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# Temporally explicit life cycle assessment as an environmental performance decision making tool in rare earth project development

Robert Pell[a,c,*], Frances Wall[a,b], Xiaoyu Yan[b,*], Jinhui Li[c], Xianlai Zeng[c,*]

[a] Camborne School of Mines, University of Exeter Penryn Campus, Penryn, Cornwall TR10 9FE, United Kingdom
[b] Environment and Sustainability Institute, University of Exeter Penryn Campus, Penryn, Cornwall TR10 9FE, United Kingdom
[c] Key Laboratory for Solid Waste Management and Environment Safety, School of Environment, Tsinghua University, Beijing 100084, China

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ABSTRACT

The study shows that a detailed LCA can be carried out for a proposed mining project as soon as Prefeasibility (PFS) data are available. The prefeasibility study is one of the key early steps in bringing a deposit towards production and results are often publically available. This study applies the technique to a rare earth deposit because rare earth element (REE) consumption is increasing owing to their use in low-carbon technologies such as electric vehicles and wind turbines. It is therefore particularly important to understand the environmental impacts of the raw materials. A number of REE deposits are under development to give additional supply and many possess novel mineral compositions and will require different processing methods than previously used. Assessing the environmental performance of the production of REE during the development of projects offers significant insights into how to improve the sustainability of a project. In this study we used life cycle assessment (LCA) to quantify the environmental impacts for producing rare earth oxide (REO) from the Bear Lodge Project, United States. The Life Cycle Impact Assessment results were produced for each year over the life of the project, generating insight about the relationships between ore composition, grade, processing method and environmental impacts. The environmental impacts vary significantly during the life of a project and a temporally explicit LCA can highlight these.

## 1. Introduction

Rare earth elements (REE) are a group of 17 chemical elements composed of the 15 lanthanoids (lanthanides) as well as scandium (Sc) and yttrium (Y). REE can be subcategorised depending on their atomic number into light rare earth elements (LREE) (e.g., La, Ce, Pr, Nd, Sm, and Eu), and heavy rare earth elements (HREE) (e.g., Y, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu). The similar physical and chemical properties of the individual REE means that they are often found together as elemental constituents of their host minerals (EPA, 2012). REE possess unique nuclear, metallurgical, chemical, catalytic, electrical, magnetic, and optical properties (Voncken, 2016). They have a broad and expanding range of uses in military and medical applications, communications, and petroleum refining, lighting, and renewable energies. The elements are considered important for many emerging alternative energy technologies, improving the performance of hybrid cars, wind turbines, rechargeable batteries and biofuel catalysts. The REE are marketed in many forms, such as mineral concentrates, mixed REOs, individual oxides, carbonates, purified metals, or metal mixtures (the so-called 'misch' metal).

China produces a majority of REE, accounting for 85% of global REE supply (USGS, 2017). However, this figure is likely lower than the genuine value as it does not include the share of illegal production, which was predicted to be around one third of official production (Mancheri et al., 2013). This high concentration of production in combination with REE's high economic importance in the low-carbon economy has led to a number of studies identifying REE as critical raw materials (Nassar et al., 2015; Mancini and Camillis, 2013; BGS, 2017; Pell et al., 2018). Country concentration of proven reserves of REE is more dilute than production. China had an average of 39% of total world reserves from 1995 to 2015 (Chen et al., 2018). There are also a mismatch between individual REE production and demand. This is known as the 'balance problem' (Binnemans, 2014).

REE are widely dispersed around the world in a diversity of deposit types but are generally found in low concentrations, limiting the amount of known economic deposits to around 200 (Goodenough et al., 2017). To date only the minerals bastnäsite-(Ce), monazite-(Ce), and xenotime-(Y) have been commercially recovered in large quantities

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[*] Corresponding authors at: Camborne School of Mines, University of Exeter Penryn Campus, Penryn, Cornwall TR10 9FE, United Kingdom (R. Pell).
*E-mail address:* rp416@exeter.ac.uk (R. Pell).

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from carbonatite-related deposits, granite-related deposits and mineral sands (Wall et al., 2017). The environmental challenges associated with REE production are closely linked to the geology of a deposit, the methods of extraction and processing employed, and the controls that are put in place to mitigate environmental impacts (Koltun and Tharumarajah, 2014).

One major environmental challenge linked with REE production is the co-extraction of radioactive elements. Thorium, and to a lesser extent U, are often incorporated in the lattice of the REE minerals or occur as separate but associated thorium-bearing minerals (Wall et al., 2017). Other acidic and chemical waste can also be produced such as hydrogen fluoride (HF) and acidic waste water (Wall, 2014; Arshi et al., 2018). REE extraction and processing can release emissions such as hydrogen fluoride (HF) and acidic waste water as well as produce solid waste (Wang et al., 2017). The processing and separation of REE can be chemically and energy intensive partly due to the similar physical and chemical nature of the lanthanoid elements, making them difficult to separate (Wall et al., 2017).

In this study, life cycle assessment (LCA) is used as a quantitative method to assess the environmental impacts during the mining and processing of mixed REE product (cradle-to-gate). LCA is a useful tool to evaluate the environmental performance of projects based on their flowsheets. The combination of simulation with LCA has been presented in recent studies, highlighting that it has the potential to be employed early in a project to assess the performance of specific process choices (Rönnlund et al., 2016a, 2016b, Reuter et al., 2015). The purpose of this work was to develop an indicator framework for the environmental sustainability benchmarking of products produced by the metallurgical industry. This approach has not yet been applied to REE production, however a number of LCAs have been completed for active REE mines, with a majority of work on the mining and processing of bastnäsite ore at Mountain Pass, USA or the bastnäsite-monazite ore at Bayan-Obo, China (Althaus et al., 2007; Du and Graedel, 2013; Haque et al., 2014; Sprecher et al., 2014). Vahidi et al. (2016) completed an LCA of a number of the ion-adsorption REE production routes from Seven Southern Provinces of China. Lee (2016) also completed an LCA for an ion adsorption clays, comparing their production to Bayan Obo and production in Sichuan, China. The results indicated that production from Sichuan had lower environmental costs among the categories measured compared to Bayan Obo. It was also noted that there was considerable potential to mitigate impacts across these production chains. Marx et al. (2018) completed a comparative study of NdFeB production from Mount Weld, Australia, Mountain Pass, USA, and Bayan Obo.

Weng et al. (2016) completed a broad comparative LCA of 26 different operating and potential REE projects, including Bear Lodge. Energy requirements and global warming potential were the only impact categories considered in this study. The study concluded that lower REE grades significantly increase the environmental impact of REE production, and that REE production causes higher environmental impacts than common metals. The study is a useful comparative approach, but due to its inconsistent inventory data, it was not a consistent LCA, as noted in the response to this paper (Pell et al., 2017).

This study is the goes beyond previous studies by introducing temporally explicit LCA for REE production. This has been applied to other industrial applications (Maier et al., 2017) but to the authors knowledge this is the first time this approach has been applied for any mining project. This allows insight into the drivers of different environmental impacts during REE production such as changing ore grade, changing processes or other project specific variables. This study also attempts to clarify the importance of LCA integration in the early development stages of a mining project. This approach has been adopted in the product development stage of many companies outside the mining industry but is often carried out as a retrospective measurement for raw material projects (da Luz et al., 2018).

Mining projects move through different stages of development to determine whether the mineral resource can be mined economically. The first stage is known as the order of magnitude study. If successful this will move to a preliminary feasibility study (PFS). During this stage, data about many processes are created and the reports are often published to the public. During this stage, geology of the site, ore deposits, resource estimates, mining and processing methods, waste management, and energy and infrastructure estimates are made. This data can be used to perform an early stage LCA. International Mineral Resource and Ore Reserve reporting codes do not quantify the levels of accuracy or uncertainty with PFS, however some research has reviewed the accuracy of these studies (McCarthy, 2003; Snowden et al., 2002) indicating that at a 90% confidence level, the cost accuracy of a PFS study is ± 15–25% and has over 20% of the engineering study complete. In contrast a feasibility study has a more detailed mine plan, a cost accuracy of ± 10–15% and around 50% of the engineering study is complete (Noppe, 2014).

The advantage of carrying out a LCA during the PFS, even in the context of higher uncertainty, is that it can inform mining companies about particular processes that have high environmental impacts in a life cycle context. This information can be useful during this stage as it allows companies to explore alternative process options as a project moves towards the higher certainty feasibility stage. This is examined in this study with the comparison of a gravity and magnetic separation stage with a flotation stage from data in the PFS and from a scientific study from Cui and Anderson (2017).

## 2. Research methodology

The Bear Lodge Project is a proposed mining and processing operation in Wyoming USA, which includes Bull Hill Mine located in the Bear Lodge Mountains, Crook County and the processing facility, located in Upton, Weston County. Bear Lodge is currently in the PFS stage and is one of the main REE prospects in the USA (Pre-feasibility Study Report, 2014).

The deposit is carbonatite, part of which is weathered, that contains bastnäsite-(Ce), synchysite-(Ce), monazite-(Ce), cerianite-(Ce) and ancylite-(Ce) as the REE-carrying minerals. The project is LREE-enriched with a total rare earth oxides (TREO) grade of 4.7 wt% (Fig. 1). A notable advantage of the Bear Lodge project is the high percentage of Nd in the REE composition of the ore, at 18% compared to 12% at Mountain Pass for example. For this reason, Bear Lodge has been suggested as a project particularly suitable to support the U.S. REE demand from the U.S. wind energy growth targets (Cui and Anderson, 2017).

The project is forecast to have a 45-year life of operation, with mining for the first 38 years and production from a high grade stockpile for the last 7 years. For the first nine years the mine will produce between 3.5 and 3.9 million tonnes per year and between 4.5 and 4.7 million tonnes during peak mining during years 15–28. The hydrometallurgy plant will be in operation for 45 years with a feed of 152,000 tonnes per year of upgraded material for the first nine years of operation, and from year 10 the plant would be expanded receiving a feed of 191,000 tonnes per year (Pre-feasibility Study Report, 2014).

The annual TREO production and average grade per year are shown in Fig. 1 alongside the ore composition. The different ore compositions represent variations in mineralogy of the deposit. These compositions have different TREO grades as well as different precipitation efficiency (Pre-feasibility Study Report, 2014) (see Table 1)

### 2.1. Goal and scope

The objective of this research is to assess the environmental impacts by applying a process-based LCA model to REO production at Bear Lodge, USA according to ISO 14044 guidelines (ISO, 2006). Different processing options have been compared and LCIA has been completed for different temporal stages of the project (Figs. 2 and 3). The functional unit for this study is 1 kg of mixed REO produced. The REO

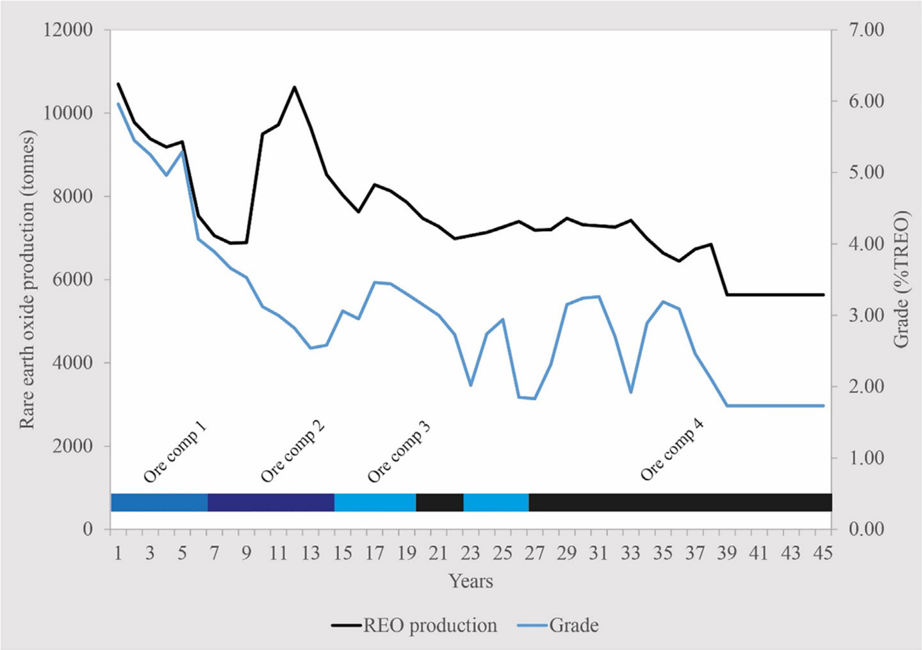

**Fig. 1.** REO production, grade, and ore composition change during production at Bear Lodge (Pre-feasibility Study Report, 2014).

production process consists of a number of inter-related component processes, which have been broken down into subsystems connected by flows. The LCA system boundary is cradle-to-gate and includes the mining, beneficiation, hydrometallurgy, waste management, and transport. This LCA does not take into account the downstream processing of the mixed REO into separates individual elements and manufacture to final products. The TRACI 2.1 impact assessment method (Bare et al., 2012) was selected in this study and the calculations were performed using the LCA software GaBi 6.

An additional comparison between an alternative beneficiation flowsheet as proposed by Cui and Anderson (2017) and the current flowsheet indicated in the Pre-feasibility Study Report (2014). A temporal environmental comparison is completed using the LCA approach as described within the manuscript.

A distinction between this study and previous papers is that the temporal dimension of the project is explored, using annual production data, geology and ore variation, and process performance predicted for the PFS. Using this approach allows for an analysis environmental impacts over the life of mine.

### 2.2. Life cycle inventory

The Life-Cycle Inventory (LCI) was created using a combination of data from the Bear Lodge PFS Study (Pre-feasibility Study Report, 2014), GaBi, Ecoinvent (Wernet et al., 2016) databases as well as calculations from literature. Data that were not available in these reports were estimated using the equations given here in the supporting information. The background data, e.g. electricity mix, were specific to US where possible. Some data such as chemical production data were not country specific due to the limited data availability of some processes. Information about the data source and quality is shown in Table 2. Dust emission data is from the Ambient Air Quality Modeling Protocol (IML Air Science, 2014) and includes the stated pollutants of concern, namely particulate matter smaller than ten microns in size (PM10) and particulate matter smaller than 2.5 µm in size (PM2.5), carbon monoxide (CO), sulfur dioxide ($SO_2$) and oxides of nitrogen (NOx).

#### 2.2.1. Mining

The Bear Lodge mine will use a conventional open-pit drill and blast method, with a focus on near-surface, oxidised sections of the deposit. The Bull Hill and the Whitetall Ridge areas of the deposit will be mined. The Bull Hill deposit has a higher grade but the Whitetall Ridge deposit is 2.5 times more enriched in heavy REE.

#### 2.2.2. Beneficiation

The physical upgrade plant would produce a REO pre-concentrate using a series of crushing, washing, screening, and separation steps. On average, the physical upgrade plant recovery is expected to be 92.8% in years 1–9 and 87.9% over the life-of-mine. There process is different depending on the ore type and the stage of the project. There is also a novel method which includes wet high-intensity magnetic separation (WHIMS) and flotation.

#### 2.2.3. Crushing and screening

From years 1–9 Bear Lodge will process high-grade ore which is expected to have a 4.7 wt% REO content. All the run of mine ore is initially crushed and screened to 3360 µm. The specific beneficiation steps that are employed from this point depend on the ore composition. Bear Lodge has allocated four crushing, screening, and separation

**Table 1**
Headgrade of the different ore compositions at Bear Lodge.

| | $SiO_2$ % | $Al_2O_3$ % | $Fe_2O_3$ % | MgO % | CaO % | $Na_2O$ % | $K_2O$ % | MnO % | TREO g/t |
|---|---|---|---|---|---|---|---|---|---|
| Comp 1 | 22.8 | 6.69 | 18.0 | 1.01 | 8.76 | 0.36 | 4.92 | 7.94 | 8.94 |
| Comp 2 | 32.3 | 9.73 | 13.6 | 1.44 | 9.21 | 0.31 | 7.50 | 4.44 | 5.20 |
| Comp 3 | 40.3 | 12.4 | 12.9 | 1.12 | 5.11 | 0.27 | 9.72 | 3.03 | 2.99 |
| Comp 4 | 45.4 | 14.2 | 13.0 | 1.15 | 0.93 | 0.30 | 11.1 | 3.21 | 2.52 |

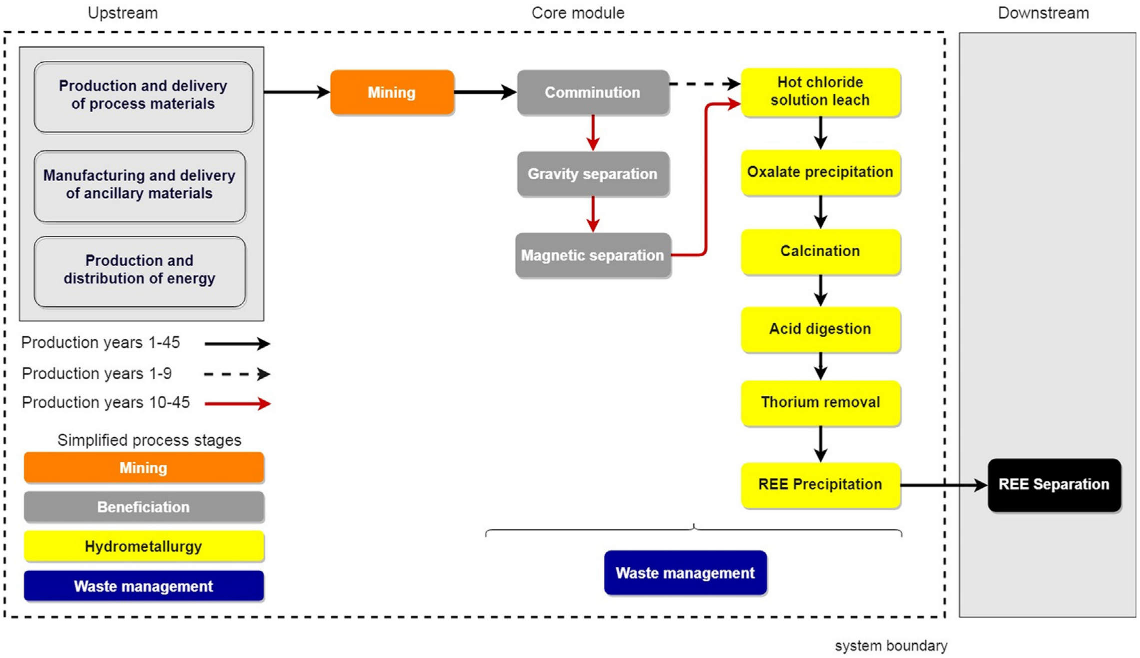

**Fig. 2.** The system boundary and proposed flowsheet at Bear Lodge REE project proposed by Pre-feasibility Study Report (2014).

processes. Ore composition 4 is crushed and screened to a 297 µm and is then thickened. Ore composition 1 and 2 is crushed and screened to 100 µm. Oversized material is sent to a spiral gravity classifier, where light material is sent to a pre-tailings belt filter and is dewatered. The heavy material is sent to the 297 µm grinding mill. Ore composition 3 is crushed and screened to 100 µm. Oversized material is sent to a magnetic separator. Magnetic material is sent to the spiral gravity separator. Liquids are recycled during this stage, and the final solid concentrate is stored in bins prior to transport to the Hydromet plant.

### 2.2.4. *Crushing, screening, magnetic and gravity separation*

From year 10 of the project gravity and magnetic separation will be included in the beneficiation phase. Testwork completed by SGS produced a concentrate grade of 6.64% REO at 86.4% recovery from a feed grade of 4.5%.

### 2.2.5. *WHIMS and flotation*

Cui and Anderson (2017) proposed a method which included comminution to minus 100 mesh, followed by WHIMS, conditioning, rougher and cleaner flotation. The WHIMS stage removes the iron content to reduce the interference of iron during the flotation process. The proposed method will produce a concentrate grade of 11.2% REO at 61.2% recovery.

### 2.2.6. *Hydrometallurgy*

The hydrometallurgy process uses hydrochloric acid to leach the

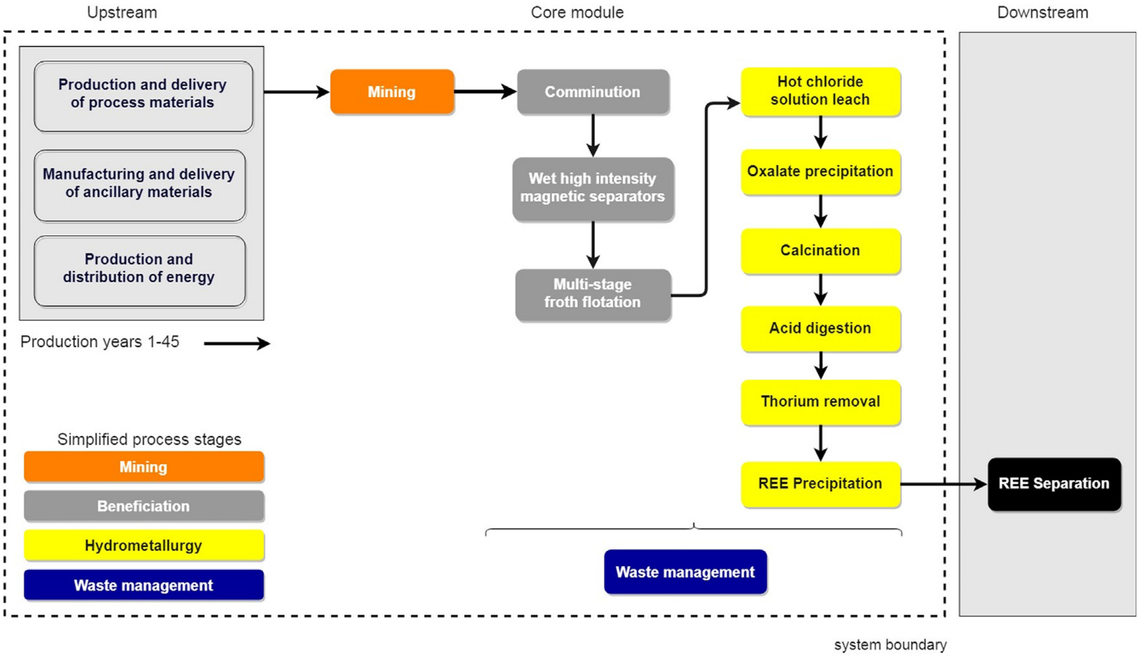

**Fig. 3.** The system boundary and proposed flowsheet at Bear Lodge REE project proposed by Cui and Anderson (2017).

**Table 2**
Life cycle inventory inputs for 1 kg REO produced at Bear Lodge (Pre-feasibility Study Report, 2014).

| Input | Unit | Low | High |
|---|---|---|---|
| Diesel | MJ | 10.70 | 17.94 |
| Electricity grid | MJ | 15.89 | 58.05 |
| Diesel generator | MJ | 3.15 | 4.42 |
| ANFO | kg | 0.00 | 0.05 |
| Process Water | L | 42.40 | 42.48 |
| Steel | kg | 0.12 | 0.12 |
| Flocculant | kg | 0.58 | 1.41 |
| Lime | kg | 0.01 | 0.01 |
| Limestone | kg | 9.27 | 17.24 |
| Sodium hydroxide | kg | 0.00 | 0.02 |
| Natural gas | MJ | 3.09 | 5.87 |
| Ammonia | kg | 0.83 | 0.85 |
| Hydrochloric acid | kg | 4.24 | 12.86 |
| Oxalic Acid | kg | 2.46 | 5.58 |
| Nitric Acid | kg | 2.18 | 2.24 |
| Hydroxamic Acid | kg | 0.02 | 0.03 |
| Strontium Nitrate | kg | 0.33 | 1.19 |

REE from the ore. Rare earth oxalates are then precipitated from the pregnant leach solution by the addition of oxalic acid and converted to REO in a kiln. Thorium and other impurities are removed by a nitric acid leach and double hydroxide precipitation method. A bulk REO powders of > 97% purity is formed as the final product.

#### 2.2.7. Waste management

Waste management involves the movement and storage of waste rock from the mining operation and the management and storage of waste as tailings from the beneficiation and hydrometallurgy stage. The waste rock facility for storage of overburden and mine waste is recountered and managed during the operation of the mine. Non-hazardous waste produced from Hydrometallurgy phase is dewatered and neutralised before being transported by truck to the tailings storage facility. Thorium and uranium will be removed to ensure radionuclide levels below 0.05% and lime stone and quicklime will be added to neutralise the material. The tailings storage facility is a zero discharge facility and non-contact surface water runoff will be diverted around the facility. During the life-of-mine 15.8 million tons of waste will be produced for the tailings storage facility and it is designed to operate as a dry stack facility. Thorium hydroxide residue is contained and transported to a third-party disposal facility.

## 3. Results

### 3.1. Environmental impacts per 1 kg of REO produced at Bear Lodge

The results of the LCIA for producing 1 kg of REO from Bear Lodge are listed in Table 3. The results generated are based on the average for production over the life of mine according to processes described in the PFS report (Pre-feasibility Study Report, 2014). The global warming impact was 12.1 kg $CO_2$ eq. compared to 14 kg $CO_2$ eq. in Sprecher's study at Mountain Pass (Sprecher et al., 2014). The acidification impact at Bear Lodge in this study is 0.06 kg $SO_2$ eq., lower than that at Mountain Pass (with an impact of 0.063 kg $SO_2$ eq. to 0.17 kg $SO_2$ eq.). It is important to understand the limitation in direct comparisons between studies due to ranges in functional equivalency. This is particularly challenging with REE due to the large range of elements considered and the fact that each deposit has a specific balance of individual REE, combined with the fact that each project has a range of final products. The system boundaries can also differ resulting in the inclusion or exclusion of individual processes which can impact the final results.

### 3.2. Temporally explicit environmental impacts over life-of-mine

The assessment results for the project can be broken down by each year of production. The impacts have been categorised into the four stages of production and shown in Figs. 2 and 3. The grade fluctuates during the life of mine, with a general decreasing trend. There is a positive relationship between global warming impact and decreasing grade. The global warming impact is lowest in the first year of production at 8.66 kg $CO_2$ eq. per kg of REO produced and highest in year 26 of production at 16.3 kg $CO_2$ eq. per kg of REO. This figure, which is almost double that of the first year indicates how much environmental impacts can change over time depending on the changing grades and physical properties or processes employed at an operation.

The termination of mining at year 38 is seen in Fig. 4 with the beneficiation feed drawing from stockpiles. During the last 7 years the global warming impact remains relatively static, with small reductions in kg $CO_2$ eq. owing to reducing waste management impacts. The

Fig. 5 presents the relationship between the annual average grade of the ore extracted, the ore composition and the global warming impact. There is a positive correlation with decreasing grade and global warming impact. The lower grades global warming impact scores have a greater range of impact. The different ore compositions relationship between grade and global warming potential can also be seen and have been isolated in smaller figures above the main figure.

The mining phase contributes between 2.2 and 4 kg $CO_2$ eq. per kg REO until year 33. From year 34 until year 38 mining is reduced and from year 39 until year 45 no new mining is carried out which is the cause of the reducing impact of the mining phase during these stages. The mining stage is influenced by a number of factors, with the most important one being the stripping ratio during each year of production. Beneficiation has a small contribution to the global warming impact category during the first 9 years of production as a simple process of crushing and grinding occurs as highlighted in Fig. 1. From year 9 until year 45 beneficiation includes gravity and magnetic separation and this results in a higher global warming impact during these years. The hydrometallurgy phase appears to steadily increase its global warming impact over the life of mine. Waste management is relatively stable with increases in global warming due to lower grades.

The contribution to the global warming impact category during the beneficiation phase (Fig. 4) and the hydrometallurgy phase (Fig. 5)

**Table 3**
Life cycle impacts for the production of REO from Bear Lodge (this study), Mountain Pass (Nuss and Eckelman, 2014), Bayan Obo (Zaimes et al., 2015), and Ion adsorption (Vahidi et al., 2016) with TRACI characterization (note that lowest impact values from these studies are used).

| Environmental impact indicator | Unit | Bear Lodge | Mountain Pass | Bayan Obo | Ion adsorption (China) |
|---|---|---|---|---|---|
| Acidification | kg $SO_2$ eq. | 6.00E−02 | 1.70E−01 | 3.08E+00 | 1.70E−01 |
| Ecotoxicity | CTUe | 1.45E+00 | N/A | 3.76E+01 | 2.79E+02 |
| Eutrophication | kg N eq. | 1.30E−02 | 1.50E−01 | 1.80E−01 | 3.00E−01 |
| Global warming | kg $CO_2$ eq. | 1.21E+01 | 1.40E+01 | 2.30E+01 | 2.09E+01 |
| Human health | kg PM2.5 eq. | 1.60E−02 | N/A | 1.70E−01 | 2.59E−02 |
| Carcinogenic | CTUh | 1.30E−08 | 1.30E−08 | 2.27E−06 | 3.00E−02 |
| Non-carcinogenic | CTUh | 1.20E−06 | 1.20E−06 | 7.70E−06 | 1.04E−05 |
| Ozone depletion | kg CFC 11 eq. | 2.40E−09 | 2.30E−09 | 3.80E−06 | 2.40E−06 |

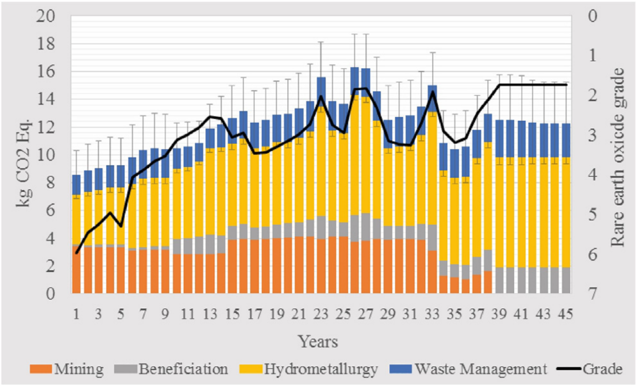

**Fig. 4.** Global warming impact (kg $CO_2$ eq. per kg REO) and reversed average grade (%TREO) during five different stages of the life of mine.

have been included. A majority of the contribution during beneficiation is due to electricity consumption during the crushing, classifying, grinding and gravity separation and the magnetic separation. The impact is around 0.2 kg $CO_2$ eq. during the first 9 years of production and then increases substantially to between 0.8 and 1.9 kg $CO_2$ eq. for the rest of the life of mine once further beneficiation has come online, and fluctuates between 0.8 and 1.9 kg $CO_2$ eq. The fluctuation is due to the changing grade and mineralogy, which impacts the energy requirements for the crushing grinding and classifying.

The hydrometallurgy phase has a higher impact on global warming when compared to the beneficiation phase due to the high direct energy consumption and the embodied carbon footprint associated with the chemicals consumed. The volatility in impacts over time is also less than the beneficiation phase. This is due to the fact that the hydrometallurgy has an input of mixed stockpiled concentrate which has more consistent physical and chemical properties. It is however still possible to see the changing grade and mineral composition in the results with particular high peaks in global warming impact during years 26 and 34 of production. These relate to low points in grade during the mining phase during similar time periods.

Assuming the overall environmental impact of all categories is 100% Fig. 6 highlights the contribution of each TRACI impact category by process over the life of mine. The largest contributor to the ecotoxicity, eutrophication, human health (particulate air formation), resources, and smog air is mining during the early stages of the project. This contribution decreases over time until the mining ends at year 39. Acidification is dominated by the hydrometallurgy phase followed by the beneficiation phase, which increases its contribution over time.

Compared to other LCA studies on REE production, Bear Lodge has a low contribution to eutrophication from the mining and waste management. Water borne emissions are often a major contributor to eutrophication, especially with REE production in China from the ion-adsorption clays in Southern China[23]. Bear Lodge claims it will have zero-discharge tailings storage facility, which explains the limited impact during this stage.

The temporally explicit LCIA data can be used to evaluate

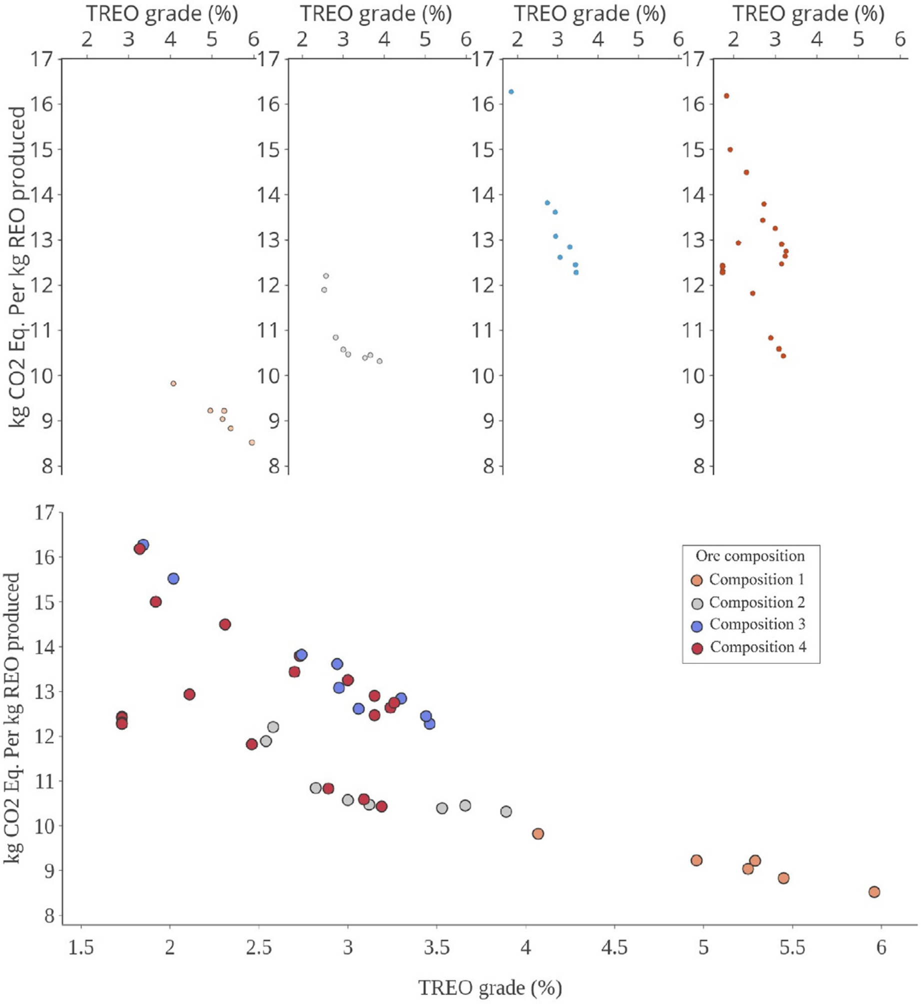

**Fig. 5.** Global warming impact relationship with grade and ore composition.

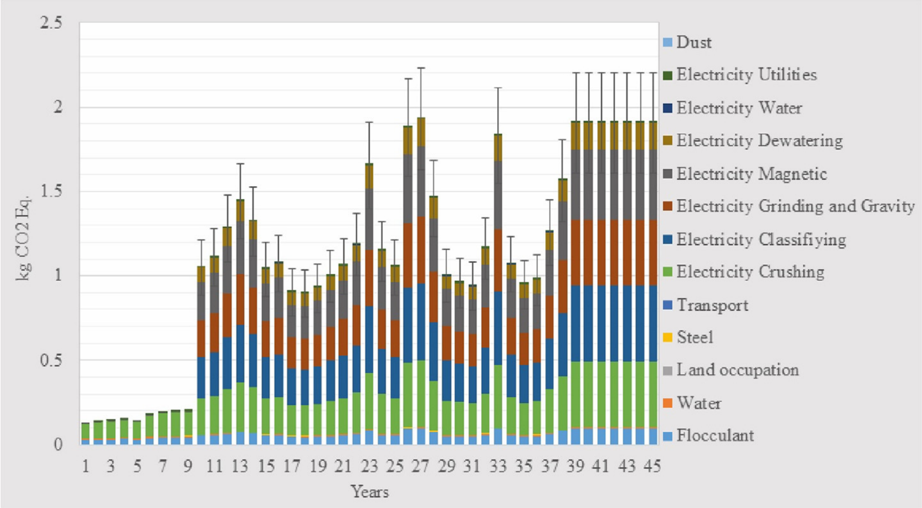

**Fig. 6.** Beneficiation contribution to global warming impact over life of mine.

processing options at the project or advise on whether specific remediation approaches should be implemented during the life of the project. For example the results indicate that the hydrometallurgy stage is the largest contribution to global warming impact. As other beneficiation options may be available and this in turn could reduce the hydrometallurgy contribution, different process options have been explored.

### *3.3. Beneficiation process comparison*

The mineral processing route proposed by Cui and Anderson (2017), Fig. 2, has been examined by using a separate LCA study, completed on the single process of processing with a functional unit of 1 kg of REO contained in the produced concentrate. It is important to note that the grade and recovery of ore achieved in each processing approach is different. The physical upgrade method proposed in the prefeasibility would produce a grade of 6.64% REO with a recovery of 86.4% whilst the flotation approach would produce a concentrate grade of 11.2% REO at 61.2% recovery. It is also important to consider the fact that the downstream hydrometallurgy impacts have not been included in this calculation, but it is likely that improved grade would lower the environmental costs during the hydrometallurgy stage.

The results are presented in Table 4 comparing the performance of the two beneficiation methods over the life of the mine and the average impacts per kg REO produced during the years 10–45. This was done as the first 9 years of beneficiation of the high grade ore using the conventional method has a low impact in all categories measured and outperforms the method proposed by Cui and Anderson (2017). This is highlighted in Fig. 7 which shows the percentage performance of the beneficiation method proposed in the Pre-feasibility Study Report (2014) against the WHIMS and flotation method proposed by Cui and Anderson (2017). It is likely that the method proposed by Cui and Anderson could be employed from year 10 once the high grade ore has been processed (see Fig. 8).

During the years 10–45, the flotation method has a lower environmental impact for the acidification, eutrophication, human health, human toxicity, ozone depletion, and smog impact categories. The flotation method has a slightly worse result in the global warming category with 0.933 kg $CO_2$ eq. produced per kg of contained REE compared to the crushing, grinding, gravity and magnetic separation which has an impact score of 0.85 kg $CO_2$ eq. Fig. 7 highlights the relative performance in each LCIA impact category through the project life (from left to right of each colour). This shows that many of the impact categories have a small percentage difference apart from the smog formation impact category. The method proposed by Cui and Anderson performs much worse in this area. This is due to the higher embodied impacts of the chemicals used in the method proposed by Cui and Anderson. The impact scores and the higher grade achieved would indicate that the method proposed by Cui and Anderson if applied in the production of REE at Bear Lodge from years 10 until year 45 would reduce the overall impact in many categories. However, further research needs to be done to understand how improved grade in the concentrate would impact the material and energy requirements in the hydrometallurgy phase (see Fig. 9).

**Table 4**
Life cycle impacts for the two beneficiation processing options of Pre-feasibility Study Report (2014), and Cui and Anderson (2017) at Bear Lodge using mass based allocation for 1 kg REO with the TRACI characterization.

| Impact category | Unit | Pre-feasibility Study Report (2014) | Cui and Anderson (2017) | Pre-feasibility Study Report (2014) | Cui and Anderson (2017) |
|---|---|---|---|---|---|
| Acidification | kg $SO_2$-Eq | 1.70E − 03 | 1.70E − 03 | 2.00E − 03 | 1.62E − 03 |
| Eco-toxicity | CTUe | 1.68E − 02 | 2.26E − 02 | 2.00E − 02 | 2.16E − 02 |
| Eutrophication | kg N-Eq | 1.00E − 04 | 1.10E − 04 | 1.00E − 04 | 1.00E − 04 |
| Global Warming INC | kg $CO_2$-Eq | 7.04E − 01 | 9.80E − 01 | 8.49E − 01 | 9.34E − 01 |
| Global Warming (Non-INC) | kg $CO_2$-Eq | 7.03E − 01 | 9.81E − 01 | 8.48E − 01 | 9.34E − 01 |
| Human Health | kg PM2.5 eq. | 1.00E − 04 | 1.30E − 04 | 1.70E − 04 | 1.20E − 04 |
| Human toxicity | CTUh | 1.19E − 10 | 1.98E − 10 | 1.41E − 10 | 1.91E − 10 |
| Human toxicity (Non-Cancer) | CTUh | 8.68E − 09 | 8.69E − 09 | 1.01E − 08 | 8.11E − 09 |
| Ozone depletion | kg CFC 11 eq. | 4.77E − 10 | 4.69E − 10 | 5.13E − 10 | 4.17E − 10 |
| Resources | MJ surplus energy | 4.37E − 02 | 1.10E + 00 | 4.45E − 02 | 1.13E + 00 |
| Smog | kg $O_3$ eq. | 2.39E − 02 | 2.23E − 02 | 2.76E − 02 | 2.10E − 02 |

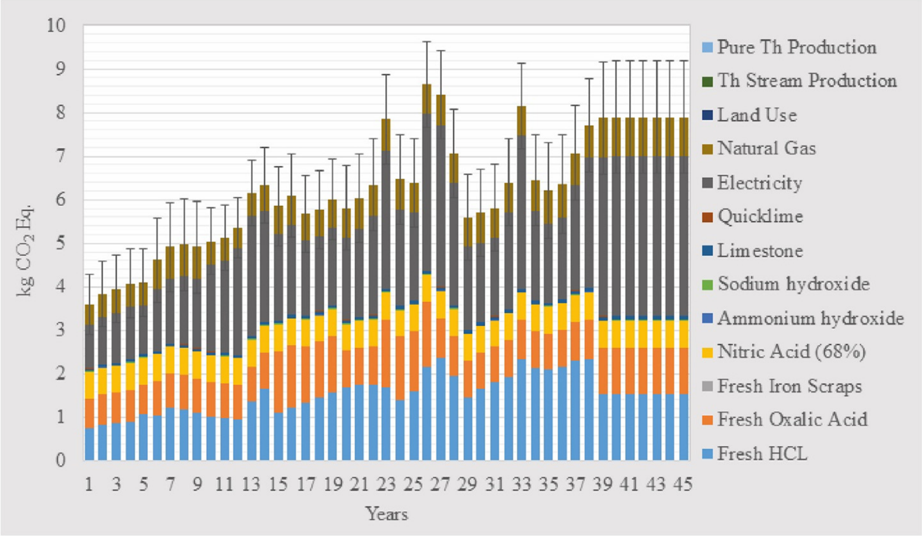

**Fig 7.** Hydrometallurgy contribution to global warming impact per kg REO over life of mine.

## 4. Discussion

This is the first cradle-to-gate LCA to examine the life cycle environmental impacts of REE over different stages of production of a mine life. It has shown that even with limited data during the early stages, it is possible to highlight the specific environmental challenges during a project lifespan. This provides an opportunity to both mitigate against these impacts and research alternative processing options, which has been highlighted here in the comparison of the two beneficiation options for the Bear Lodge project. The results indicate that there is potential for the WHIMS and flotation method to be employed from years 10–45.

LCIA impacts against different temporal stages of the Bear Lodge REE project were investigated, examining relationships between impact categories and changing grade, processing options and material and chemical consumption. The results highlight that a predictive LCA at a project scale can be a useful tool in identifying environmental hotspots and advising on processing options. Another important consideration is the fact that it is possible for outside agencies to carry out a detailed LCA and quantify environmental impacts with publicly available data, either to assess an individual project or to compare projects. There are country specific guidelines to disclose details of mineral projects such as National Instrument 43-101 or Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC). The data used here were acquired from the Pre-feasibility Study Report which was generated according to National Instrument 43-101 guidelines. This is a step that most exploration projects progress through and so provides an opportunity for public awareness of the environmental impacts or projects.

The LCIA methods and data selected for this work are not all equivalent. For example there is a strong consensus and a catalogue of research on impacts such as global warming, whilst greater uncertainty on other categories such as those used for toxicity calculations are considered as interim and results should be taken with this in mind (Rosenbaum et al., 2008; Hauschild et al., 2008).

The results generated from the LCA are useful, however it is important to understand the role that LCA has to play in the context of risk assessment. LCA may generate data about the environmental performance of a process, but it may fail to indicate whether a particular process choice has an increased spatially and temporally explicit risk to the environment, such as a tailing dam failure or groundwater seepage of ions and cations. LCA is useful in evaluating global impacts while

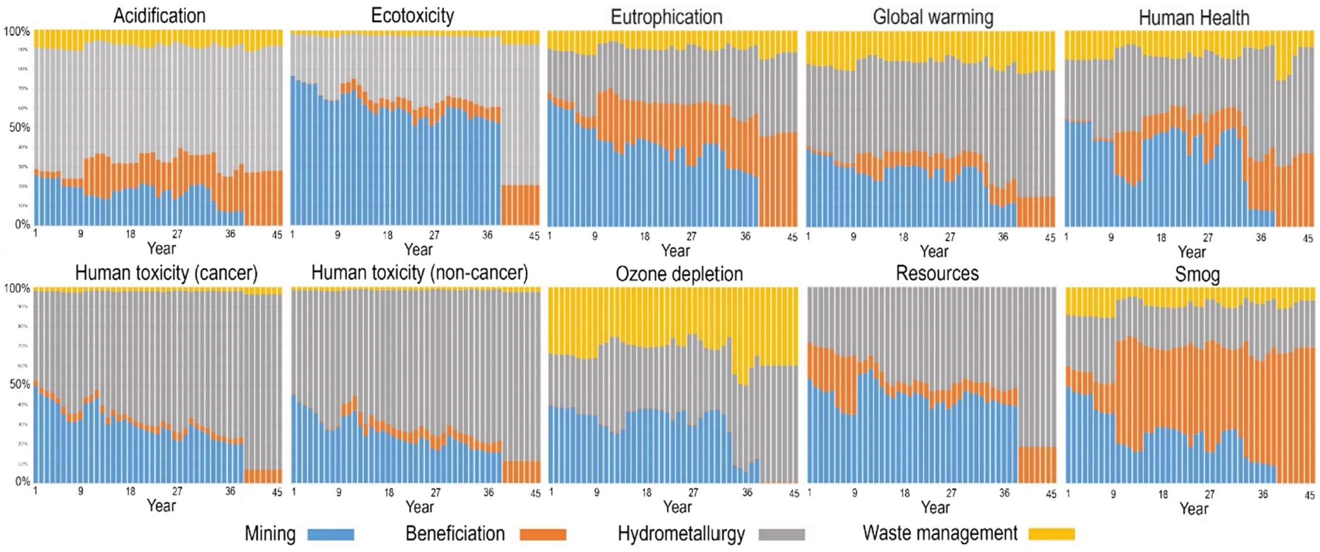

**Fig. 8.** Share of production process on total impact of 1 kg of REO production over the life of mine with project life moving left to right for each impact category.

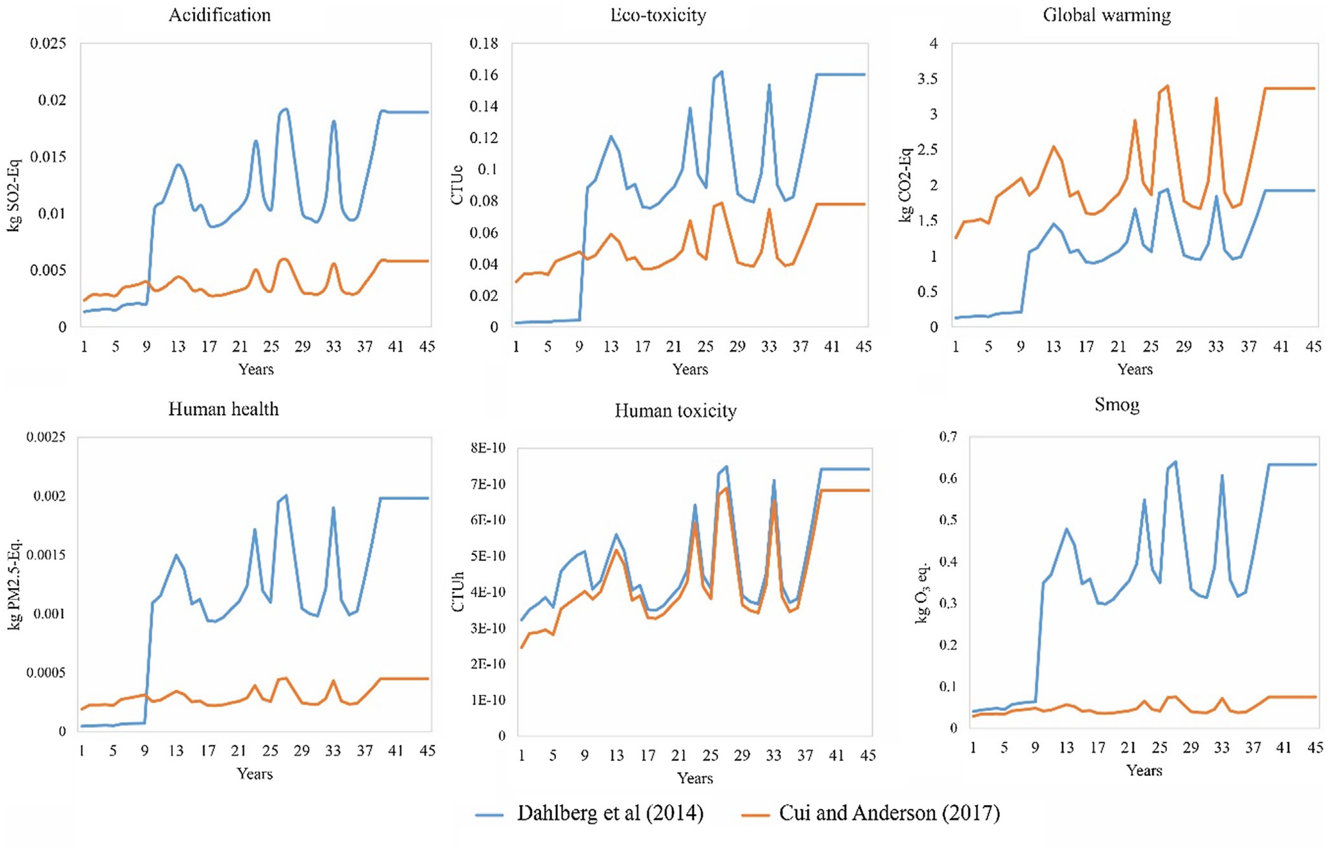

**Fig 9.** Comparison of using either the Pre-feasibility Study Report (2014) or Cui and Anderson (2017) beneficiation flowsheets on six TRACI impact categories over the life of mine.

quantitative risk assessment (QRA) is a more suitable approach when assessing local impact assessments. QRA integrates a range of data across a broad range of disciplines including source characterisation, fate and transport, modelling, exposure assessment, and dose-response assessment. Instead it is advised that the results of both assessments are considered before decisions about a change in process choice is made (Linkov et al., 2017).

### 4.1. Uncertainty analysis

The uncertainty analysis carried out in this project does not consider the accuracy of the process choices described in the PFS and whether these processes would feature if the project moves into production. The uncertainty of the data is based on the data quality indicator classification system of the American Association of Cost Estimation (Bull et al., 2012), a method suggested by Arshi et al. (2018). This refers to the uncertainty of the LCI data for each stage of production (see Table 5).

**Table 5**
Data quality of the four stages of production (data quality 3 is calculated, modelled, stoichiometric calculated, up-scaled data, data quality 5 is roughly estimated data).

| Stage | Data quality | Deviation |
|---|---|---|
| Mining | 3 | −20 to +30 |
| Beneficiation | 3 | −20 to +30 |
| Hydrometallurgy | 3 | −20 to +30 |
| Waste management | 5 | −50 to +100 |

## 5. Conclusions

The results highlight that a predictive temporally explicit LCA at a project scale can be a useful tool in identifying environmental hotspots and advising on processing options that could improve the environmental performance of a rare earth project. Adding a temporal dimension provides a greater opportunity to explore the relationships between the properties of the deposit, the mining and mineral processing methods and the environmental impacts. The results indicate that there is a positive relationship between decreasing grade and global warming impact, but there are also patterns that exist between the ore composition and the global warming potential.

The beneficiation approaches compared generated different environmental impacts over time. The beneficiation process presented in the Pre-feasibility Study Report (2014), which included crushing, grinding, magnetic and gravity separation had a higher average impact over the life of mine for the acidification, eco-toxicity, human health, human toxicity, and smog, whilst the flotation approach presented by Cui and Anderson had a lower global warming impact.

Applying the LCA methodology higher uncertainty in this stage of a project for both the geology of the deposit and the mining and mineral processing methods that will be used is offset by the fact that high impact areas can be explored and changes can be implemented as a project moves through development into the feasibility stage.

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## Notes

The authors declare no competing financial interest.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mineng.2019.02.043.

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