct impacts (Potting et al. 2012; Larrey-Lassalle et al. 2017). Inclusion of potential impacts taking place outside of a project location is strongly encouraged in Europe by EU Directive 2014/52 "On the assessment of the effects of certain public and private projects on the environment" (European Parliament and Council of the European Union 2014).

Furthermore, regarding the nature of impacts, some regulations, such as the European directive (Larrey-Lassalle et al. 2017) or those of the Ivory Coast, emphasize the need to expand the impact categories considered in an EIA to include resource depletion, energy, climate change, and human health. An LCA is a holistic approach, and such categories are systematically taken into account. Larrey-Lassalle et al. (2017) compare EIAs that do and do not integrate an LCA approach for a wastewater treatment plant in France. The authors determined that including an LCA approach in the EIA led to significant improvements in the EIA due to the assessment of off-site impacts generated by background activities and the consideration of additional impacts, such as climate change or resource depletion, that were previously neglected in EIAs.

Metals are important raw materials extracted from the environment. They are found in most products and industries, such as buildings, electronics tools, and pharmaceutical industries (Durucan 2006; Santero and Hendry 2016; Cenia et al. 2018). Obtaining metals in the appropriate form requires various steps, often carried out in different locations and with a large range of environmental impacts. More specifically, mining activities, whether open-pit or underground, can induce local impacts on soil, water, and air and considerable impacts outside of the mine area due to the use of considerable amounts of energy imported from other locations (Ferreira and Leite 2015). These characteristics suggest that LCA approaches will improve EIAs of such projects. However, to date, the use of an LCA in an EIA analysis in the mining sector is not common.

LCAs have been used to assess environmental impacts associated with various production processes of the mining industry since the end of the last century (Valderrama et al. 2012), but their use in the mining and mineral processing sector is still limited (Durucan et al. 2006). This limited use of LCAs is in part due to the difficulty of quantifying the various inputs and outputs involved (Norgate et al. 2007). Table 1 summarizes the main LCA studies (nonexhaustive list) in the mining and mineral processing sector. This table presents the goals, system limitations, and impact categories assessed.

Many studies (Durucan et al. 2006; Awuah-Offei et al. 2009; Norgate and Haque 2010; Awuah-Offei and Adekpedjou 2011; Haque and Norgate 2014) have focused on specific midpoint impact categories (1 or more) but have not consider evaluating the endpoint damages on human health or ecosystem quality. Reid et al. (2009) and Ferreira and Leite (2015), in addition to midpoint impact categories, quantified endpoint damages related to the tailings management of the Louvicourt mine (in Quebec) and the cradle-to-grave iron ore processing in a mine (in Brazil), respectively. Reid et al. (2009) focused their work on the development, exploitation, and closure phases related to the management of mining waste but did not consider all of the mining activities. Although Ferreira and Leite (2015) included several mining activities, including mining, processing, transporting, and disposing industrial waste, they did not distinguish between off-site and on-site impacts.

Among the LCA studies carried out to evaluate mining processes and processing of mineral resources, none have addressed the benefits of integrating an LCA into the mining EIA process. Even if mining activities have been recognized as producing important local impacts, their influence in the rest of the world has not been well documented. It is thus necessary to appreciate the location of the impact during the different steps of a mining project life cycle. The key issue in this context is how to allocate the responsibility for environmental impacts at local and global scales. Eder and Narodoslawsky (1999) and Loiseau et al. (2013, 2014) have addressed this territorial responsibility issue in terms of environmental impacts. Three categories of territorial responsibility have been proposed: "consumption-based," "production-based," and total responsibility for a territory (Eder and Narodoslawsky 1999). Here, we used the total responsibility of the territory. Territorial responsibility accounts for all of the impacts related to consumption activities and the impacts of imported goods and services (life cycle thinking). Territorial accountability also accounts for the impacts related to goods and services produced within the geographical borders of the territory. However, the impacts related to the distribution, use, and end-of-life handling of exported goods and services are not attributed to the territory studied (we will return to this in the *Methodology* section).

Therefore, this paper aims to determine the overall impacts of all of the life stages of a Au mine (Afema mine) in the Ivory Coast by implementing a territorial LCA within the EIA. The territorial LCA will then allow the direct (on-site) and indirect (off-site) impacts to be separated.

METHODOLOGY

Case study description

The case study relates to the Afema mine located in the Aboisso district (southeastern Ivory Coast) (Supplemental Data Appendix S1). Previous mining operations were carried out from 1992 to 1998, exploiting only the oxidized ore. With the new exploitation, the opencast mining technique was retained. The mineral resources identified were 10.1 million t of Au ore with a grade of 2.4 g/t Au (Rockstone Gold 2013).

Table 1. Main life cycle assessment (LCA) studies in the mining and mineral processing sector (nonexhaustive list)

References	Objectives of the LCA study	System boundaries	Functional unit	Impacts categories
Durucan et al. (2006)	Developing a tool (LCA database) to represent the mining system in a comprehensive way: case study of a bauxite mine	– Ore extraction (production) – Ore processing – Waste handling	—	Acidification – Climate change – Human toxicity – Ecotoxicity eutrophication – Abiotic resources depletion
Yellishetty et al. (2009)	Present a critical review of existing LCA methods in the mining and metals sector and discussed a number of related issues	—	—	—
Awuah-Offei et al. (2009)	Evaluating the environmental impacts of belt conveyors and truck haulage systems in a surface Au mine located	Rock (ore) transportation	Hauling of 4000 t/h of rock from pit to dump sites	Climate change Acidification
Reid et al. (2009)	Quantify and compare the environmental burdens related to different scenarios of mine tailings management methods and to evaluate the contribution of the land-use category to the overall impact	– Development stage – Exploitation/operation – Closure	Handling of 13.3 Mt of tailing	– All the midpoint impact categories of the IMPACT 2002+ method – All the damage categories of the IMPACT 2002+ method
Norgate and Haque (2010)	Determine the energy consumption and greenhouse gas emissions of various steps of mining and mineral processing operations to identify the steps that require efforts to reduce these impacts. Case study of Fe, bauxite and Cu	Ore extraction: Drilling, blasting, ventilation and dewatering (for Cu), loading/haulage Ore processing: crushing/grinding, concentrating (for Cu), beneficiation (for bauxite)	1 t of ore or concentrate ready for ship loading	– Energy consumption (Embodied energy) – Greenhouse gas emissions (climate change)
Awuah-Offei and Adekpedjou (2011)	A review of the current application of LCA in the mining industry. Discussion and recommendations to increase the application of LCA in the mining industry	—	—	—
Norgate and Haque 2012	The environmental profile of Au production with regards to embodied energy, greenhouse gas emissions, embodied water and solid waste burden	– Mining – Au production: comminution (crushing & grinding), metal extraction (cyanidation), recovery and refining	—	Embodied energy Greenhouse gas emissions (climate change)
Haque and Norgate (2014)	Determining the GHG footprint of In situ leaching (ISL) mining and comparing it with that of conventional mining methods (open pit and underground mining): case study of U, Cu, and Au mines	– Extraction of U from the ore-body (ISL), separation and processing as U_3O_8 as a product in the form of yellowcake – Extraction of Au (ISL), cyanidation, electrowinning/smelting and, refining – Extraction of Cu (ISL), solvent extraction and, electrowinning	1 kg of U as yellowcake 1 kg of Au (metal) 1 kg of Cu (metal)	Greenhouse footprint (climate change)

(*Continued*)

Table 1. (*Continued*)

References	Objectives of the LCA study	System boundaries	Functional unit	Impacts categories
Ferreira and Leite (2015)	Evaluate the effect of mining activities and cradle-to-gate Fe ore processing in a mine in Brazil	– Mining: dismantling, loading and transportation of ore and waste, extraction, production and transportation of raw materials, supplies and equipment to the company, as well as the generation of electricity and its transmission to the mining site – Processing: crushing, milling – Support system: personnel and generation transportation activities, transportation and disposal of industrial waste	1 t of Fe ore concentrate	– Water use – Land use – Energy consumption – Damage to human health – Loss of ecosystem quality – Abiotic resources depletion and – Climate changes
Masindi et al. (2018)	Identify the environmental performance and the main environmental hotspots of a robust AMD treatment method	Post-closure phase: Magnesite treatment – Lime treatment – Soda ash treatment – CO_2 bubbling	The effective treatment of 1 m3 of AMD	ReCiPe midpoint categories ReCiPe endpoint categories
Cenia et al. (2018)	Quantify the energy requirement and the CO_2 emissions for small-scale Au mining in the Philippines	– Ore mining – Comminution (crushing, milling) – recovery (ore processing) – Refining	100 g Au	– Energy consumption (Embodied energy) – CO_2 emissions
Chen et al. (2018)	Assesses the environmental impacts of Au production in China by using life cycle assessment	– Raw materials and energy production – Waste disposal – Transport of raw materials – Direct emissions of all stages of Au production	1 kg Au production	ReCiPe midpoint categories ReCiPe endpoint categories

From a geological point of view, the formations found can be grouped into 2 main types: metavulcanites and metasediments (Assié 2008). The contact zone of these sets represents the mineralized area (shear zone) oriented Northeast-Southwest (Supplemental Data Appendix S1). This ore composition indicates the method of exploitation and the major contaminants that could be released to the environment.

The region of Afema has a subequatorial climate (Assié 2008). Annual rainfall is high (approximately 1600 mm/y).

Afema mine LCA case study

Goal and scope definitions. The objectives of this study are to assess the environmental impacts of the Afema Au mine to determine the importance of off-site effects based on territorial responsibility in terms of environmental impacts. Therefore, this work aims to determine the impacts generated by activities carried out on-site at the mine (on-site effects and impacts or direct impacts) and the impacts caused by activities carried out in other territories but whose products (materials and energy) are used on-site at the mine (off-site effects and impacts or indirect impacts). To carry out this effort, as shown in Azapagic et al. (2007) and Loiseau et al. (2013, 2014), it is important to differentiate the foreground system (which corresponds here to activities taking place within the geographical borders of the mine site) from the background system (representing all activities required for mining activities but located off-site) (Figure 1).

The functional unit (FU) was defined as the production of 1 kg of Au, and the reference flow was set at 1 kg of Au produced.

A careful selection of the system boundaries has an important influence on an LCA (Alyaseri and Zhou 2017). The boundaries of the system include all of the phases of the mine: exploration, construction, operation, and rehabilitation (Figure 2). Each of the mine stages contains several processes, including material production and transport, equipment transport and operation, machinery operation, and electricity and diesel consumption. The ore extracted from this opencast mine is sent to a processing plant (mill) to extract minerals with a market value. The transport of waste rock and ore from the pits to the processing plant was also considered. Furthermore, the tailings produced as a pulp must be managed properly to minimize their environmental impacts.

For the exploration stage, only the clearing of vegetation to construct exploratory trenches was considered because the trenches are opened manually. Indeed, in the mining context, the exploration stage can be carried out, and it is only after a long time, when economic and technical conditions justify the profitability of an extraction, that the mine will open. Therefore, it can sometimes be difficult to obtain data covering all of the activities of this first stage.

The development stage includes all of the preparation and construction activities (offices, accommodations, plants, waste dams, etc.) related to the mine. The operating stage also includes clearing activities, drilling, and blasting. Excavation operations and ore transport as well as waste management were also considered. Finally, the rehabilitation stage encompasses all of the actions needed to return the site back to a state as close as possible to the initial one.

The clearing of vegetation is carried out by dozers. Excavation operations are also performed by dozers and with the use of explosives. Ore is transported from the pit to the processing plant by off-road diesel trucks. The same applies to waste from the pit to the waste storage areas.

At the processing plant, the ore undergoes comminution (crushing and milling), recovery, and refinement to Au. The cyanide leaching process (CIL) is used. The tailings produced as a pulp are pumped to the tailing's ponds. After settling the sludge, the supernatant is pumped back to the wastewater plant for treatment. Then, it is reintegrated into the factory's operating circuit. The settling will undergo appropriate treatment.

The operating time of the machines for housing and office construction in the mining camp were not considered in the study. The same was true for dismantling equipment at the

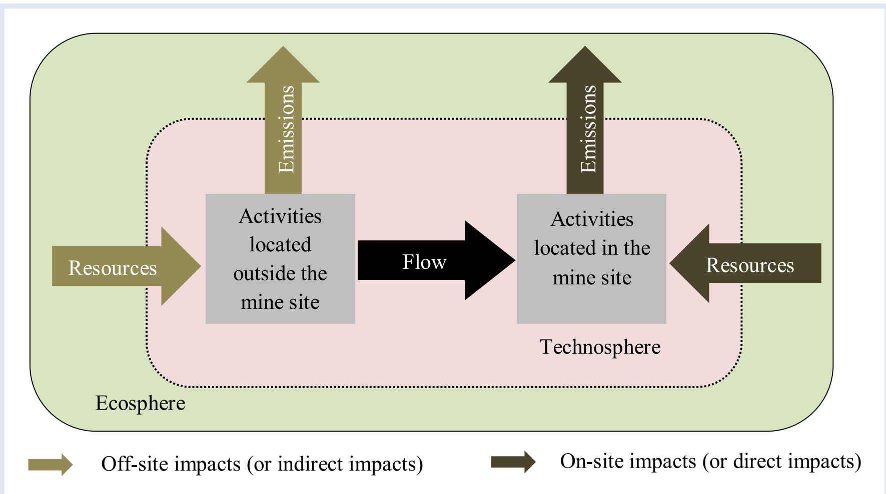

Figure 1. Studied system boundary differentiation between direct impacts and indirect impacts (adapted from Loiseau 2014).

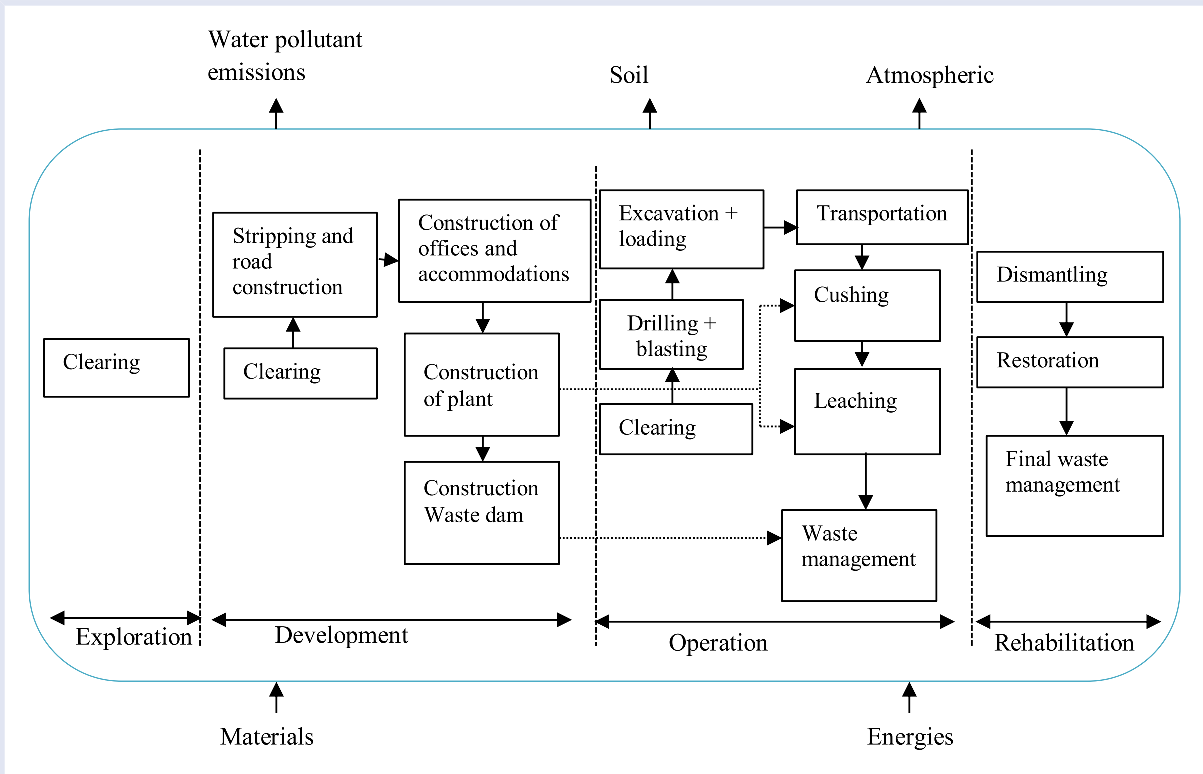

Figure 2. System boundaries.

end of the mine's life. In addition, the need for food and electricity consumption, access to health care, and many other needs of mine employees were not included in the study.

Data collection and main assumptions. Environmental modeling was performed using the SimaPro 8.3 software package based on the LCA methodology (ISO 2006a, 2006b). For each of the mine stages, the materials, energy, and equipment were defined. LCI data for the system under study were collected from a number of sources. They consisted of primary and secondary data. The primary LCI data refer to the data retrieved from the same mine EIA report (Rockstone Gold 2013) and the data obtained during the field visits, as well as those from the processing of the satellite images. The data provided by the EIA report included the mine plan, the geology of the mine area, the ore grade, the average operating time (9 y), and the equipment and heavy machinery required. Satellite images (Landsat 8 OLI/TIRS) were analyzed using ENVI 5.1 software. Combining the results of this analysis with the information provided by the EIA report on the mine plan, the type of vegetation (natural forest, crops, etc.), and the area to be cleared for the needs of the mine were estimated.

Secondary LCI data were mining literature data (Reid et al. 2009) that were used as proxies. When the available information was incomplete (e.g., energy and explosive consumption), we estimated based on the quantities used in typical mines (Tanzania and Papua New Guinea) included in Ecoinvent data (Ecoinvent V3.3) (Classen et al. 2009). Inventory data for the machinery used (excavators, dumpers, loaders, off-road diesel trucks, and drills) were from the manufacturer's data (Caterpillar), based on the information retrieved from the EIA report. The inventory data for the buildings were compiled from the information contained in the EIA report and from observations conducted during the field visits.

For missing information, such as the quantities of processing materials such as fatty alcohol and hydrochloric acid, similar processes were selected from the Ecoinvent database. The electricity used on the site was hydroelectric (hydroelectric dam built on a river). However, given the absence of the Ivorian energy mix in the Ecoinvent database, we used the "electricity, high voltage {RoW} | electricity production, hydro, run-of-river,|" which corresponds to the world average. Despite the fact that several machines were used with different power ratings and were all higher than 74.57 kW, for machine operations, the Ecoinvent process "machine operation, diesel = 74.57 kW, high load factor {GLO} | machine operation, diesel, > = 74.57 kW, high load factor" was used. This choice was motivated by the fact that in the Ecoinvent database, there were no other processes that better matched the specific machines that were used.

To estimate the potential emissions from these machines, a linear relationship between engine power and emissions was assumed. Thus, multiplying factors were defined to calculate the emissions of the machines used at the mine site. Notably, for housing and offices, the buildings were made by KwikSPACE. The quantities of the materials used in the manufacturing of these buildings were estimated from various data sources (http://www.kwikspace.co.za, http://www.algeco.fr). Data about energy consumption for equipment assembly could not be obtained. We considered only civil works (foundation) to support these installations and the area they occupy. The inventory data normalized per functional unit (1 kg Au) with their corresponding sources are given in the Supplemental Data.

Impact assessment

The impact assessment method chosen was the hierarchical approach in ReCiPe v1.13 (Goedkoop et al. 2013). ReCiPe can express results both at the midpoint and endpoint levels (Goedkoop et al. 2013; Ioannou-Ttofa et al. 2016; Larrey-Lassale et al. 2017). Endpoint impact assessment allows the visualization of the contributions of midpoint impacts to each area of protection and thus facilitates the choice of the midpoint categories.

ReCiPe has many indicators and 2 levels of normalization: European level and global level (ILCD 2010). At the midpoint level, ReCiPe contains 18 impact categories. These are climate change (CC), O_3 depletion (OD), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PM), ionizing radiation (IR), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), water depletion (WD), metal depletion (MD), and fossil depletion (FD). These midpoint impact categories were then converted and aggregated into 3 damage categories at the endpoint level called areas of protection (AoP): damage to human health (HH), damage to ecosystem quality (EQ), and damage to resource depletion (RD) (Table 2). The ReCiPe method has been used in several studies carried out outside the European context (Alyaseri and Zhou 2017; Masindi et al. 2018). Since the mine is located in Africa (Ivory Coast), we used ReCiPe with the normalization values of the world with the weighing set belonging to the hierarchical perspective (i.e., world ReCiPe H/H). To obtain a holistic understanding of the environmental impacts of the Afema mine, both the midpoint and endpoint approaches were used. In the first step, we worked at the endpoint level to identify the impact categories (midpoint) that accounted for the most damage to the areas of protection. The purpose of this was to help identify and select the main contributing categories to focus them at the midpoint level and identify the activities that would drive these impacts.

RESULTS

Afema gold mine impact assessment results

First, the overall results, i.e., without distinguishing between the impacts of the mine's life stages, are presented. Then, the contributions of off-site and on-site impacts for

Table 2. Area of protection and midpoint impact categories of ReCiPe method

Midpoint impact categories	Unit	Area of protection	Unit
Climate change human health	kg CO_2-eq	Human Health	DALY
O_3 depletion	kg CFC11-eq		DALY
Human toxicity	kg 1,4-DCB-eq		DALY
Photochemical oxidant formation	kg NMVOC-eq		DALY
Particulate matter formation	kg PM_{10}-eq		DALY
Ionizing radiation	kBq U_{235}-eq		DALY
Climate change ecosystems	kg CO_2-eq.kg^{-1}	Ecosystems Quality	species.yr
Terrestrial acidification	kg SO_2-eq		species.yr
Freshwater eutrophication	kg P-eq		species.yr
Terrestrial ecotoxicity	kg 1,4-DB-eq		species.yr
Freshwater ecotoxicity	kg 1,4-DB-eq		species.yr
Marine ecotoxicity	kg 1,4-DB-eq		species.yr
Agricultural land occupation	m^2a		species.yr
Urban land occupation	m^2a		species.yr
Natural land transformation	m^2		species.yr
Metal depletion	kg Fe eq	Resource Depletion	$
Fossil depletion	kg oil eq		$

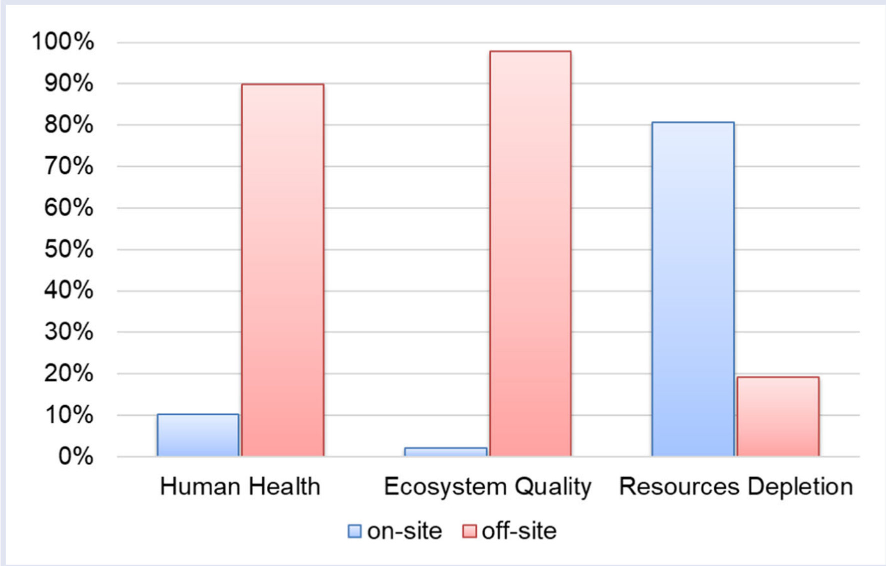

Figure 3. Damage from off-site and on-site activities in the 3 areas of protection.

each mine life stage are presented. Last, for each damage category, the main contributing midpoint categories are identified as well as the main activities responsible for the damages.

Overall results. Figure 3 shows the relative contribution of location (on-site and off-site) to the damage to the 3 AoPs. In comparison to the on-site impacts, the off-site impacts were higher on human health (90%) and ecosystem quality (98%) but not on resource depletion (19%). This higher share of the 2 first AoPs was due to the contribution of secondary activities (off-site impacts). Even for resource depletion, the off-site share was not negligible. These results reveal the importance of taking into account background activities (off-site impacts). The distinction between off-site and on-site impacts highlighted the pollution transfer from other territories to the mine site.

Figure 4 shows the contribution of each mine's life stages to the overall environmental impacts (without the distinction of on-site and off-site impacts). This figure shows that the main contributor to the damage to the 3 AoPs was the operating stage, which is responsible for 99%, 85%, and 99% of the damage to human health, ecosystem quality, and resource depletion AoPs, respectively. Although these results illustrate the importance of operational activities in terms of both material consumption and emissions, the effects of closure (rehabilitation) and construction (development) activities were not negligible on the ecosystem quality AoP at

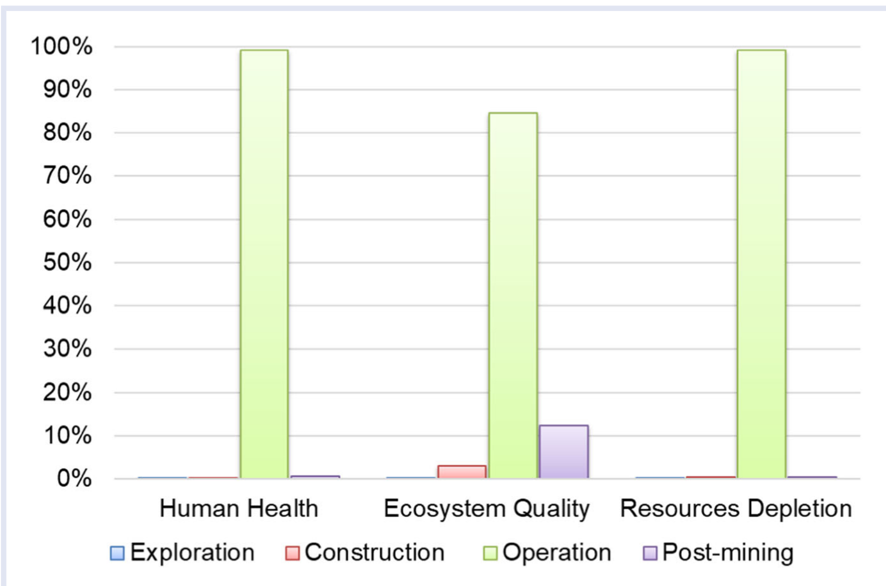

Figure 4. Contribution of the mine's life stages to the overall impacts.

Table 3. Relative contribution of off-site and on-site damages generated by the different life stages of the mine on each of the areas of protection

	Exploration		Development		Operating stage		Rehabilitation	
Areas of protection	Off-site	On-site	Off-site	On-site	Off-site	On-site	Off-site	On-site
HH	≈0%	≈0%	≈0%	<1%	≈100%	96%	≈0%	3%
EQ	≈0%	≈0%	≈0%	1%	≈100%	82%	≈0%	17%
RD	≈0%	≈0%	2%	≈0%	97%	≈100%	1%	≈0%

19% and 3%, respectively. The impacts of the exploration phase were insignificant for the 3 protected areas.

Off-site and on-site impacts according to the mine's life stages. The data presented in Figures 3 and 4 were classified by impact location and mine stage (Table 3). Details of the results are presented in the Supplemental Data. The analysis reached the same conclusions as those derived from the overall results. The operating phases both on-site and off-site generated most of the impacts for the 3 AoPs. However, the proportions varied according to whether they were on-site or off-site effects. Table 3 shows that the operating phase was entirely responsible for damage to human health and ecosystem quality with respect to off-site impacts. For damage to resource depletion, this phase accounted for 97% of all damage. Regarding on-site damage, the share of the operating phase accounted for 96%, 82%, and 100% of the damage to human health, ecosystem quality and resource depletion, respectively. Note that, here, resources correspond only to fossil and metallic resources because the ReCiPe method does not evaluate the impacts of water use at the endpoint level. This relative importance of off-site effects can be explained by the fact that all of the products (materials and energies) consumed by the mine were produced elsewhere, in other territories, and then transported to the site. The impacts of production and transportation activities were generated in other territories and were therefore accounted for by off-site effects. The impacts of the other phases were almost negligible, except for damage to the ecosystem quality produced by the postmining phase (on-site level) at 17% of the damage.

Prioritization of environmental impacts

Further analysis of the results highlighted the contribution of the midpoint impact categories to the damage to the AoPs.

Overall impacts. Regarding the overall impacts (without distinction between off-site or on-site), damage to human health was mainly caused by impacts related to human toxicity (over 90%), climate change, and particulate matter formation; O_3 depletion, photochemical oxidant formation, and ionizing radiation accounted for less than 1% and were considered negligible (see Supplemental Data). For damages to ecosystem quality, the main midpoint contributors were those related to climate change, which alone accounted for 70% of the effects, and impacts related to land use (agricultural land occupation, urban land occupation, and natural land transformation) accounted for 23.2%. Freshwater eutrophication and freshwater ecotoxicity accounted for 3% and 2% of the damage to ecosystem quality, respectively, while terrestrial ecotoxicity, marine ecotoxicity, and terrestrial acidification account for less than 1% and were considered negligible.

The other impact categories were minor or negligible (Supplemental Data). Damage to resource depletion was mainly generated by impacts related to metal depletion (90%). Impacts related to fossil depletion accounted for only 10% of the damage to resource depletion. Flows in fossil resources were much larger in mass than flows in metals, but resource depletion, as AoP took into account the scarcity of different resources, and Au reserves were smaller than petrol.

Off-site impacts. For off-site effects, the main driving midpoints for damage to human health were those related to climate change, which accounted for over 98% of the damage. Particulate matter formation and human toxicity accounted for less than 2% of the damage to human health (Figure 5). Ecosystem quality effects were essentially caused by impacts related to climate change (Figure 5). Moreover, damage to resource depletion was dominated by fossil depletion (88%).

On-site impacts. Damage to human health was mainly generated by human toxicity (78%), climate change (12%), and particulate matter formation (9%) (Figure 6). Other impacts (O_3 depletion, ionizing radiation, and photochemical oxidant formation) accounted for less than 1% of the damage to human health. The main midpoint categories contributing to ecosystem quality damage were climate change, agricultural land occupation, urban land occupation, natural land transformation, freshwater eutrophication, and freshwater ecotoxicity (Figure 6). Damage to resource depletion was only caused by metal depletion.

For climate change effects, 3 midpoint categories were observed for overall, on-site, and off-site impacts. These were human toxicity, climate change, and particulate matter formation. They were therefore selected for an in depth analysis. The results differed more for ecosystem quality effects than for other effects. The main contributors to

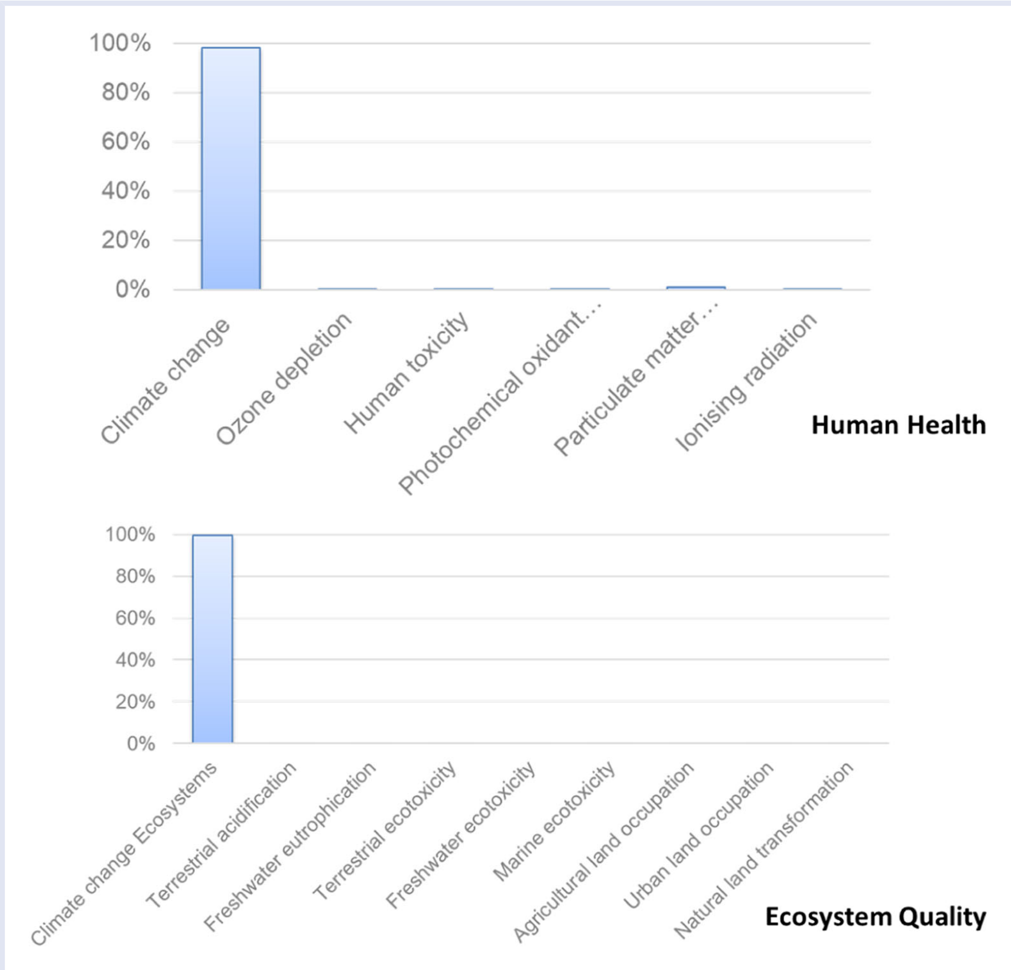

Figure 5. Contribution of midpoint impacts to off-site human health and ecosystem quality effects.

off-site impacts were climate change due to fuel consumption, while at the on-site level, the midpoint impacts related to land use (urban land occupation, natural land transformation, and agricultural land occupation) as well as the impact on water quality (freshwater eutrophication and freshwater ecotoxicity) were not negligible. Therefore, these midpoint categories were selected for the last part of the study. Last, on-site resource depletion was mainly caused by metal depletion, and off-site resource depletion was caused by both fossil depletion and metal depletion. Nevertheless, these on-site effects did not take into account local water use; thus, further research on water is necessary. Table 4 summarizes the main impacts contributing to the damage.

The background (off-site impacts) and foreground activities (on-site impacts) related selected midpoint impacts were compared (Supplemental Data). The results illustrate that for most local impacts (human toxicity, particulate matter formation, urban land occupation, agricultural land occupation, freshwater ecotoxicity, and freshwater eutrophication), on-site effects were greater than off-site effects. However, on-site natural land transformation impacts were less than off-site natural land transformation impacts. Conversely, on-site global effects were minor except for metal depletion.

Main contributors to environmental issues

Off-site impacts. Off-site impacts from climate change were mainly caused by liquid wastes generated by diesel generators that are treated off-site, diesel, ore processing reagents, and explosive production and transportation at more than 99%. The same scenario occurred for particulate matter formation for which these activities represented 87% of the impacts. Operating phase activities, namely, the production of diesel as well as ore production and ore processing reagent transportation (activated C, lime, NaCN, etc.) and explosives accounted for 11% of the impacts, while construction activities (materials production and transportation) represented 2% (Supplemental Data). The main contributors were the processes selected from the Ecoinvent database (diesel burned in the diesel-electric generating set and explosives). Afema mine inventories (ore processing reagents) generated few impacts. Thus, the proxies would have resulted in an overestimation of the impacts.

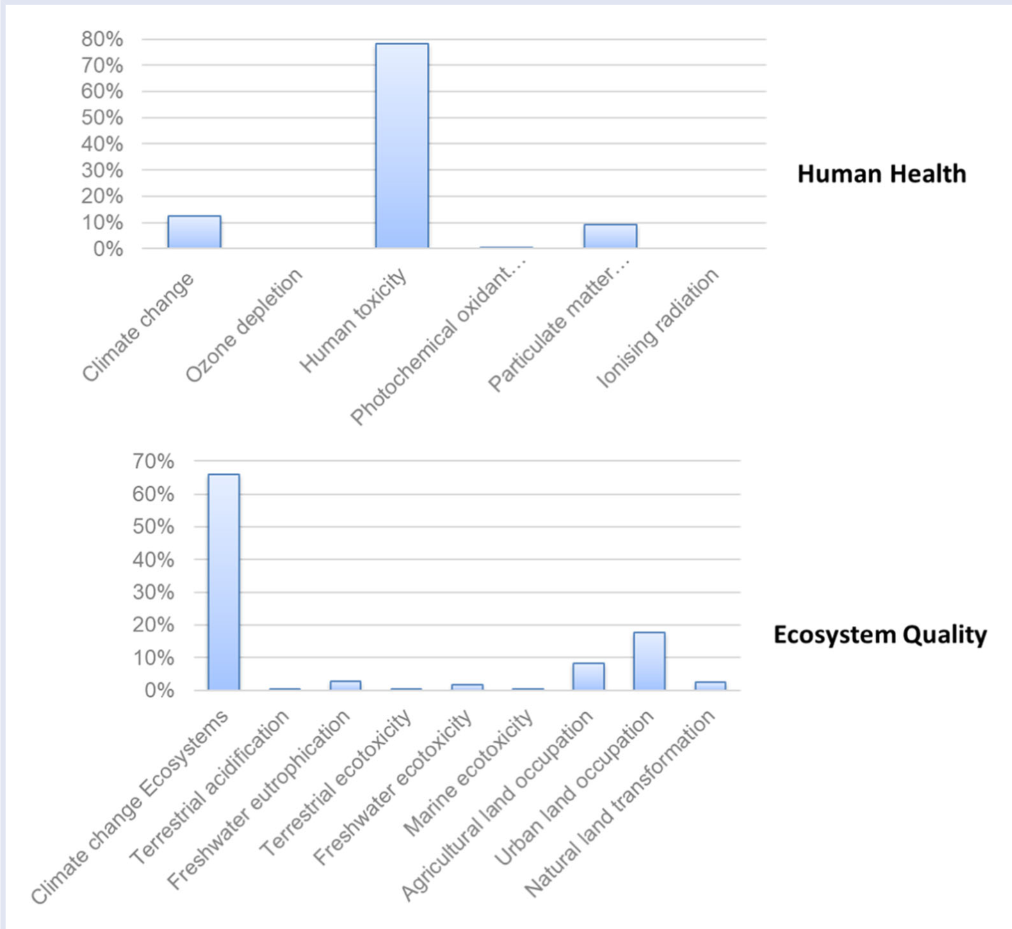

Figure 6. Contribution of midpoint impacts to on-site human health and ecosystem quality effects.

On-site impacts. The climate change impacts were generated by operating stage activities: excavation and transportation operations (ore and waste rock) and ore processing activities (diesel combustion by an electric generator), and these activities accounted for 76% of the impacts. The remaining impacts of climate change were due to site reclamation activities (23%) and mine construction activities (1%) (Supplemental Data Figure S6). The human toxicity impacts were exclusively from ore processing and sulphidic tailing management, accounting for 99.9% of these impacts. In addition, operating activities such as blasting, excavation and transportation as well as processing (diesel combustion) were responsible for the formation of 93% of the particulate matter. Rehabilitation operations represented 6% of these impacts, while construction operations represented approximately 1% (Supplemental Data Figure S6). Land-use impacts (urban and agricultural land occupation) were also caused mainly by operating stage

Table 4. Summary of primary midpoints to damages

	Overall impacts	Off-site impacts	On-site impacts
Human Health	Human toxicity, climate change and, Particulate matter formation	Climate change, Particulate matter formation	Human toxicity, climate change and, Particulate matter formation
Ecosystem quality	Climate change, natural land transformation and, land occupation (urban and agricultural)	Climate change	Climate change, natural land transformation and, land occupation (urban and agricultural), freshwater eutrophication, freshwater ecotoxicity
Resources depletion	Fossil depletion and, metal depletion	Fossil depletion and, metal depletion	Metal depletion

activities (vegetation clearing for ore extraction). Concerning resource depletion, metal depletion was the main contributor.

DISCUSSION

Potential hypothesis biases

The majority of the endpoint damage was generated by exploitation activities (Figure 4). A detailed analysis of midpoint impacts confirmed that this phase was responsible for the potential impacts of almost all of the categories studied. However, our results have some limitations related to assumptions and uncertainties regarding the data used. The first limitation is the assumptions made to overcome the insufficiency or lack of data. Some data that were not available were assumed to be equivalent to the generic data contained in the Ecoinvent database, which correspond to European or global averages. The use of such data may distort the conclusions. Another source of potential bias is the ReCiPe and LCIA methods (Goedkoop et al. 2013). ReCiPe is a European method and has been designed with European characteristics that might not be entirely able to be superimposed on African conditions. Nevertheless, the updated version of ReCiPe, that is, ReCiPe2016, provides characterization factors that are representative of the world instead of Europe, and this version maintains the potential for several impact categories to be adapted to a country or continental scale (Huijbregts et al. 2017).

In addition, despite our desire to cover all of the activities of the mine, some data were not available. Although the building materials were taken into account, the impacts generated by the equipment used for construction and dismantling were not accounted for. Food and electricity consumption, access to health care, and other needs of mine employees were not included in the study. Despite this, many mine-specific data as well as other data on materials used in the manufacture of containers used for housing and offices were collected. Consequently, the results obtained seem relatively similar to reality.

Comparison of Afema LCA results with those of other mining LCA studies

The endpoint results obtained for the 3 areas of protection allow a prioritization of the most critical midpoint impacts. The impacts were climate change, human toxicity, particulate matter formation, agricultural land occupation, urban land occupation, natural land transformation, freshwater eutrophication, freshwater ecotoxicity, metal depletion, and fossil depletion. These impact categories have been recognized as relevant to conducting a mining LCA by various authors (Durucan et al. 2006; Mangena and Brent 2006; Awuah-Offei et al. 2011). Yellishetty et al. (2009) highlighted the importance of considering land use (land occupation and land transformation) in mineral LCAs, as these impacts can sometimes be considerable. Agricultural land occupation, urban land occupation, and natural land transformation are the 3 midpoint impacts addressing land use. Santero and Hendry (2016) recognized that these impact categories have relevant environmental concerns but conclude that the impact categories recommended by the metallurgy sector for LCA studies can be limited to climate change, terrestrial acidification, freshwater eutrophication, particulate matter formation, and O_3 depletion. They further specify that other categories of impacts can be studied, but the position of the working group that made these recommendations is that these additional impacts should not influence decision making.

In this study, climate change and particulate matter formation appear to be mainly responsible for damage to human health; these impacts are generated by heavy machinery operations consuming high amounts of diesel (Ferreira and Leite 2015). The impacts on human toxicity and freshwater eutrophication are largely due to tailings treatment and management operations, a result consistent with those in previous reports (Reid et al. 2009).

Most LCA studies identified in the mining literature have quantified impacts at the midpoint level except for those by Reid et al. (2009), Ferreira and Leite (2015), Chen et al. (2018), and Masindi et al. (2018), who have also evaluated damages (endpoint level). The impact categories generally studied have been climate change (which is reflected in almost all studies), land acidification (Giurco et al. 2001; Durucan et al. 2006; Awuah-Offei et al. 2009; Reid et al. 2009), energy consumption and/or abiotic resources (Durucan et al. 2006; Reid et al. 2009; Norgate and Haque 2010; Ferreira and Leite 2015), ecotoxicity (Giurco et al. 2001; Durucan et al. 2006; Reid et al. 2009), and particulate matter formation (Giurco et al. 2001; Reid et al. 2009). Only the works by Reid et al. (2009), Ferreira and Leite (2015), and Masindi et al. (2018) looked at impacts on land use. However, these studies did not cover entire mining operations and considered overall impacts rather than classifying them between on-site and off-site impacts.

Due to several factors, such as the differences in energy mixes, system boundaries, selected functional units, and life cycle impact assessment (LCIA) methods, the comparison study of results from different LCA studies is difficult. In addition, published LCA studies on Au production are limited (Norgate and Haque 2012; Chen et al. 2018). Additionally, there are currently no LCA studies that separate on-site and off-site impacts.

Although they did not study all stages of mine life and did not separate on-site and off-site impacts, the work of Chen et al. (2018) is similar to this study in that they used the same LCIA method (ReCiPe) and selected the same functional unit (1 kg Au production). However, since they studied Au production, we compared their results with the overall impacts (without the distinction of on-site and off-site impacts) at the operating stage obtained in this study. Table 5 shows that for most impact categories, environmental impacts generated by the operating stage were higher than those reported by Chen et al. (2018), mainly because of the differences in ore properties (i.e., ore grades and leachability)

Table 5. Comparison of midpoint impacts with those of Chen (2018)

Midpoint			
Categories	Unit	This study	Chen et al. (2018)
Climate change	kg CO_2 eq	1.17E+06	5.55E+04
O_3 depletion	kg CFC-11 eq	3.56E−03	1.15E−03
Terrestrial acidification	kg SO_2 eq	2.50E+02	207.25
Freshwater eutrophication	kg P eq	1.96E+02	0.12
Marine eutrophication	kg N eq	2.11E+01	5,55
Human toxicity	kg 1,4-DB eq	2.23E+05	4.37E+03
Photochemical oxidant formation	kg NMVOC	3.41E+02	130.84
Particulate matter formation	kg PM10 eq	1.29E+02	67.6
Terrestrial ecotoxicity	kg 1,4-DB eq	1.09E+1	11.5
Freshwater ecotoxicity	kg 1,4-DB eq	4.68E+03	13.06
Marine ecotoxicity	kg 1,4-DB eq	4.23E+03	19.61
Ionizing radiation	kBq U235 eq	1.40E+03	163.67
Agricultural land occupation	m^2a	1.12E+03	330.41
Urban land occupation	m^2a	1.86E+03	1.69E+03
Natural land transformation	m^2	5.73E+00	3.57
Water depletion	m^3	4.26E+02	461.25
Metal depletion	kg Fe eq	7.83E+04	2.16E+10
Fossil depletion	kg oil eq	6.69E+03	9.98E+03

and energy structure. Norgate and Haque (2012) argued that the environmental impact generated from Au production increases greatly with the decline in ore grade.

Benefits of on-site and off-site impact assessments

No LCA studies on minerals and mining activities have addressed the distinction between on-site and off-site impacts. A territorial analysis of the system under study allowed the detection of the location of the impacts generated instead of combining all of these impacts. Such works were conducted by Loiseau et al. (2013, 2014) in a territorial (consumption and production) impact assessment, Larrey-Lassalle et al. (2017) in a wastewater treatment impact assessment, and Jouini et al. (2019) in a cropping system analysis focused on rural territory management.

The impact assessment of the Afema mine revealed that off-site impacts are greater than on-site impacts, whereas the opposite could have been expected. This relative importance of off-site effects can be explained by 2 main factors:

1) All consumables (reagents, diesel, sand, and all of the material needed for infrastructures) are produced elsewhere in other territories and transported to the site. The impacts of material and energy production and transport activities are generated in other territories and therefore account for off-site effects.
2) The liquid wastes generated by the diesel generators have to be treated off-site. Thus, the impacts linked to the processing activities of these wastes have been accounted for off-site.

On-site effects on human health and ecosystem quality are less than off-site effects. However, off-site damage to human health is only due to climate change, whereas on-site effects are due to climate change, land use (natural land transformation, urban land occupation, and agricultural land occupation), and water quality degradation (freshwater ecotoxicity and freshwater eutrophication).

The results of the comparison of background and foreground activities on selected midpoint impacts illustrate that local impacts (human toxicity, particulate matter formation, urban land occupation, agricultural land occupation, freshwater ecotoxicity, and freshwater eutrophication) are due to foreground activities except for natural land transformation. This is a consequence of the local land use that is mainly agricultural. The impacts on natural land transformation occur from off-site activities (i.e., petroleum extraction). Global effects on climate change and fossil depletion are mainly caused by background activities, whereas metal depletion is caused by foreground activities.

Benefits of applying the LCA methodology in the EIA procedure

EIA and LCA have essentially the same purpose in terms of environmental aspects: supporting the decision making of a major project (Manuilova et al. 2009). An EIA is a procedure to evaluate the potential positive and negative environmental impacts of a planned, future project. An LCA is a tool used to perform the environmental assessment of a product, service, or process. An LCA is also used to identify possible improvements throughout the life cycle of a product. An EIA is recognized as incapable of easily addressing global and regional environmental effects throughout the life cycle of a product (Manuilova et al. 2009; Larrey-Lassalle et al. 2017). The implementation of an LCA that analyzes the entire life cycle of a product can compensate for this weakness and thus play an important role in improving EIAs. The Society of Environmental Toxicology and Chemistry (SETAC) has discussed this possibility and concluded that LCAs can be complementary to EIAs since they provide further and more detailed information on analyzed objects (see Manuilova et al. 2009). In addition, an LCA allows the inclusion of all upstream and downstream activities, considering all relevant effects along a life cycle that can be crucial for an accurate comparison of different alternatives. Tukker (2000) argued that an LCA has added value for assessing the impacts of abatement alternatives. Larrey-Lassalle et al. (2017) showed that an LCA can be used to test mitigation measures by assessing their impacts. As Manuilova et al. (2009) used an LCA for a C capture and storage (CCS) project and Larrey-Lassalle et al. (2017) used an LCA for a wastewater treatment project, in this work, the LCA permitted the assessment of global versus regional impacts. This mining LCA case study reveals the high level of impacts from climate change, fossil depletion, and metal depletion. The land use (land transformation and land occupation) effect has also been characterized, whereas these effects are not generally assessed in conventional EIAs. In our case study, we considered only the impact assessment stage in the EIA procedure. However, Larrey-Lassalle et al. (2017) demonstrated the value of the implementation of an LCA throughout the EIA procedure, including mitigation measures.

CONCLUSION

Mining activities result in major environmental changes, both in the vicinity of the mine location and in other locations often very distant from the mine itself. Most EIA studies address impacts taking place locally but neglect potential impacts taking place elsewhere. Mining EIAs are not the exception. The importance of those off-site impacts and their temporal distribution according to the development period of the activity can be analyzed by coupling an LCA to an EIA analysis. In this work, we used an LCA to evaluate the environmental impacts of the Afema Au mine (located in the Ivory Coast) throughout the mine lifespan.

Off-site impacts, mainly induced by fuel consumption, represent the majority of the total impacts for 2 of the 3 areas of protection (human health and ecosystem quality). From a temporal perspective, the study revealed that, of the phases, the operating phase has the most impact. These impacts are mainly due to extraction activities, especially excavation, ore and waste rock transportation, blasting, ore processing, and tailing treatment.

Our study confirms the importance of considering both on-site and off-site impacts and the pertinence of including an LCA perspective in mining EIA studies. Furthermore, the LCA methodology addresses the requirements of the European Union and Ivory Coast regulations to consider several environmental impacts.

Acknowledgment—This research has been supported by IMT Mines Ales (France) and the UFR STRM of the Université Félix Houphouët-Boigny (Ivory Coast). The authors thank the members of the ELSA research group (Environmental Life Cycle and Sustainability Assessment, http://www.elsa-lca.org/) for their advice.

Data Availability Statement—Data and associated metadata and calculation tools are available upon request by contacting corresponding author Kouadio Assemien François Yao (kouadioyao.assemien@gmail.com).

SUPPLEMENTAL DATA

Figure S1. Geographical location and hydrographic network of the study area.

Figure S2. Geological map of the study area (after Delor et al. 1992).

Figure S3. Contribution of midpoint impacts to human health and ecosystem quality effects.

Figure S4. Comparison of on-site and off-site impacts for selected midpoint impacts.

Figure S5. Identification of the main contributors to off-site impacts on climate change and particulate matter formation.

Figure S6. Identification of the main contributors to on-site impacts on climate change and particulate matter formation.

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