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Perforation Potential in Life Cycle Assessment: A Method for the Identification of Land Use Activities in Remote Areas

FORSCHUNGSERGEBNISSE AUS DER BAUPHYSIK BAND 43

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In the end, our society will be defined
not only by what we create but
by what we refuse to destroy.

John Sawhill, president of New York University (1975–1980)
and president of The Nature Conservancy (1990–2000)

Abstract

Life cycle assessment (LCA) is a holistic tool dedicated to the assessment of the environmental impacts of products or services. Different approaches to the assessment of the impacts on biodiversity in LCA have been proposed. Existing methods addresses impacts concerning the land use in relation to a reference state, but do not explicitly identify if a land use activity takes place in a remote area or an area with few human influences. Humans have altered terrestrial ecosystems for millennia and such dominance is a concern from a biodiversity conservation point of view. This is an issue that is particularly relevant for areas of low human influence due to not only their intrinsic and instrumental values but also due to the rate of the loss of the last remaining wilderness worldwide.

This thesis proposes a method to include an assessment of the surroundings of the land use. It uses concepts derived from landscape ecology and biodiversity conservation and brings them to LCA. The main focus is the identification of land uses that potentially contribute to the fragmentation configuration's types perforation and dissection. Perforation and dissection occur when a habitat area surrounds an area of non-habitat. In other words, the non-habitat, such as quarry, perforates the surrounding landscape, or a road dissects a pristine habitat. Since habitats are species-specific, data availability hinders its inclusion in LCA. Therefore, in this thesis, a method was developed to overcome this problem by using an existing cumulative index of human pressures as an indicator of the potential that a land use has to perforate or dissect. The method aims at identifying land uses that occur in areas of low human pressures or remote areas, as these are where perforation and dissection are more likely to occur.

Based on conservation biology literature, a 1 km distance buffer zone was created around the border of the land use, being referred to in this thesis as a *context area*. This context area was overlaid by the Human Footprint Index (HFI) map, and the average values of the HFI were calculated for the context areas. In this way, a land use can be explicitly associated with the existing pressures in the surroundings, with low pressures indicating remoter areas.

The method is applicable for any land use type, as long as its spatial boundaries can be defined. To demonstrate its suitability, the proposed method was applied to most common land use types: built environments, cropland, pasture, roads, rails,

and quarries or mines. The HFI values for the context areas were calculated for these land use types for the entire world. The results of the distribution of the HFI and its location varied depending on the land use type and within countries and regions.

How much an area of lower HFI is more likely to perforate, or at which value of HFI it can be said that the land use would no longer perforate has to be determined in order to use the HFI as an indicator for perforation or dissection. To provide the knowledge to answer these questions, two main procedures were carried out for a random sample of quarries and mines: a verification step and a valuation step.

The verification step objective was to check the existence of a perforation-like configuration around the quarries and mines, meaning that the context area of that site is composed entirely by natural habitat. A sample of context areas with an average HFI of zero was inspected with the support of aerial base maps. The verification step identified that a strict perforation configuration was rare since roads and tracks were often observed in the context areas, but the HFI input map did not capture those as they are not major roads.

The valuation was carried out for quarries and mines located in forest biomes because the land cover of these biomes is widely available and more straightforward to identify compared to, e.g., savanna biomes, composed of a mix of vegetation types. The valuation took into account the HFI and the amount of forest cover in the context area. Each context area was given a score according to their resemblance to the perforation and dissection landscape pattern. One of the most important outcomes of this step was the need to disaggregate HFI pressures in two categories: pressures that are related to a modification of the original cover such as cropland and built-up areas, and pressures that occur independently of the land cover, such as nightlights.

The average values of the HFI pressures were calculated for quarries and mines' context areas. The HFI pressures were converted into perforation contributions based on literature. The Perforation Potential was defined as being maximum when both land cover modifying and non-modifying contributions are low, obtained by the multiplication between the two contributions.

The method was applied to a product system to provide an example of how to use the method in LCA. The product chosen was steel, and the system was modeled with iron ore from Canada, Brazil, and Australia, and metallurgical coal from Canada. The result was that mining activities in Canada, both for coal and iron ore were the ones with the highest potential to perforate. The method was designed to be used in combination with other impact assessment methods, and two other impacts methods were applied to demonstrate how the Perforation Potential can be used in LCA.

The novelty of the method is that it allows the identification of a land use that borders areas of low human influence because they are valuable to biodiversity conservation due to its remoteness. In practical terms, the use of a cumulative pressure map does not rely upon any direct measure of species or habitats, although such data can be used if available. The method was designed without weighting between land use type itself, its ecosystem type, or intensities because other impact methods address these. The proposed method provides decision makers with one more aspect of the assessment of land use impacts on biodiversity, contributing to one of the primary aims of an LCA, which is to avoid burden shifting.

Zusammenfassung

Die Ökobilanz (LCA) ist ein ganzheitliches Instrument zur Bewertung der Umweltauswirkungen von Produkten oder Dienstleistungen. Es wurden verschiedene Ansätze für die Bewertung von Auswirkungen auf die Biodiversität im Rahmen der Ökobilanz vorgeschlagen. Bestehende Methoden befassen sich mit den Auswirkungen der Landnutzung in Bezug auf einen Referenzzustand, identifizieren aber nicht explizit, ob eine Landnutzungsaktivität in einem abgelegenen Gebiet oder in einem Gebiet mit wenigen menschlichen Einflüssen stattfindet. Der Mensch hat die terrestrischen Ökosysteme über Jahrtausende hinweg verändert, und eine solche Dominanz ist mit Blick auf die Erhaltung der Biodiversität bedenklich. Der Erhalt von Biodiversität ist besonders für Gebiete mit geringem menschlichen Einfluss von Bedeutung, nicht nur wegen ihrer intrinsischen und instrumentellen Werte, sondern auch vor dem Hintergrund der Verlustrate der verbliebenen Wildnissen weltweit.

Diese Arbeit schlägt eine Methode vor, die eine Bewertung des Kontextes der Landnutzung einschließt. Sie verwendet Konzepte aus der Landschaftsökologie und der Erhaltung der Biodiversität und bringt sie in die Methode der Ökobilanz ein. Der Schwerpunkt liegt dabei auf der Identifizierung von Landnutzungen, die potenziell zur Fragmentierung von Flächen durch Perforation und Zerschneidung beitragen. Perforation und Zerschneidung treten auf, wenn ein Habitat ein Nicht-Habitat umgibt. Eine Fläche kann beispielsweise durch ein Nicht-Habitat wie einen Steinbruch perforiert werden, oder durch eine Straße zerschnitten werden. Da Habitate artenspezifisch sind, erschwert die geringe Datenverfügbarkeit ihre Aufnahme im Rahmen einer Ökobilanz. Daher wurde in dieser Arbeit eine Methode entwickelt, die dieses Problem überwindet, indem ein bestehender kumulativer Index der menschlichen Belastungen als Indikator für das Potenzial zur Perforation oder Zerschneidung einer Landnutzung verwendet wird. Die Methode zielt darauf ab, Landnutzungen zu identifizieren, die in Gebieten mit geringer menschlicher Belastung oder in abgelegenen Gebieten auftreten, da dort Perforation und Zerschneidung mit größerer Wahrscheinlichkeit auftreten.

Auf Grundlage von Literatur zur Naturschutzbiologie wurde eine 1 km breite Pufferzone um die Grenze der Landnutzung geschaffen, die in dieser Arbeit als *Kontextgebiet* bezeichnet wird. Dieses Kontextgebiet wurde mit der Karte des Human Footprint Index (HFI) überlagert, und die Durchschnittswerte des HFI wurden für die

Kontextgebiete berechnet. Auf diese Weise kann eine Landnutzung explizit mit den bestehenden Belastungen in einem Gebiet in Verbindung gebracht werden, wobei niedrige Belastungen auf abgelegenere Gebiete hinweisen.

Die Methode ist für jede Landnutzungsart anwendbar, wenn die räumlichen Grenzen definiert wurden. Um die Eignung der vorgeschlagenen Methode zu demonstrieren, wurde sie auf die meisten gängigen Landnutzungstypen angewandt: bebaute Gebiete, Ackerland, Weideland, Straßen, Schienen sowie Steinbrüche und Bergwerke. Die HFI-Werte für die Kontextgebiete wurden für diese Landnutzungstypen für die ganze Welt berechnet. Die Ergebnisse der Verteilung des HFI und seines Standorts variierten je nach Landnutzungstyp und innerhalb von Ländern und Regionen.

Um den HFI als Indikator für die Perforation oder Zerschneidung zu verwenden, muss ermittelt werden, um wie viel ein Gebiet mit niedrigerem HFI eher perforiert oder bei welchem Wert des HFI gesagt werden kann, dass die Landnutzung nicht weiter perforierend wäre. Um diese Fragen zu beantworten wurden anhand einer Stichprobe von Steinbrüchen und Bergwerken jeweils eine Verifikation und eine Bewertung durchgeführt.

Die Verifizierung hatte zum Ziel, das Vorhandensein einer perforationsähnlichen Konfiguration um die Steinbrüche und Minen herum zu überprüfen, was bedeutet, dass der Kontextbereich dieser Stätte vollständig aus natürlichem Lebensraum besteht. Eine Stichprobe von Kontextgebieten mit einem durchschnittlichen HFI von Null wurde mit Hilfe von Satelliten und Luftbilddaten untersucht. Der Verifizierungsschritt ergab, dass eine strenge Perforationskonfiguration selten ist, da in den Kontextbereichen häufig Straßen und Wege beobachtet wurden, die HFI-Eingangskarte diese jedoch nicht erfasst hat, da es sich nicht um Hauptstraßen handelt. Die Bewertung wurde für Steinbrüche und Bergwerke durchgeführt, die sich in Waldbiomen befinden, da die Landbedeckung dieser Biome weit verbreitet und einfacher zu identifizieren ist als z.B. bei Savannen-Biomen, die sich aus einer Mischung von Vegetationstypen zusammensetzen. Bei der Bewertung wurden der HFI und die Waldbedeckung im Kontextgebiet berücksichtigt. Jedes Kontextgebiet erhielt eine Punktzahl entsprechend seiner Ähnlichkeit mit dem Perforations- und Sezierungsmuster der Landschaft. Eines der wichtigsten Ergebnisse dieses Schrittes war die Notwendigkeit, die HFI-Belastungen in zwei Kategorien zu disaggregieren: Belastungen, die mit einer Veränderung der ursprünglichen Bedeckung zusammenhängen, wie Ackerland und bebaute Gebiete, und Belastungen, die unabhängig von der Landbedeckung auftreten, wie z.B. Nachtlichter.

Die Durchschnittswerte der HFI-Belastungen wurden für Kontextgebiete mit Steinbrüchen und Bergwerken berechnet. Die HFI-Belastungen wurden auf der Grundlage der Literatur in Perforationsbeiträge umgerechnet. Das Perforationspotenzial wurde als maximal definiert, wenn sowohl die die Landbedeckung verändernden als auch die nicht verändernden Beiträge gering sind, was durch die Multiplikation der beiden Beiträge ermittelt wurde.

Die Methode wurde auf ein Produktsystem angewandt, um ein Beispiel für die Anwendung der Methode im Rahmen einer Ökobilanz zu liefern. Das gewählte Produkt war Stahl, und das System wurde mit Eisenerz aus Kanada, Brasilien und Australien sowie mit metallurgischer Kohle aus Kanada modelliert. Das Ergebnis war, dass die Bergbauaktivitäten in Kanada, sowohl für Kohle als auch für Eisenerz, das höchste Potenzial zur Perforation hatten. Die Methode wurde so konzipiert, dass sie in Kombination mit anderen Folgenabschätzungsmethoden verwendet werden kann, und zwei weitere Folgenabschätzungsmethoden wurden angewandt, um zu zeigen, wie das Perforationspotenzial in der Ökobilanz verwendet werden kann.

Die Neuheit der Methode besteht darin, dass sie die Identifizierung einer Landnutzung ermöglicht, die an Gebiete mit geringem menschlichen Einfluss grenzt, weil sie aufgrund ihrer Abgelegenheit für die Erhaltung der biologischen Vielfalt wertvoll sind. In der Praxis beruht die Verwendung einer Karte der kumulativen Belastung nicht auf einer direkten Messung von Arten oder Lebensräumen, obwohl solche Daten verwendet werden können, wenn sie verfügbar sind. Die Methode wurde ohne Gewichtung zwischen der Art der Landnutzung selbst, ihrem Ökosystemtyp oder den Intensitäten entwickelt, da andere Belastungsmethoden diese berücksichtigen. Die vorgeschlagene Methode bietet Entscheidungsträgern einen weiteren Aspekt der Bewertung der Auswirkungen der Landnutzung auf die biologische Vielfalt und trägt damit zu einem der Hauptziele einer LCA bei, nämlich der Vermeidung von Lastenverlagerungen.

List of acronyms

AUS	Australia
CA	Context Area
CAN	Canada
CF	Characterization Factor
CMB	Conditions to Maintain Biodiversity
BRA	Brazil
ELU	Ecological Land Units
DNP	Distance to Nature Potential
HFI	Human Footprint Index
HFI_{mod}	Human Footprint Index pressures that modify the land cover
$HFI_{non\text{-}mod}$	Human Footprint Index pressures that do not modify the land cover
HII	Human Influence Index
GIS	Geographical Information Systems
LCA	Life Cycle Assessment

LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
OSM	OpenStreetMaps
PDF	Potentially Disappeared Fraction of species
PP	Perforation Potential
Q	Quality
SETAC	Society for Environmental Toxicology and Chemistry

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1 Introduction

1.1 Background and rationale

Living organisms depend on a unique set of characteristics such as light, chemicals, and nutrients; they interact with each other and with their environment in different ways, composing the variety of life on our planet. Biological diversity encompasses life in all forms (Farnham 2007, p. 11), and can be broadly organized in three levels: the ecosystems, which are for example forests; the species, which are the organisms in those ecosystems; and the variety of genes reflecting each species' individuality (Wilson 2002, pp. 10–11).

At its most simplistic interpretation, biological diversity reflects the measurable component of the variety of life forms (Farnham 2007, p. 2). The term is often used to bring attention to a crisis surrounding the loss of the natural variety of life, also implicitly suggesting concern over human degradation of the environment (Farnham 2007, p. 2). In that sense, biological diversity is also characterized as a component of nature's conservation, which also includes concepts such as the protection of the wilderness, the utilitarian use of resources, and the encouragement for the preservation of endangered species (Farnham 2007, p. 4). The study field of conservation biology has the goal of providing governments and interested parties with principles and tools for preserving biological diversity (Soulé 1985).

The first use of the term *biodiversity* as a contraction of the term biological diversity might be attributed to E. Norse in a scientific report in 1980 (Whittaker and Ladle 2011, p. 6). The term gained the media spotlight after the National Forum on BioDiversity held in Washington, D.C., in 1986 (Farnham 2007, p. 22). The United Nations Conference on Environment and Development, which took place in Rio de Janeiro, established the Convention on Biological Diversity (United Nations 1992). The convention is a legally binding treaty with the overall objective of encouraging actions that will lead to sustainable development.

The dramatic human transformations on the Earth's surface result in these areas not being able to support its original species (Laurance 2010). Land surfaces are noticeably dominated by humans (Vitousek et al. 1997), estimations of the amount of human transformed or degraded landscapes range around 50 % of the Earth's terrestrial surface (Daily 1995; Hooke and Martín-Duque 2012). Such modification has taken place over millennia but has been exacerbated in the last two centuries (Laurance 2010). Human dominance over terrestrial ecosystem is shown in Figure 1, which is a map that takes into account human presence instead of only the original assemblage of living organisms (Ellis and Ramankutty 2008); and shows human presence on all continents.

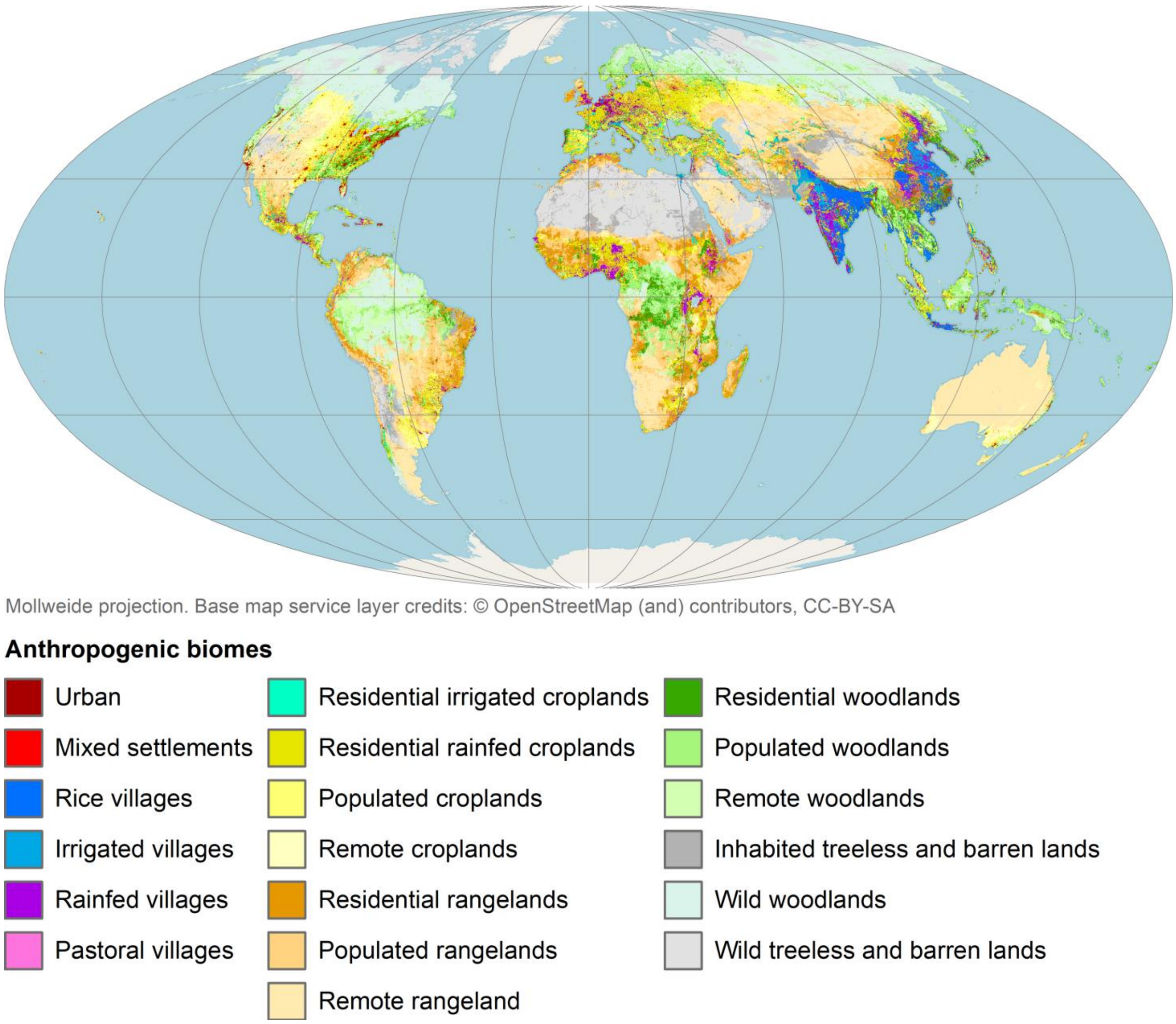


Figure 1 World map of the distribution of biomes considering potential natural vegetation, human population, and land use intensity. Data from Ellis and Ramankutty (2008).

The modification of natural habitat by human activities has resulted in the unmodified habitats to be divided into smaller fragments (Vitousek et al. 1997). This modification of configuration affects the composition of species if compared to unmodified ecosystems (Saunders et al. 1991); therefore, not only the amount but also the configuration of modified landscapes is relevant for biodiversity conservation.

The production of goods and services is the driver for the anthropogenic use of land (Vitousek et al. 1997), and the increased demand for material goods such as food, feed, wood, and fiber also increased its impact on nature (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES 2019). Governments, landowners, policy makers, and consumers are examples of those who directly or indirectly play a role regarding decisions that can minimize or eliminate the impacts of such goods or services.

To inform the relevant players about the impacts of products, life cycle assessment (LCA) provides decision makers with scientifically backed information about the environmental profile of a product or service. The LCA community, especially in the last 20 years, has made efforts to evaluate and communicate the potential impacts of the supply chain of a product or service on biodiversity (Winter et al. 2017). These efforts have been mostly hindered by the difficulty in consistently measuring biological diversity worldwide and by limited data availability. Advances in geographic information technologies, the growing access to globally relevant data, and the development of new methods are allowing researchers to overcome these problems and improve the assessment of biodiversity in LCA.

1.2 Motivation and goal

Previous LCA methods to assess the impact of land use on biodiversity applied to the whole world have given higher impact values for locations in which the natural habitat has already been degraded (de Baan et al. 2013b; Taelman et al. 2016). The uniqueness of the species in an area has also been taken into account (Chaudhary et al. 2015). Current methods cannot explicitly identify if a land use takes place in wilderness and remote areas unless those have been previously considered to be areas of concern for their conservation status. To address this issue, the focus of this thesis is to develop an LCA coherent method that can explicitly communicate whether or not a land use takes place in a remote area. Three main research questions were defined:

1. Is it possible to use and transfer concepts from landscape ecology and biogeography to allow us to compare land use activities depending on its surroundings?
2. Is it possible to implement those concepts as part of an impact category in life cycle assessment?
3. Is it possible to create a method that is simple enough to be applied globally but still relevant for biodiversity conservation?

In addition to the main research question, complementary questions will address the main obstacles to the full implementation of such a method in LCA in regards to:

- the method development,
- the method applicability, and
- the simplicity of the implementation.

1.3 Structure

Chapter 1 contains a general introduction to the topics dealt with in this thesis and a description of the research questions. Chapter 2 is a literature review and starts with relevant fundamental concepts on the topics of life cycle assessment, land use, geospatial analysis, biodiversity, and spatial configuration. The literature review then explores the methods quantifying anthropogenic pressures (section 2.8), as well as the life cycle assessment literature specific to the assessment of land use and its impact on biodiversity (section 2.9). This theoretical background forms the basis for Chapter 3 in which the problem statement is defined. Chapter 4 consists of the requirements for the ideal method to address biodiversity in life cycle assessment and is followed by the method chapter (Chapter 5). In the method chapter the structure, and data used are described in section 5.1 leading to the method development (section 5.2) and a description of the integration with other methods for biodiversity in life cycle assessment is presented in section 5.3. A practical example of an application of the method in the scope of LCA is presented in Chapter 6. Chapter 7 is an evaluation of the proposed method against the method requirements. Chapter 8 provides a synopsis of the method and its application. An outlook covering improvement opportunities is presented in Chapter 9. This structure is summarized in Figure 2.

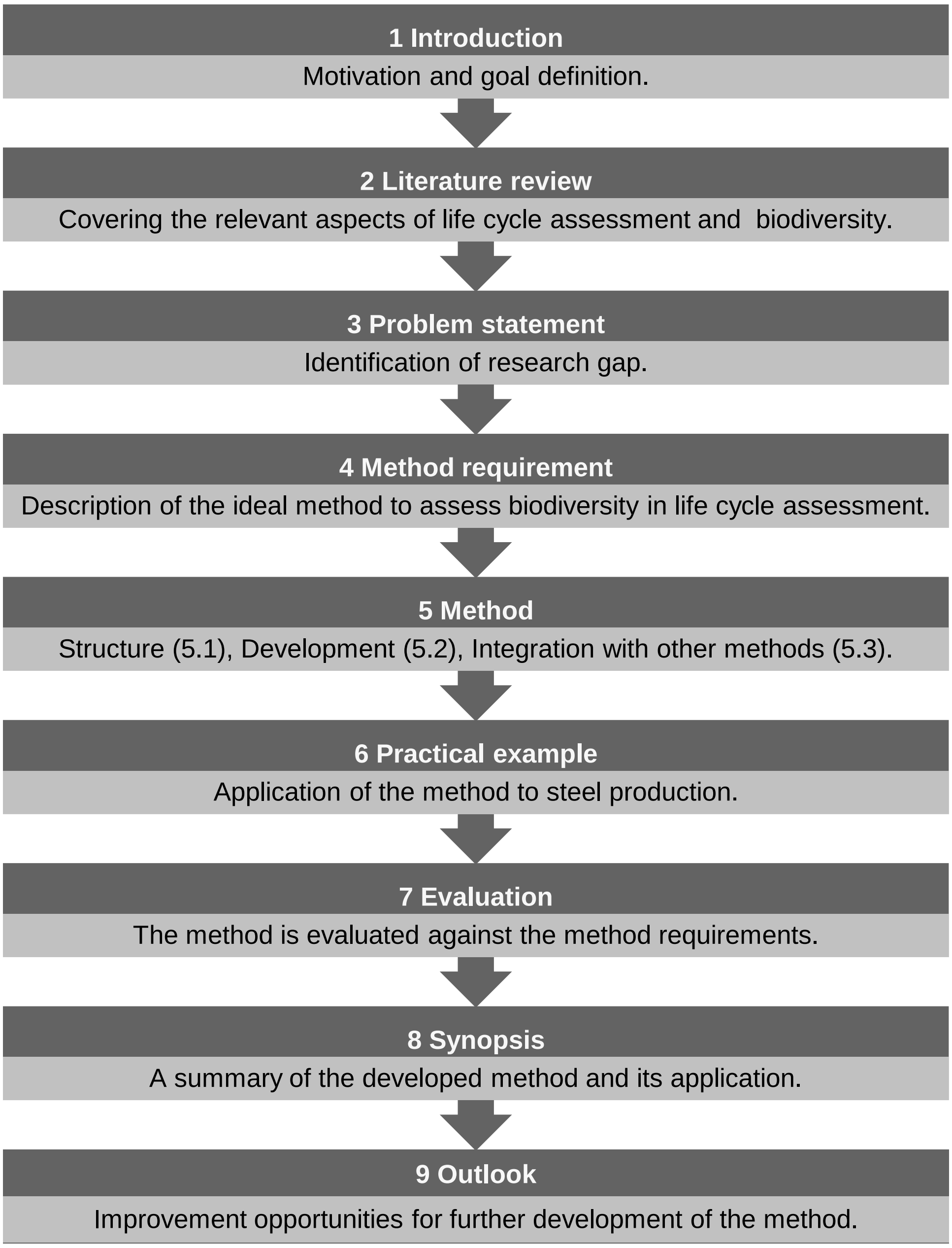


Figure 2 Schematic structure of the work.

2 Literature review

The relevant literature for the development of the method proposed in this thesis consists of life cycle assessment, concepts of biodiversity conservation, and landscape ecology. The literature review will cover fundamental topics of life cycle assessment, land use, spatial information, classification of biomes and ecoregion, biodiversity, and the importance of remote areas. These topics introduce theories and definitions that are essential for the understanding of specific literature review covering spatial configuration, anthropogenic impacts, and specific methods for the assessment of land use on biodiversity.

2.1 Life cycle assessment

LCA is a standardized tool that evaluates the impact of a product on the environment (ISO 14040:2006; ISO 14044:2006). It accounts for energy and materials' inputs and outputs of a product, and by considering the full supply chain it gives a holistic understanding of the impacts of a product. In LCA, products are assessed by their function, calculating energy and material flows in relation to a functional unit. As a consequence of its holistic approach, LCA allows the identification of potential environmental *burden shifting.* This burden shifting occurs when the reduction of one impact leads to the increase of another environmental burden (Sala et al. 2016).

Energy and material inputs of a product are classified according to the environmental problem they cause and then characterized depending on the extent of their environmental impact (Baumann and Tillman 2014, p. 134). This conversion is based on scientific models of the cause-effect chain linking the emissions and resource use to environmental problems (Baumann and Tillman 2014, p. 131). These scientific models are the basis for the characterization models, also called impact assessment methods, which result in characterization factors (CF). The CFs are the operators that convert the inventory (the inputs and outputs) into impacts (environmental problems). When assessed in LCA, a particular type of environmental problem is called an impact category.

2.1.1 Framework for the assessment of land use in LCA

The assessment of the impacts of land use on biodiversity has received dedicated attention from the LCA community. To consistently assess land use in LCA, a framework was agreed upon by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC), the UNEP-SETAC working group (Milà i Canals et al. 2007). It established that the land use's impact is quantified in terms of a quality measure. The idea behind it is that human activities in a piece of land can decrease its environmental quality (Q), and after the land use no longer takes place, the quality of that piece of land would increase, the latter being called the relaxation period. The assessment depends on the determination of a quality axis, and the framework does not determine how Q should be defined. The main objective of the framework is to capture a relative change of the quality of the land due to a specific land use compared to a reference state. A graphical representation of the land use framework is shown in Figure 3. The Q axis stands for a quantitative representation of the quality of a piece of land and is used for the representation of the impact of land use on biodiversity.

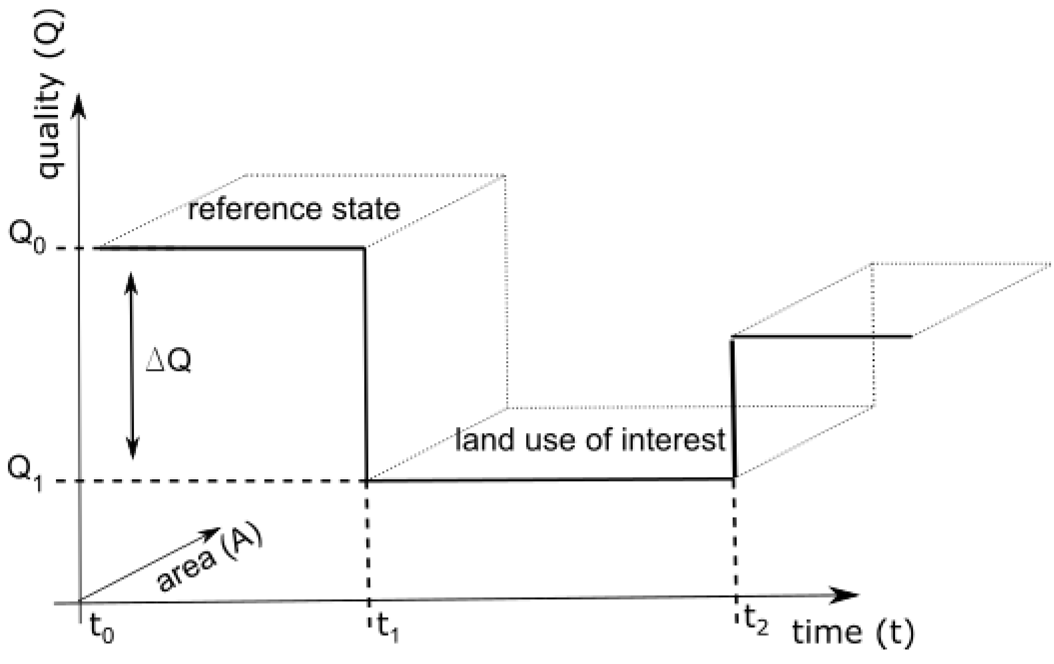


Figure 3 Visual representation of the LCA framework for quantification of land use. Adapted and simplified from Milà i Canals et al. (2007).

Land use impacts in LCA are quantified by the difference in the land use quality of a reference state and the quality of land use being assessed (ΔQ). In other words, the impact of land use is quantified through its comparison with what should be there. For every unit of the area being used in a year, for instance, for the production of a crop, this land use prevents the relaxation process; this in LCA is called occupation impact.

Geographical differentiation, or the location dependency of an impact, is referred to in LCA as regionalization. Regionalization of the impact model, in combination with a location-specific inventory, helps improve the reliability of the results (Frischknecht et al. 2019).

2.1.2 Land use classes in LCA

When assessing a product's use of land, LCA accounts for the type of land use and the required occupied land in a period of time. For example, in investigating the impact of steel, the land use type for the extraction life cycle phase is mining. Land use types or classes proposed by Koellner et al. (2013a) are derived from land cover classification. Despite being generally accepted that land use and land cover are not the same things (Haines-Young 2009) and such differentiation has been acknowledged by the LCA community (Koellner et al. 2013a; Mattila et al. 2011), land use and land cover, are often undifferentiated and have been described as land use/cover by several authors (Koellner et al. 2013a; Beck et al. 2010; Yamaguchi et al. 2016; Koellner et al. 2013b). In short, land use classes in LCA have been mostly derived from land cover, and the terms are used almost interchangeably. Details on the difference between land use and land cover are explained in section 2.2.

2.2 Land use and land cover

Land use is the social or economic activity that takes place in the land (Haines-Young 2009). Land use representations are derived from land cover (Martínez and Mollicone 2012). Land cover is the term used to refer to the physical cover of the area, usually vegetation (Haines-Young 2009). A collection of trees may be classified simply as the land cover forest cover, while these can be native or exotic, natural or planted, and used or not used. Land use classifications are more detailed and aim to determine the predominant activity (Martínez and Mollicone 2012). Pastureland, for example, can be used for sheep or cattle grazing. An illustrative example is shown in Figure 4.

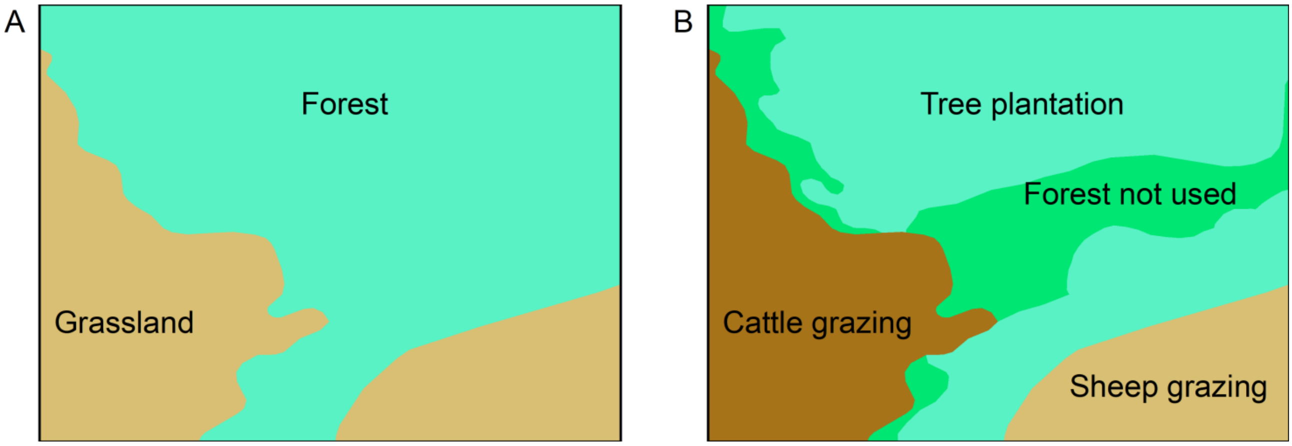


Figure 4 Illustration of (A) land cover and (B) land use.

2.3 Geographic information systems

Land use and land cover maps can be used, for example, for natural resources management, environmental monitoring, and planning. Land use and land cover can be delineated with different levels of accuracy. Most global land cover maps are available with a resolution from 300 m to 1 km (Chen et al. 2015). Mapping land cover at a global scale with finer resolution such as 30 m is complex given the extent of the Earth terrestrial surface of about 150 million km^2 (Chen et al. 2015). Chen et al. (2015) developed a global land cover map, GlobeLand30, at 30 m resolution, for ten land cover types, namely: water bodies, wetland, artificial surfaces, cultivated land, permanent snow or ice, forest, shrubland, grassland, bareland, and tundra. The quality of GlobeLand30 was evaluated to have an overall accuracy of over 80 %, being an advance when compared to other datasets that typically achieve 65 % of accuracy (Chen et al. 2015).

The organization of spatial information is the focus of geographic information systems (GIS), a framework derived from geography sciences (Esri 2019). These systems capture, store, retrieve, analyze, and display spatial data (Clarke 1986). Geospatial data can be in two main formats: vector and raster. Vector representations can be points, lines, or polygons (Mitchell 1999, p. 14). Points are represented by a single pair of coordinates without shape or size attributes, lines represent features by at least one line segment, and polygons are a representation of areas defined by borders (Huisman and de By 2009, pp. 95–98). Raster data are regularly spaced cells with an associated value, and the size of raster cells determines its resolution

(Huisman and de By 2009, p. 86). An example of vector and raster representation is given in Figure 5.

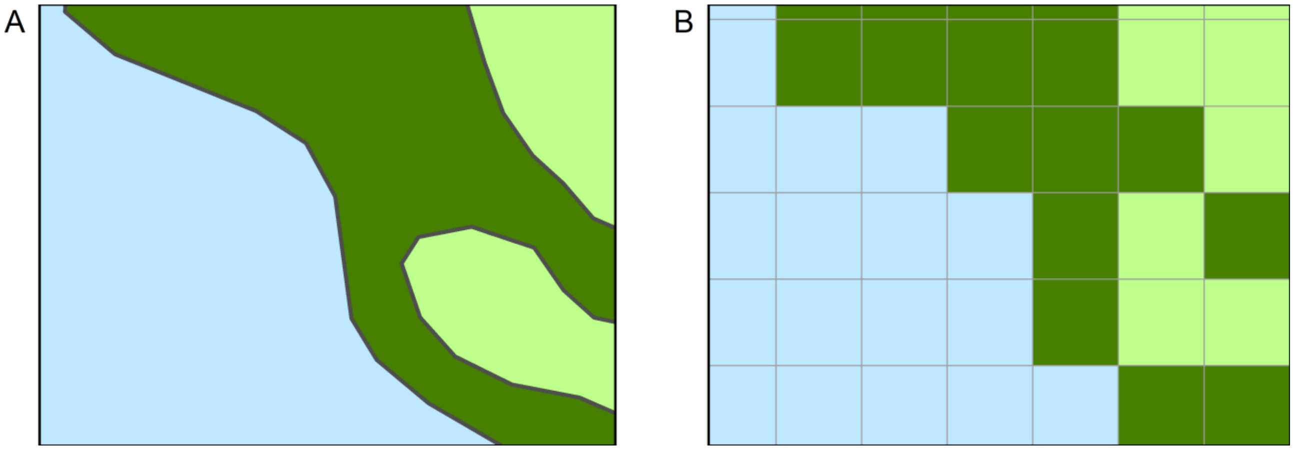


Figure 5 Representation of (A) vector polygons and (B) coarse resolution raster data with grid lines.

Buffers

GIS software packages have a particular set of functions that are used to evaluate the characteristics of the neighboring area (Huisman and de By 2009, p. 346), providing information about the characteristics within a distance of a feature (Mitchell 1999, p. 116). The best known of these types of function is buffering (or *buffer* zone), which is a function that determines the spatial envelope neighboring a given feature (Huisman and de By 2009, p. 346). Buffering can be applied to any GIS data type, an example of buffering vector data is shown in Figure 6.

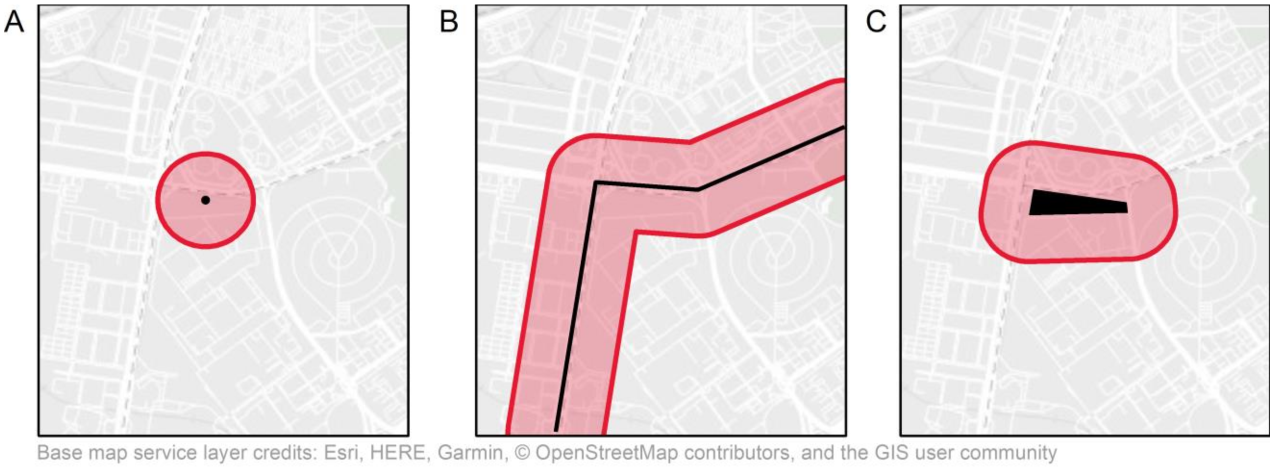


Figure 6 Example of buffer zones created for (A) points, (B) lines, and (C) polygons.

Zonal Statistics

GIS can be used to provide information about what is inside one or several areas making possible a comparison between them (Mitchell 1999, p. 88). One example of such a tool in biodiversity conservation is the determination of the amount of forest in a watershed to target them for conservation (Mitchell 1999, p. 88). The amount of forest is obtained using a *zonal statistics function*, which returns, for example, average, minimum, maximum, and range of the input value for each area of interest (Holcombe et al. 2007). This function extracts the statistics of the values of each cell within a zone, however, the zone and the cells do not always align (Bunting et al. 2014). Different GIS software packages use different criteria to solve this problem, and the software ArcGIS uses the cell-center method, in which only the pixels with the center inside the zone will be computed (Bunting et al. 2014). Zones or parts of a zone that do not overlap a cell-center are uncaptured and are called the *missing zones*.

One way to solve the missing zones problem is the redefinition of the cell size (Chatterjee 2018). The redefinition of the cell size in the GIS software virtually creates a new grid, with an increased number of center cells. This new grid with smaller cell size is used to reduce or avoid zones to be uncaptured by the zonal statistics tool (Chatterjee 2018). An example is given in Figure 7.

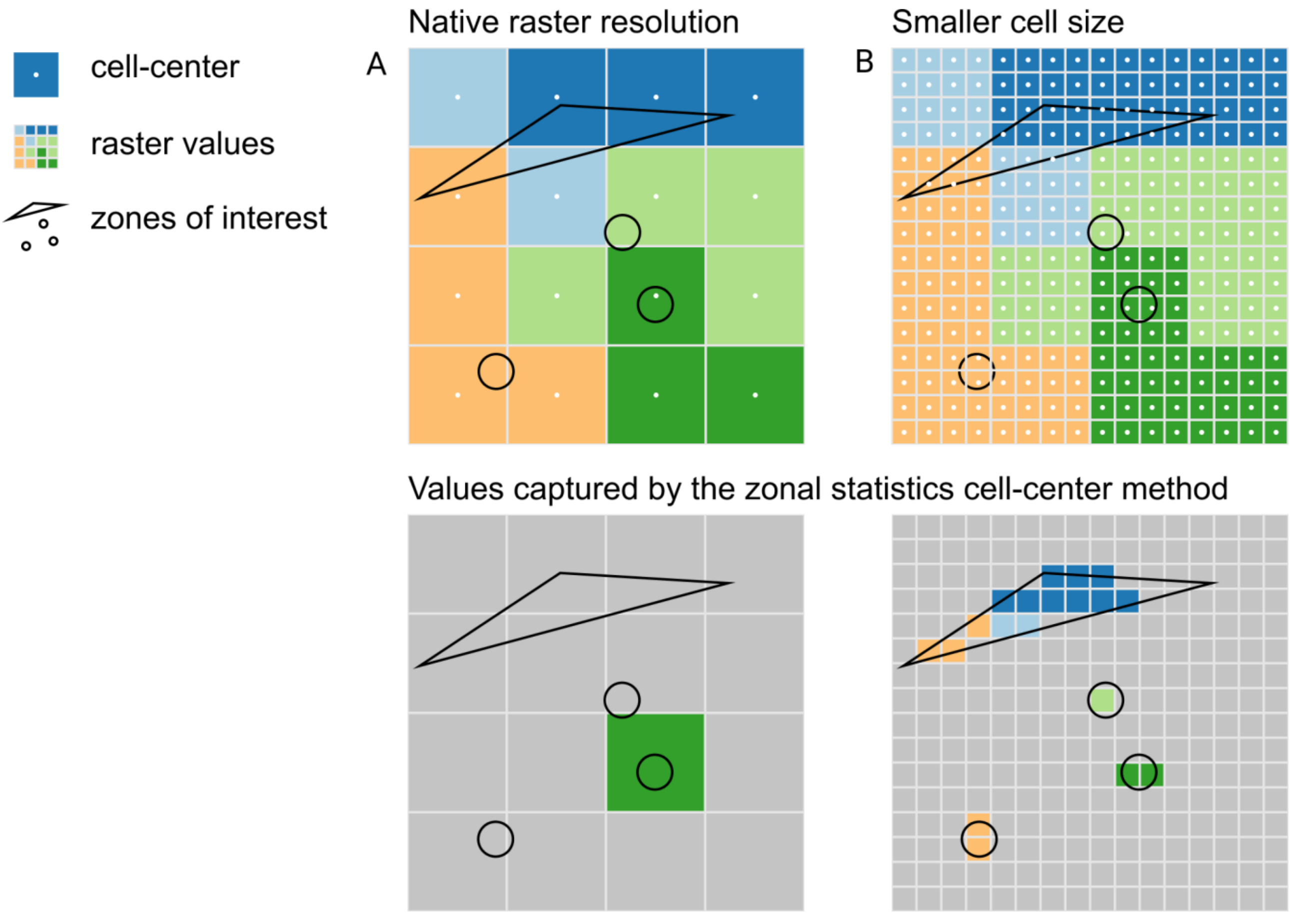


Figure 7 Zonal statistics calculated using the cell-center method for (A) native resolution (top) and the resulting captured raster cell (bottom) and (B) smaller cell size (top) and the resulting captured raster cells (bottom). Adapted from Chatterjee (2018).

2.4 Biomes and ecoregions

A major natural vegetation land cover that occurs with a particular combination of climatic conditions and physical and chemical characteristics of the soil forms the notion of major ecosystem types, or biomes (Riddle et al. 2011, p. 78). Major terrestrial biomes are tundra, boreal forests, deciduous and evergreen forests, tropical deciduous forests and savannas, grasslands, deserts, and semi-deserts (Lomolino et al. 2010, p. 136). Biomes have been widely used in biological diversity conservation planning to ensure the representation of different ecosystem types and communities (Riddle et al. 2011, p. 79).

Global biodiversity is complex and distinctive communities can be unnoticed in broad classifications such as biomes, which has lead Olson et al. (2001) to develop the Ecoregions classification. Ecoregions are “relatively large units of land containing a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land-use change” (Olson et al. 2001). This classification counts with 825 terrestrial ecoregions, and their aggregation at coarser level results in 14 biomes.

2.5 Biodiversity

Biological diversity discipline’s central interest is the variety of life on earth, and its interest on non-living things such as geologic, physical or chemical characteristics is related to its connection to biological life (Farnham 2007, p. 2). The discipline addresses the biology of species, communities, and ecosystems that are perturbed, either directly or indirectly, by human activities or other agents (Soulé 1985). More specifically, the term conservation biology refers to the research which aims to inform management decisions about the conservation of biodiversity (Whittaker and Ladle 2011, p. 5) with the goal to provide principles and tools for preserving biological diversity (Soulé 1985).

Biodiversity conservation research is primarily based on science and technology. However, the desire to preserve the variety of biological life is based on ideas and beliefs (Ladle et al. 2011, p. 13). Conservation values can be separated into intrinsic and instrumental. Intrinsic values are those based on an aesthetical or intellectual appreciation of nature, while instrumental values are concerned with the survival, well-being, and material development of human beings, focusing on the purposes of human use (Sandler 2012).

To conserve biodiversity it is necessary to describe how species are distributed (Purvis and Hector 2000). Data on species presence in a determined location can be gathered by survey records or a compilation of species range’s maps (McPherson and Jetz 2007). However, there are limitations regarding species measurements. An example of this limitation is the difference between species richness and evenness (Purvis and Hector 2000). The authors exemplified that a random sampling of individuals in an area with many different species (high species richness), but with a significant difference between the number of individuals of each species (low evenness) may lead the survey to only find individuals belonging to the same species. A survey in a site with high evenness and low richness may find individuals of different species. With this example, the authors illustrated an inherent problem of biodiversity estimations. They stressed that there is no wrong or right way of measuring species, but no single number can be achieved without loss of information (Purvis and Hector 2000).

In addition to the problem of biodiversity measurement per se, there are practical limits to our knowledge of biodiversity. Such knowledge gaps, or shortfalls, are a consequence of the overwhelming complexity of the natural world (Hortal 2008). The discrepancy between the number of species that have been described and the number of species that are thought to exist is known as the Linnean Shortfall (Lomolino et al. 2010, p. 701). Also, the measurement of species and its derived scientific knowledge is often limited to political boundaries that do not follow the natural boundaries where species occur; this knowledge gap is called the Wallacean shortfall (Riddle et al. 2011, p. 56).

The investigation of species extinctions is also hindered by our limited knowledge. For example, species can go extinct before they are discovered (Linnean extinction), or they might not have been documented for many years, but it might be that they just have not been found (Wallacean extinction) (Riddle et al. 2011, pp. 58–61). Also, species can experience local extinction when they are extinct in a geographic location, but wild populations still exist elsewhere (local extinction). In addition to the knowledge problem, species loss may not be detectable several generations after the habitat alteration, which is called *extinction depth* (Triantis and Bhagwat 2011, p. 201). The quantification of extinction depth is essential to conservation planning; however, an accurate assessment of extinction rates and future projections require data that is generally lacking (Triantis and Bhagwat 2011, p. 201).

While the inventory of species in a plot of land is measured objectively, captured by a field survey of living organisms, the classification of living organisms is not objective. This issue is referred to in the field of biology as *species problem*, which is "the worrying thought that a given group of organisms could be classified as one, or two or many species, depending on the standard of evidence used or personal inclination of the classifier" (Sigwart 2018, p. 2).

Countering the view that conservation should be based on strict measures, N. Barnes warns for the trap of measuring things that are easily measured and “if we are not careful, only what is counted that counts” (Barnes 1996, p. 223).

2.6 Remote areas

Conservation that is oriented to the preservation of ecosystems, as opposed to being organism-oriented, has shifted attention towards wilderness areas (Plutzar et al. 2013). Wilderness are areas where human presence does not occur or has a minimal impact (Watson et al. 2016). These areas have ecosystem regulating functions that maintain the ecosystems and the biosphere health, harboring refuge and reproduction habitats to wildlife, contributing to biodiversity conservation, providing material goods and energy for human consumption and represent a reference state for biological science research (de Groot et al. 2003). As these aspects always provide a service to humans, and always stress anthropogenic benefits, they refer to instrumental values (Carver and Fritz 2015, p. 4). However, natural processes, landscapes, species, ecosystems, and wilderness do not have to be commodified to be tangible to us (Carver and Fritz 2015, pp. 4–5).

While efforts have been made to increase the areas dedicated to the protection of biodiversity and its conservation, the protection of wilderness areas has not received as much attention or has not been systematically tracked (Lovejoy 2016). Human activities pose an unprecedented threat to wilderness areas, with those areas being lost at a rate that is double the rate of its protection (Watson et al. 2016).

Areas that are protected and managed to preserve their natural conditions are classified as *wilderness areas* by the International Union for Conservation of Nature (Dudley 2008). These protected areas are usually large unmodified or slightly modified areas, retaining their natural character and influence, without permanent or significant human habitation, or are an area of low human influence (Dudley 2008). An area where there is little or no anthropogenically modified land cover, and where humans have little or no access, will be referred to in this thesis as *remote areas* to distinguish them from areas which have been established and gazetted as a wilderness area.

Conservation approaches that focus on areas with a low threat are referred to as a *proactive approach*, while a *reactive approach* focuses on the protection of threatened species (Brooks et al. 2006). Hence, the conservation of wilderness and remote areas can generally be classified as a proactive approach.

2.7 Spatial configuration

Anthropogenic activities drive biodiversity loss through the removal of habitats, the increasing spread of invasive species, pollution, uncontrolled human population growth, and over-harvesting (Wilson 2002, p. 50). Wilson emphasized the danger of habitat destruction and human population presence to biodiversity because they increase all other drives for biodiversity loss. In ecology, the definition of habitat is "the ecosystem where a species lives, or the conditions within that ecosystem" (Forman 1995, p. 39). A habitat, be it living or non-living, is species-specific; therefore, suitable habitat for one organism may not be suitable for another. Additionally, some species may require more than one habitat type in their life cycle (Hall 2015).

Habitats are not exclusively pristine areas, and modified landscapes may provide a suitable habitat for some species (Lindenmayer and Fischer 2006, p. 96). One example is a study that found that following forest modifications the loss of specialist species was accompanied by an increase of generalist species adapted to open-habitat (Gardner et al. 2010). For cultivated land, many species are dependent on low-yielding high nature value farmland and would be threatened by both intensification and abandonment (Feniuk et al. 2019). Also, urban areas can provide a stopover for migratory species (Chan et al. 2014), and in a study investigating habitat preference of a deer species, the authors found that the deer preferred manipulated habitats over natural habitat (Zhang et al. 2019).

Being species-dependent, the study of habitat is species-specific and landscape ecology researchers have the difficult task of developing suitable measures for a heterogeneous combination of land use and habitat types (Collinge 2009, p. 104). Landscape ecology is the focus of the next section.

2.7.1 Theory of landscape ecology

A landscape is an “area that is spatially heterogeneous in at least one factor of interest” (Turner et al. 2001, p. 3) and landscape ecology is concerned not only with the quantity of a particular component of the environment but also how it is arranged (Turner et al. 2001, p. 4). The field of landscape ecology has its roots in Central and Eastern Europe (Turner et al. 2001, p. 10) with term *landscape ecology*’s first use attributed to Carl Troll, in a presentation in 1938, in which the term *Landschaftsökologie* was used (Wiens et al. 2006, p. 8). Landscape ecologists investigate the interaction of a landscape structure (a spatial pattern of an ecosystem), and the landscape functioning (energy flows, matter, and species within an ecosystem) (Kupfer 1995). In landscape ecology, *pattern* refers to both the amount or density of habitat and its spatial arrangement (Bissonette and Storch 2003, p. 17).

An integral part of landscape ecology is not only the spatial configuration of habitats but also the suitability of habitats and the matrix. The *matrix* is the dominant and most extensive, often most modified, patch type in a landscape (Lindenmayer and Fischer 2006, p. 33). A *patch*, a term also very commonly used in landscape ecology and biogeography, refers to a “relatively homogeneous nonlinear area that differs from its surroundings” (Forman 1995, p. 39).

Some species are not able to disperse through the matrix (Lindenmayer and Fischer 2006, p. 64). The matrix can prevent dispersal and movement of a species even in the absence of a physical barrier such as a fence. An illustrative example is the case of crickets in the study presented by With et al. (1999) in which the crickets preferred the grass habitat patch and resisted to leave the grass patch when a sandy matrix separated the patches. This example describes a case in which habitat fragmentation hinders movement, introducing two concepts that are relevant both for landscape ecology and the impacts of land use activities on biodiversity: *context* and *fragmentation*. These will be explained in the following paragraphs.

Context

The understanding that wildlife reserves are not self-contained units and that its success depends on adjacent habitat has been identified in the late 70s (Kushlan 1979). Human activities impose barriers that prevent the flow of species, cause disturbances, and alter nutrient or material flow across the landscapes (Collinge 2009,

p. 10). The importance of the context is that “the land uses and natural habitats that surround a fragment may exert strong influences on the patch” (Collinge 2009, p. 94).

The surrounding matrix has profound effects in the fragment dynamics (Collinge 2009, p. 102). Landscape ecology research has recognized that the amount of light, moisture, temperature, and wind are more pronounced in forest fragments edges and may significantly alter plant and animal communities (Collinge 2009, p. 96). Examples of such influence are a study on forest patches that concluded that the distance from the perimeter of the patch altered its dynamics (Laurance et al. 1998), and a study in Amazonia found that tree mortality in patches surrounded by cattle pasture was higher than in areas surrounded by second-growth forests (Mesquita et al. 1999).

When researchers investigate the effects of the *landscape context*, they describe the landscape surrounding a defined patch and calculate the percentage of the land cover of interest in that area excluding the patch itself (Collinge 2009, p. 105).

Fragmentation

The threat of habitat modification to biodiversity is complex and is a result of concurrent loss and increased fragmentation of the remaining habitat (Hadley and Betts 2016). In the broad sense of the term, habitat fragmentation refers to the process of breaking apart a habitat (Forman 1995, p. 39). The study of fragmentation was stimulated by the influential general theory of species distribution called the theory of island biogeography (MacArthur and Wilson 1967). The theory suggested that the biota of any island is a dynamic equilibrium between the immigration of new species onto the island and extinction of species already present (Simberloff 1974), and brought to light the need for thinking of biodiversity reserves’ size and its connectivity (Laurance 2008).

The role of humans or anthropogenic activities that influence landscape *patterns* is an essential component of landscape ecology. Under the umbrella term of fragmentation, the literature on the ecology of landscapes defines five ways humans modify the landscape (Forman 1995, pp. 407–409; Lindenmayer and Fischer 2006, p. 16). 1) perforation, e.g., mining in a remote area, 2) dissection, e.g., a road in a remote area, 3) fragmentation, e.g., remnant vegetation in grazing lands, 4) shrinkage, i.e., a patch size reduction, and 5) attrition which refers to the removal of patches in highly modified landscapes). A schematic representation of these landscape modifications is shown in Figure 8.

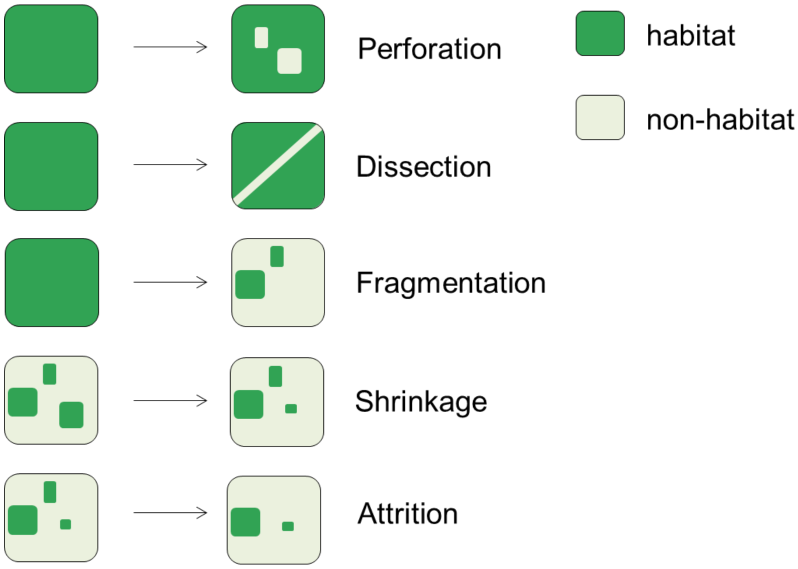


Figure 8 Different types of ways humans modify the landscape. Figure based on Forman (1995, p. 407).

Perforation and dissection are often considered to be the initial processes that modify the landscape (Forman 1995, p. 407). It is possible to imply that these two processes are likely to take place in remote areas. Perforation and dissection patterns similarity is that a non-habitat area is surrounded by habitat area. Here pattern refers to the static spatial configuration of an area, or the end state visible in the second column of Figure 8. More detail about perforation and dissection will be given in the next two paragraphs.

Perforation occurs when a patch surrounded by the native land cover is, for example, cleared by a harvest, mining activity, or scattered houses. The name is derived from its resemblance to the process of making holes in an object, i.e., the non-habitat perforates the habitat. Perforation is a type of landscape pattern that does not break the habitat apart per se because the remaining habitat still forms a continuum (Collinge 2009, p. 5). Landscape ecology literature describes perforation as one of the first processes of landscape alteration (Forman 1995; Collinge 2009; Lindenmayer and Fischer 2006), and perforations in the surrounding halo of habitat may grow and coalesce (Riitters et al. 2000).

Dissection occurs when carving up or subdividing the land with equal width lines (Forman 1995, p. 407), this pattern has also been called bisection (Collinge 2009, pp. 4–5). The most common example of dissection is a road network in a remote area such as roads in the United States of America in the Midwest (Forman 1995), or the Trans-Amazonian highway. The latter had its construction initiated in the 1960s to facilitate settlement and exploitation of the vast underpopulated Amazon River Basin (Encyclopaedia Britannica 2018). The pathways in which populations of wildlife are affected by linear infrastructures will be described in more detail in section 2.8.1 on page 22.

The five ways humans modify the landscape have different relative importances on the process of landscape change (Forman 1995, p. 409). When the habitat cover is high, perforation and dissection have greater relative importance. When less of original cover remains, fragmentation and shrinkage have higher importance. Finally, when there is minimal left of the original cover, attrition will be the most dominant process, while perforation and dissection will no longer take place (Figure 9).

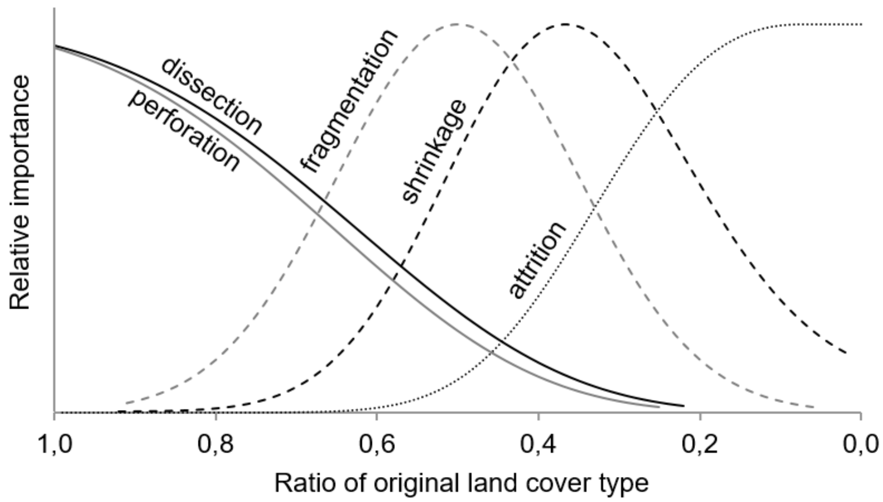


Figure 9 General model for an indication of peaks and overlaps of land transformation processes. Figure based on Forman (1995, p. 409).

Knowledge shortfalls also affect landscape ecology, and although there has been research which investigated fragmentation of tree populations, e.g., Tiep (2015) and Laurance et al. (1998), the literature of landscape ecology is biased towards the study of animals rather than plants (Lindenmayer and Fischer 2006, xvii).

Percolation threshold

Regarding species persistence and the amount of habitat remaining, landscape ecology defines a *percolation threshold*: a point where it becomes more difficult for individuals to disperse through the landscape. After this threshold, the population rapidly declines (Figure 10) (Desmet 2018). A cover of 60 % of the original habitat has been suggested as the percolation threshold (Desmet 2018). At this point, the size of continuous patches significantly decreases (Andrén 1994), making it less likely for perforation and dissection patterns to exist.

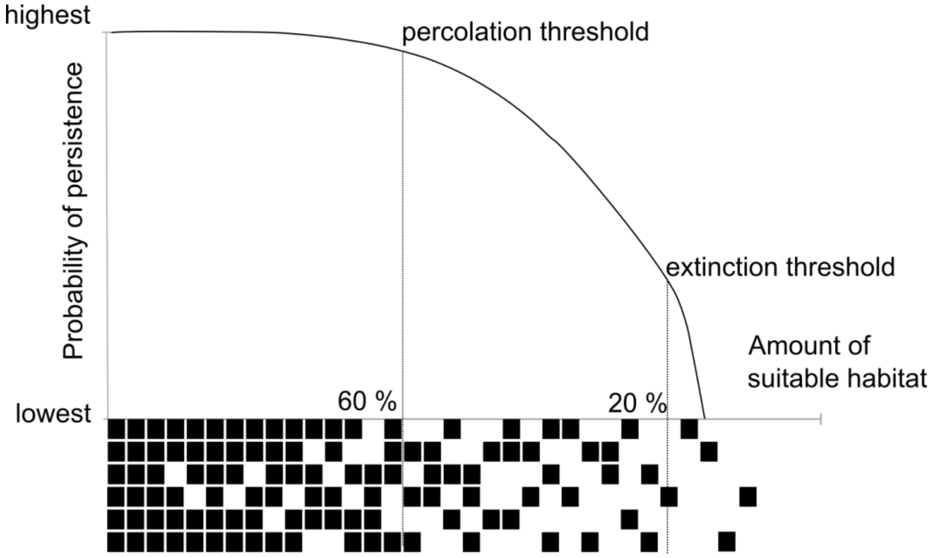


Figure 10 Conceptual model of the impact of habitat loss in population persistence. Figure based on Desmet (2018).

2.8 Methods quantifying anthropogenic pressures

The impact of anthropogenic activities' on the environment can be described through a cause-effect-relationship. The environmental mechanisms that can potentially have an environmental impact are of particular interest for conservation priority setting as they identify the drivers and their consequences. The disproportional lethality which humans have on wildlife has been identified in the literature (Darimont et al. 2015; Clinchy et al. 2016; Gaynor et al. 2018). This section describes main paths in which humans activities affect biodiversity focusing on linear structures, effects beyond its physical extent, human presence, and cumulative pressures.

2.8.1 Roads, railways and other linear features

The impacts on biodiversity which are caused by habitat loss, habitat degradation, barrier or filter movement, wildlife mortality, species' avoidance, attraction, and corridor movement caused by roads and linear infrastructure are the main focus of *road ecology* research (van der Ree et al. 2015, pp. 4–6). Although to a lesser extent than roads, railways, recreational trails, and industrial linear corridors are also investigated by researches of the field of road ecology.

Habitat loss affects wildlife by the alteration or destruction of the vegetation adjacent to roads (van der Ree et al. 2015, pp. 4–6). Immediate edges along the linear feature structure can alter microclimatic conditions making it more prone to weed invasion or favor species that can adapt to such conditions (van der Ree et al. 2015, pp. 4–6).

Roads and linear infrastructure may create gaps in habitats, which can lead to species movement avoidance, be it daily for resources access, seasonal, or movement which occur only once in the animal's life cycle (van der Ree et al. 2015, p. 5). Traffic can lead to mortality by collision, or species may avoid the road effect zone due to traffic; linear infrastructure can also attract species by increased foraging opportunities and also increase the attraction of scavengers which feed on roadkill, or in highly modified landscapes roadside may be the only habitat to wildlife (van der Ree et al. 2015, pp. 5–6).

Roads have an effect zone which is dependent on: the vegetation type, such as grassland, open woodland, shrubland or dense forest; the position of the road in relation to the direction of wind and slope (downstream and downwind areas will be more affected than upstream and upwind), the topography such as mountainous and flatland; and the road traffic intensity (van der Ree et al. 2015, p. 4).

Railways have only recently gained more attention in the literature (Popp and Boyle 2017; Borda-de-Água et al. 2017). Railways can be barriers to wildlife movement (Santos et al. 2017), they may transport native and non-native species (Ascensão and Capinha 2017), and in the case of high-speed railways, they can also have particular effects in some species (Malo et al. 2017; Clauzel 2017).

An industrial linear corridor is another type of linear feature and includes power lines, telephone lines, pipelines, and seismic exploration lines (Latham and Boutin 2015, p. 229). The authors described that its effects are the altered predator-prey dynamics, for example, when a species is attracted to the linear feature and become more vulnerable to predation (Latham and Boutin 2015, p. 231).

2.8.2 Effects beyond the infrastructure extent

The effects of human infrastructures have been recognized to go beyond the extent of its physical boundaries. Proactive conservation schemes have excluded areas near roads (Ibisch et al. 2016) and other infrastructures (Potapov et al. 2008), as those were not considered to be suitable for inclusion in such schemes.

Roads have direct impacts beyond the extent of the road itself, and the *effect zones* can be considerably greater when considering indirect effect (Treweek 2009). Ibisch et al. (2016) carried out a literature review of 282 publications with the aim of determining *roadless areas* (Ibisch et al. 2016). The authors found that 58 publications took into account the spatial influence of the road, i.e., the distance of these effect zones. These studies documented road effects within 1 km zones from each side of the roads, with this zone being the area with the highest intensity and variety of impacts caused by roads. Although there were detected effects beyond 5 km from the road, those were mostly due to deforestation alongside the road or due to the increased resource extraction or hunting (Ibisch et al. 2016). The final roadless areas map used a 1 km distance from roads to indicate roadless areas, with a buffer distance of 5 km used for comparison purposes.

In a conservation scheme designed to determine areas of intact forest or naturally treeless areas, Potapov et al. (2008) excluded agricultural, timber and industrial activity areas (logging, mining and oil, and gas exploration), and also areas within 1 km from settlements, transport infrastructure, pipelines, and power transmission lines (Potapov et al. 2008).

2.8.3 Human presence as a pressure

One of the paths through which humans can disturb biodiversity is the species' temporal behavior (Gaynor et al. 2018), meaning that human presence can influence the behavior occurring within 24 hours, including both diurnal and nocturnal hours (called *diel activity*). A meta-analysis of published literature indicated an increase in animals nocturnally (Gaynor et al. 2018). The study covered 62 mammal species of medium and large size distributed over six continents and revealed that non-lethal activities had similar effects as lethal activities (Gaynor et al. 2018). The authors suggested that those temporal shifts alter natural patterns of animal activity influencing fitness, population persistence, community interactions, and evolution. This type of disturbance occurs because animals may perceive and respond to the presence of humans as threats.

2.8.4 Cumulative pressures

Human activities not only affect biodiversity through individual paths but they may also overlap, resulting in *cumulative effects* on biodiversity. In the attempt to map human influences and identify the last remaining areas of undisturbed wildlife, a group of researchers created the Human Influence Index (HII), which is also referred to as Human Footprint (Sanderson et al. 2002). For the construction of the index, the authors have assigned individual pressures scores to different human pressures. The primary motivation for the creation of the index was the protection of what the authors refer to as the *last of the wild*. Sixteen years from the publication of the HII, the input data for the index was updated (Venter et al. 2016b), hereafter HFI (Human Footprint Index).

The Human Footprint addressed the research gap of pressures that were often not accounted for in conservation priorities. More specifically, it was designed as a cumulative threat map, calculated based on a combination of different pressures, namely: built environments, population density, nightlights, cropland, pastureland, roads, railways, and navigable waterways. The construction of the HFI is explained in the next subsection, followed by examples for which the index was used as an indicator for setting conservation priorities.

Pressure score in the HFI

For the construction of the Human Footprint, each pressure was given a score based on scientific publications and consultation with biologists, social scientists, and conservationists (Sanderson et al. 2002). Scores range from 0 to 10, with 0 meaning no pressure and 10 meaning the maximum score for an individual pressure (Venter et al. 2016b, 2016a). The individual scores are added, creating the HFI, which ranges from 0 to 50. A graphical example summarizing the pressure scores is shown in Figure 11.

Pressure map	Scores
Roads	8 (4 exponentially decaying up to 15 km)
Navigable waterways	4 (exponentially decaying up to 15 km)
Pastureland	1 to 4 depending on amount of pasture
Population density	continuous values up to 10
Nightlights	continuous values up to 10
Built environment	10
Cropland	7
Railways	8

Cumulative map	Scores
Human Footprint Index	0 to 50

Figure 11 Human pressure scores used in the Human Footprint Index (Venter et al. 2016b).

For build environments, the authors attributed an individual pressure score of 10 since it does not provide habitat for many species of conservation concern. Cropland areas received a value of 7. Pastures received values from 0 to 4 according to the percentage of pastureland in each raster cell representing 1 km^2. Nightlights were quantified and scaled continuously from 0 to 10. Population density of more than 1000 people per·km^2 received a score of 10, and for less densely populated areas, the value was logarithmically scaled because even a low human population density can have effects on biodiversity. Roads and railways were given a value of 8 for each side of the feature because roads and railways cause impacts due to the modification of habitats. More specifically, they alter the physical characteristics of the environment, such as humidity, and provide human accessibility to an otherwise remote area. In addition to the direct pressure effect of 8, a score of 4 exponentially decaying to 0 for areas within a distance of 500 m from the road out to 15 km is attributed due to the indirect effect of roads. Railways were not given indirect impacts. Navigable waterways were given a pressure score of 4 exponentially decaying to 15 km. The classification of navigable waterways was based on the presence of human settlements, which was indicated by nightlights and an assumed travel distance of 80 km, meaning that if a point in a river or coastline is beyond that distance, it is considered as being too remote for navigation. For a river to be considered navigable, it must have a depth greater than 2 m. In short, this pressure will occur when humans have access to areas using waterways.

The final map has a resolution of 1 km at the equator, for which the individual pressures scores are added, resulting in HFI values ranging from zero (for no human influence) to 50 (maximum human influence). Maximum pressure occurs in areas where built environment is present, and population density, nightlights, major roads, railways, and navigable waterways have the maximum value.

The authors grouped all land areas assessed by the HFI into five classes, with each pressure class containing approximately the same amount of surface area (Venter et al. 2016b). This type of grouping is called a quantile classification and relates only to the amount of land that falls in each class. The authors suggested that values of 0 indicate no pressure, values from 1 to 2 indicate low pressure, values from 3 to 5 indicate moderate pressure, values from 6 to 11 indicate high pressure, and values from 12 to 50 are areas of very high pressure. The global map of HFI grouped by its pressure classes is shown in Figure 12. The authors' choice of using a quantile classification can be interpreted as a consequence of the absence of pre-defined pressure classes.

The authors of the HFI carried out a technical validation of the final index. They warn that due to the presence of false negatives (meaning that pressures could be there but was not captured by the maps used), that the HFI should be interpreted as a conservative estimate of human pressures on the environment (Venter et al. 2016a).

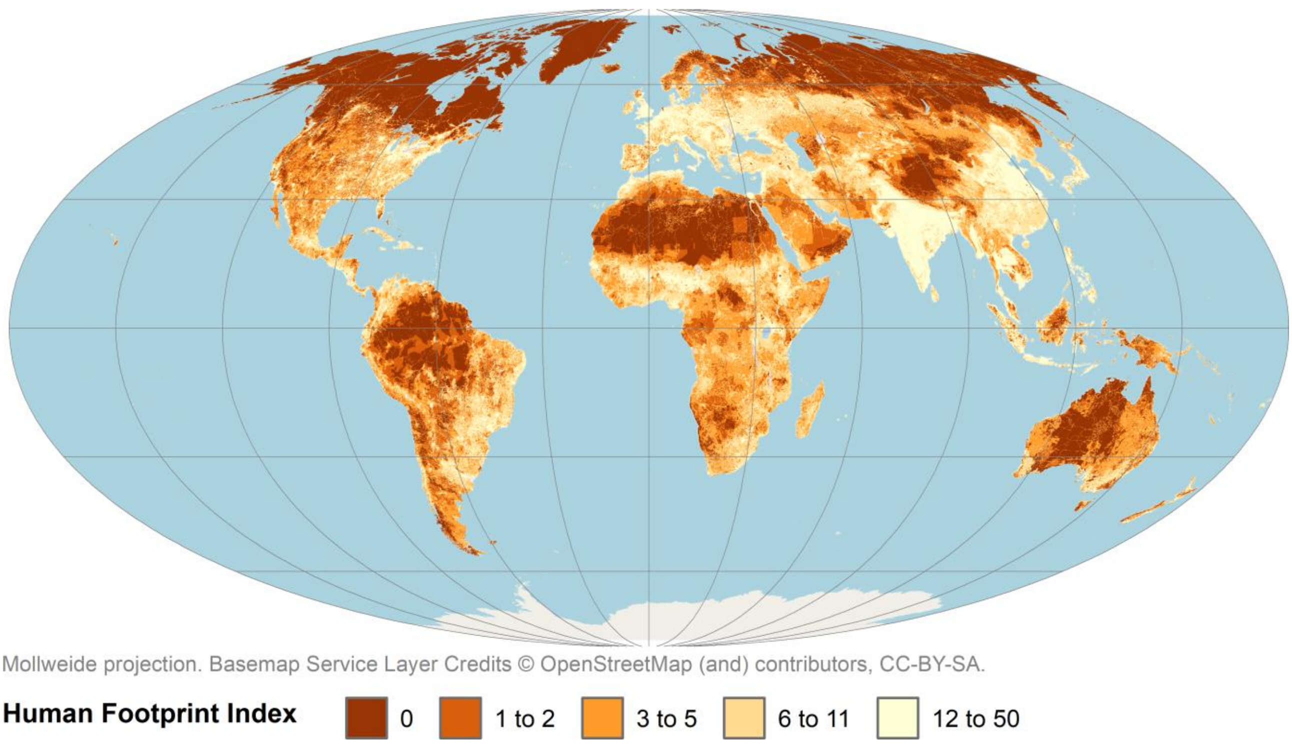


Figure 12 Global Human Footprint Index (Venter et al. 2016b) presented using quantile classification.

Human Footprint as an indicator for reduced animal movements

Using the HFI from Venter et al. (2016b) in addition to the amount of vegetation cover, a study has found a correlation of those two parameters to the reduction of terrestrial mammalian movement (Tucker et al. 2018). The authors found a strong negative effect of the Human Footprint on median and long-distance displacements, meaning that mammals' travel distances in areas of high Human Footprint were shorter than the displacements of individuals in areas of low Human Footprint, and also suggest that animals may move more tortuously in areas of higher Human Footprint. In summary, the movement range reduction was attributed to altered movements relative to the Human Footprint or to the absence of species that have a higher movement range (Tucker et al. 2018).

Human pressures as a threat to protected areas

Protected areas play a fundamental role in biodiversity conservation (Coetzee et al. 2014; Gray et al. 2016). The term protected area has an overarching meaning and applies to areas that have been allocated by a state body or are a private area for which its primary function is to conserve valuable attributes of nature (Whittaker and

Ladle 2011, p. 14). Traditionally, protected areas have been areas that have retained biodiversity, structure, and ecological function, or which have the potential to be restored to that state (Cumming 2016).

Human pressures also threaten biodiversity even in areas designated for their conservation. An area being protected is not a sole guarantee for its conservation, there are areas which are called “paper parks” (Bruner et al. 2001), a denomination used for areas that have been designated as having a nature conservation value, but are not managed accordingly. Protected areas under responsible management, as opposed to paper parks, are less subjected to direct land conversion and habitat loss. As such, a measurement of the effectiveness of a protected area is the avoidance of the anthropogenic conversion of the natural habitat (Paiva et al. 2015).

The presence of alien species is of great concern for the management of protected areas (Moustakas et al. 2018). Those are organisms that have been dispersed due to human action and might survive and reproduce outside its natural range (Falk-Petersen et al. 2006). Human population density surrounding protected areas has been identified as a predictor of the presence of alien species of plants and animals (Spear et al. 2013).

In order to identify increasing pressure in protected areas, Geldmann et al. (2014) used a cumulative index of pressures similar to the HFI; specifically: land use, human population, and nightlights. The investigated pressures were limited to three datasets due to the lack of data that fit the authors’ quality criterion (Geldmann et al. 2014). Although rudimental, the study demonstrated the recognition of the relationship of cumulative human pressures and biodiversity conservation in protected areas.

With the interest of warning about the threats to conservation in protected areas and prevent biodiversity loss, the HFI has been used to quantify the share of protected land under intense human pressure (Jones et al. 2018). Another study, investigating mammals’ response to anthropogenic pressure in the Alberta province in Canada, has found that even though the species’ response to a pressure would be a more valuable measure, in the absence of detailed information, a total footprint can be used as a cumulative index of the effect of human pressures on biodiversity (Toews et al. 2018).

2.9 Land use and biodiversity in LCA

In LCA, biodiversity is often assessed in the land use category because land use is the most significant driver for biodiversity loss (Millennium Ecosystem Assessment 2005). The simplest way to assess land use in LCA is to provide the results in terms of the area used (area · year). This type of quantification does not represent an impact per se but rather the mere quantification of the amount of area used. As such, the assessment does not consider the location where the land use is taking place, which land use type, or its intensity. However, when considering the effects of land use on biodiversity, both the location and the type of intervention are of relevance.

Several methods to assess the impacts of land use on biodiversity within LCA have been developed and were the focus review papers (Michelsen and Lindner 2015; Pavan and Ometto 2016; Gabel et al. 2016; Curran et al. 2016; Winter et al. 2017). In the next subsections, 2.9.1 and 2.9.2, a chronological approach will be taken describing the most relevant methods for the assessment of the land use impacts of biodiversity in LCA, separated into early development and post 2008, leading to the most recent method and review including fragmentation in LCA.

2.9.1 Land use and biodiversity in LCA – early development

The first reference to qualitative regionalization of land use in LCA is probably the report entitled "Biodiversity and life support indicators for land use impacts in LCA" by Lindeijer et al. (1998). The report contains what is likely to be the first sketch of a cause-effect chain of land use impacts in the LCA framework, a world map showing the distribution of biodiversity factors, a differentiation of land use classes, and a mention of the concept of naturalness. Regarding the land use classes, it was argued whether land use could be accounted for in an ordinal scale (Lindeijer et al. 1998, p. 39), and concerns had been raised that the hemeroby, or naturalness, scale lacked scientific backing. The main findings of the report were then published by Lindeijer (2000) and the model further developed by Weidema and Lindeijer (2001).

Parallel development on the integration of biodiversity in LCA was also published in S. J. Cowell's thesis in 1998 (Cowell 1998). As part of the author's proposed Physical Habitat Factor, the method aimed to include: contributions to global ecosystem diversity, number of rare species, number of species, and number of individuals. The author warned that when assessing rare species, the reasons for the species being rare had also to be taken into account. The author argued that if a species is threatened by management practices, an increase in the area of this ecosystem will not improve the biodiversity in that area. The author also proposed a Physical Management Factor, which included a score for how beneficial the management practice was for biodiversity in the system and a weighting factor for which management practice is of most importance for improving the biodiversity in that ecosystem.

In an LCA methodology specific paper, Goedkoop et al. (1998) proposed a method that relied on the assumption that the species diversity in an area is a function of the area quality and the size of that area. The authors argued that "the reduction or enlargement of natural area in a region would directly influence the number of species in a region" (Goedkoop et al. 1998). This point of view was at least partially different from the views of Cowell (1998), who stressed the need for understanding the reason for the loss of species. A characterization model that quantified damages on ecosystems from land use applicable worldwide was published in 2007 (Koellner and Scholz 2007), labeled Ecosystem Damage Potential.

An LCA methodology was proposed based not only on the presence of species but also grouped by land use intensities (Koellner 2000). It used vascular plants as an indicator for biodiversity (vascular plants have a vascular system, while non-vascular plants such as mosses and algae do not). The scientific strength of the method was that it was based on the species-pool concept; the weakness was the difficulty in applying it globally due to lack of data. The species-area relationship is a mathematical model that dates from 1921 (Arrhenius 1921) and confirms the general but somewhat intuitive idea that in a larger surveyed area one would encounter a higher number and a greater diversity of species (Lomolino et al. 2010, p. 3). Another innovation of the method proposed by Koellner (2000) was land use classes, which were derived from the European Environmental Agency, CORINE (short for coordination of information on the environment). In his proposal, Koellner (2000) uses local scales for areas of 1 km^2 and regional scales for areas from 100 km^2 to 10.000 km^2, makes a reference to the contrast of the intervention, and attempts to capture the difference of the impacts from different intensities of use.

Characterization factors for biodiversity were published for different regions as well as test cases (Lindeijer et al. 1998; Lindeijer 2000), but case studies published at this point were specific to the United Kingdom (Cowell 1998) and Switzerland (Koellner 2000). Probably the first LCA case study to compare biodiversity impacts between products from different locations was published for the case of oil crops for Sweden, Brazil, and Malaysia (Mattson et al. 2000). Part of the assessment included the number of tree species, other vascular plants, mammals, birds, and butterflies (Mattson et al. 2000). The analysis was both quantitative and qualitative, and despite applied to a specific land use type, it would have been equally applicable to the assessment of full supply chain or other products.

Differently from methods proposed at this period, Brentrup et al. (2002) suggested a method for land use impact assessment based on the divergence from the natural state of the vegetation, referred to as hemeroby. The approach has its basis on the hemeroby scale, which reflects man-made, non-natural, disturbances (Kowarik 1990). Hemeroby can provide general insight into the response of species, plant communities, or sites to the effects of human activities vegetation of a site (Kowarik 1990). The first suggestion of the use of hemeroby in LCA was made by Klöpffer and Renner (1994), but the original proposal did not include aggregation into a summarizing land use indicator (Brentrup et al. 2002). The concept of hemeroby was operationalized into LCA with characterization factors being provided by Brentrup et al. (2002).

In essence, in the various biodiversity assessment proposals, the core elements of land use type, location, and management practices were already present or at least mentioned around the year 2007. At this point, the differentiation of land uses was mostly addressed in terms of land cover. The understanding that different ecosystems have different values, mostly measured in terms of the species richness, brought focus on the location differentiation. Among the earlier proposals, there was, although somewhat timid, a suggestion of an explicit valuation of management practices as proposed by Cowell (1998). Land use intensity, coarsely distinguished between low and high intensity for the forests and agricultural land, was taken into account by other authors (Koellner and Scholz 2007) and may also be considered as an attempt to include the element of management practices.

Conditions to maintain biodiversity

Management practices were the focus of a subsequently proposed method by O. Michelsen (2008). The author suggested that biodiversity was to be assessed using three elements: ecosystems scarcity (or rarity of an ecosystem), ecosystem vulnerability (an indicator of how degraded the ecosystem is), and the conditions to maintain biodiversity (CMB). This proposal differed from most of the previous methods as the author opposed the use of an explicit measurement of species in LCA. The author justified his argument by citing a considerable amount of research supporting that there is no correlation of species richness between taxonomical groups (Michelsen 2008).

Michelsen (2008) developed a CMB for forestry in Norway, making the element of management practices explicit. This index, which was intended to be a first proposal included: the amount of decaying wood, areas set aside (for the conservation of forest dynamics which may not necessarily happen in managed forests), and alien tree species.

The author stated that CMBs would have to be constructed for different regions, but does not detail how to deal with cases in which the land use is incompatible with the desirable land cover. Although it is straight forward to apply the CMB for a forestry land use in other regions, a difficulty arises from the conceptual gap that the land use presented in the case study corresponds to the desirable land cover. The study region of the presented case study was an area in which forest was the land cover before significant human interference, being also the reference or ideal cover. The assessment of any land use with a different land cover from forest would invalidate the use of the amount of decaying wood and the introduction of alien tree species as parameters.

2.9.2 Land use and biodiversity in LCA – post 2008

The methods proposed up to around 2008 lacked consistent global applicability or were simply data deficient. Advances in geospatial technologies increased the availability of biodiversity data worldwide and globally applicable methods gained momentum. Life cycle inventory for land use assessment in LCA guidelines included a system for regionalization for terrestrial assessments: 1) differentiation between terrestrial and freshwater biomes, 2) climatic regions, 3) biomes, 4) ecoregions and 5) grid cells of 1,23 km^2 or less (Koellner et al. 2013a).

A global approach to assess land use impacts on biodiversity in LCA published by de Baan et al. (2013a) used data on biodiversity changes compared to the original state of ecosystems. The model's input data was still spatially biased and there was also an absence of data for undisturbed reference sites in regions that have already been under intense human use (de Baan et al. 2013a). Nonetheless, the method merits recognition for its remarkable advancement towards regionalized factors.

Subsequent developments building on this model also considered that not all human land uses are hostile to biodiversity (de Baan et al. 2013b). It incorporated an updated matrix-calibrated species-area relationship, which meant that for land uses which are suitable for certain species, they would be accounted for as such. If detailed enough data is available, it is theoretically possible to include management practices. The authors observed that the model's results were found to overlap biodiversity hotspots, or what is called by conservation experts as a *reactive approach*.

Using similar modeling choices from de Baan et al. (2013b), Chaudhary et al. (2015) used a countryside species-area relationship and vulnerability indicators, with results expressed in terms of potential global extinctions per unit of land use. Most recently, the model was improved to include three management intensity levels: minimal, light, and intense use (Chaudhary and Brooks 2018). The authors proposed CFs for different land uses and terrestrial ecoregions in terms of potential species extinctions.

Following the approach of assessing land use based on the hemeroby concept, other LCA characterization factors have been proposed (Coelho and Michelsen 2014; Fehrenbach et al. 2015; Taelman et al. 2016). The hemeroby approach has been criticized for its lack of empirical basis and no spatial differentiation (de Baan et al. 2015). The critique was partially addressed by a proposal that converts hemeroby, or the naturalness classes, into CFs for the use in LCA based on the proportion of the amount of total surface area that is not considered under the lowest hemeroby class (Fehrenbach et al. 2015). The authors proposed CFs that indicate a Distance to Nature Potential (DNP).

The use of species data into LCA models have the advantage that they are coherent with other impact paths and can be combined into single indicators. Additionally, methods using the number of species can be readily understood and directly verified. However, methods relying on species numbers are subjected to limitations such as measurement location bias and biodiversity shortfalls.

Biodiversity contribution method

Focusing on the conditions for maintaining biodiversity published by Michelsen (2008), a proposal by J. P. Lindner (2016) aimed at addressing the differences in management practices and resolve the issue concerning the reference point for which biodiversity should be compared. The author used a collection of individual parameters that are relevant for biodiversity as well as the interaction between parameters applying fuzzy thinking to translate the aspects that are not necessarily objectively measured by numbers. The parameters and their relationships can be defined by conservation goals, literature review, or expert judgment (Lindner 2016). A relationship curve for each parameter's contribution to biodiversity is established, e.g., if the relationship is positive or negative, if biodiversity would be highly sensitive or if it would be resilient to the parameter.

Lindner (2016) converts these quantitative or qualitative contributions into functions. The relationship of a parameter to biodiversity can be translated into a contribution curve.

$$y = \gamma + \varepsilon e^{-\frac{\left|\left(x^{\delta}-\beta\right)^{\alpha}\right|}{2\sigma^{\alpha}}} \qquad [\,] \qquad (1)$$

Where the exponent (α), width (σ), horizontal shift (β), vertical shift (γ), horizontal stretching (δ), and vertical stretching (ε) are altered to form a suitable curve. The construction of such a curve is also valid in the absence of a qualitative unit. In this case, a general response curve is created building on questions such as: whether more of the parameter improves or harms biodiversity (positive or negative contribution); if the system is resilient to that parameter or if a small increase or decrease of the parameter amount causes a strong effect (resilience or immediate sensitivity); and at which point more or less of the parameter does no longer poses an effect (Lindner 2016). Examples are depicted in Figure 13 to represent an immediate negative contribution, a negative contribution with resilience to the parameter, and a positive contribution with resilience. The basic function constants: $\alpha = 2$, $\sigma = 15$, $\beta = 0{,}5$, $\gamma = 0$, $\delta = 1$, and $\varepsilon = 1$ (Lindner 2016, p. 76) were altered to illustrate the other types of contributions.

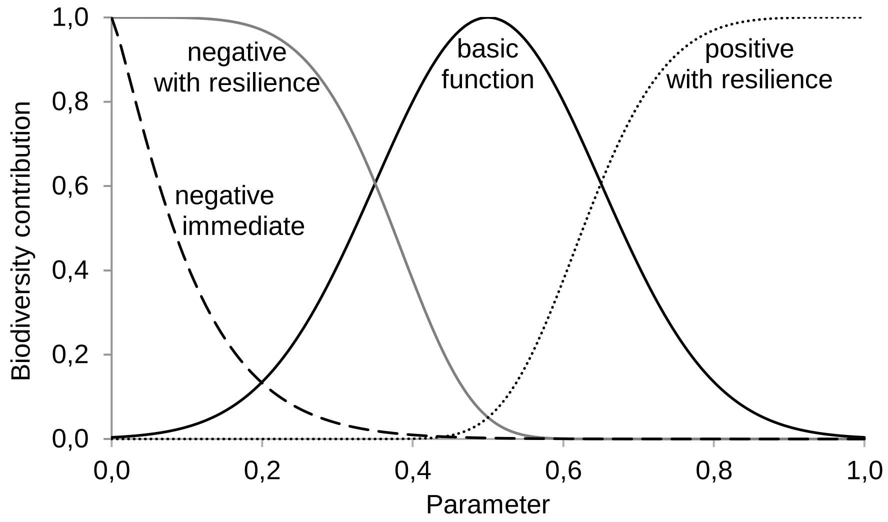


Figure 13 Basic function of a parameter's contribution to biodiversity and three generic variations of the curve's shape. Based on Lindner (2016).

The approach differs from other previous methods as it does not necessarily require any direct measurements of species, but it also included a *context parameter*. The context parameter captures that not only land use practices itself matter to biodiversity. One example is the distance to the next natural area outside of the land use plot. As defined by Lindner (2016), the context parameter modifies the biodiversity contribution of one or more management parameters.

The method proposed by Lindner (2016) also translates the interaction between the parameters: for maximum biodiversity, is one parameter sufficient, or would it require a combination of parameters? If the parameters are related, their functions can be combined using the logical operators AND or OR. The AND relationship represents a case where both parameters have to be present to maintain biodiversity. The graphical representation of an AND relationship between two parameters is shown in Figure 14, and is governed by the following equation:

$$y_{AB}(x_A, x_B) = y_A(x_A) \cdot y_B(x_B) \qquad [\,] \qquad (2)$$

The OR relationship is used in cases for which the presence of either parameter is sufficient to maintain biodiversity, for the governing equation and graphical visualization see Lindner (2016, p. 85).

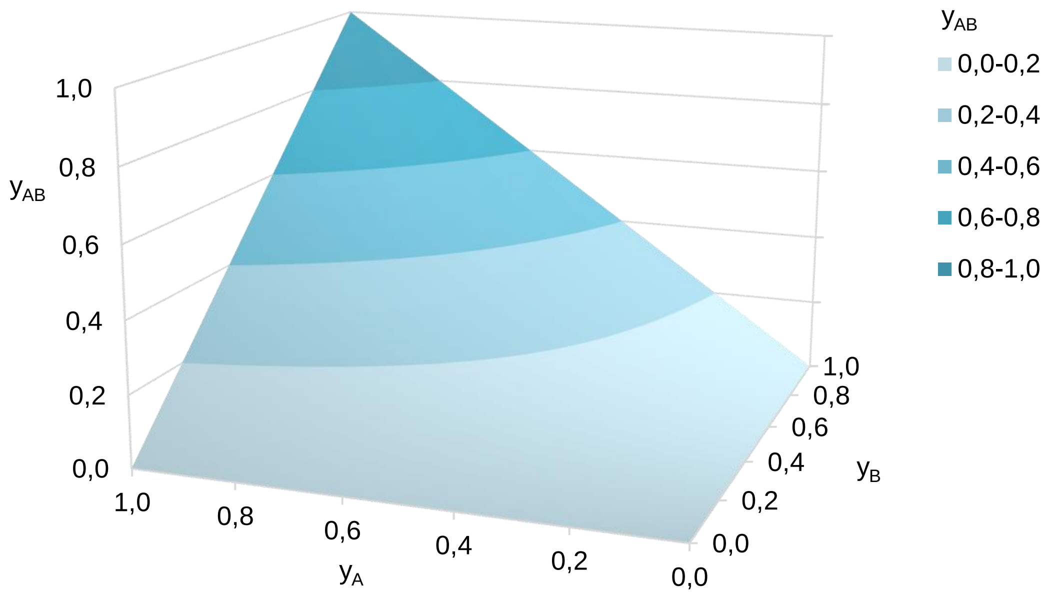


Figure 14 Relationship AND between two parameters' contribution y_A and y_B.

Landscape configuration in LCA

Probably the first explicit reference to landscape configuration in LCA was a description of an ecosystem being divided into smaller areas and named *intersecting effect* (Blonk et al. 1997). In the authors' view, intersecting effects were a matter of area and shape, and they also pointed out that this intersection caused effects outside the area of the land use activity itself. The authors warned for the fact that adding this intersecting factor in the quantitative ecosystem degradation that they were proposing would result in an implicit weighting factor, and they suggested it should be dealt as a separate weighting factor.

Fragmentation was part of the "Qualitative sustainability factors" developed for forests and was incorporated under the criterion "Have appropriate measures been taken to avoid fragmentation or isolation of important habitats?" (Peter et al. 1998). Fragmentation and barrier effects have been mentioned in the Biotope method (Kyläkorpi et al. 2005), but also only as part of a qualitative assessment because the authors considered these impacts to be beyond the system's boundaries.

Jordaan et al. (2009) included in the LCI of oil sands also a zone of influence of this activity. The approach can be interpreted as the addition of a virtual area to the inventory. The study was developed for oil sands exploration in Canada. The approach goes beyond the land use area itself, and it can be considered the first quantitative application of spatial context in LCA, but it was limited to the LCI.

Characterization factors for land fragmentation impacts on biodiversity have been developed for areas of less than 30 % natural vegetation cover (Larrey-Lassalle et al. 2018). The attention to areas of lower habitat cover is justified by the existence of an extinction threshold typically around 20 to 30 % of the original cover (Fahrig 1997; Desmet 2018; Andrén 1994), see Figure 10 on page 21, commonly referred to in landscape ecology literature as the 20 % rule. The use of the term fragmentation in the LCIA method proposed by Larrey-Lassalle et al. (2018) is most likely to refer to the overarching idea of a patchy landscape configuration instead of strictly to the particular type of landscape pattern *fragmentation* as in Figure 8, on page 19. Larrey-Lassalle et al. (2018) proposed a fragmentation potential for forest regions, calculated by a large region being subdivided into grid squares, and for each grid square, the amount of forest cover was calculated.

The method proposed by Larrey-Lassalle et al. (2018) uses the landscape's capacity to sustain *metapopulation*. The term metapopulation is used to "describe the collection of populations that experienced extinction but were linked by colonization (immigration)" (Collinge 2009, p. 26), derived from a mathematical model proposed by R. Levins (1969) for the introduction biological control in agricultural fields for the control of pests (Collinge 2009, p. 26). Metapopulation theory is a useful tool to bring awareness about populations in fragmented landscapes (Pope et al. 2000). However, while it can be adequate for some species, it must be applied with caution for species for which the habitat versus non-habitat categorization of the landscape is not appropriate (Pope et al. 2000). Another drawback is that in fragmented landscapes, the species dispersal is determined by their ability to detect patches and the dispersal distance, a characteristic that varies among species (Fahrig and Paloheimo 1988). These models are species-specific, bringing us back to the daunting task of measuring and valuing a selection of species and using them as a representation of biodiversity as a whole.

A review of the most relevant aspects of habitat fragmentation for the inclusion in LCA was carried out by Kuipers et al. (2019). The authors do not describe fragmentation in different types, focusing on configuration characteristics such as patch area, edge effects, shape, and isolation as well as matrix hospitality. Although fragmentation models have the potential to be incorporated in LCIA, improving the characterization factors, the challenges to work with currently available data is recognized by the authors (Kuipers et al. 2019).

3 Problem statement

Methods to assess the impacts of land use on biodiversity in LCA rely on the principle that human land use prevents that land from recovering to a natural, potentially natural, or a state of conservation value. In the LCA terminology, this is called environmental quality.

The methods to assess biodiversity in LCA have long identified the need to differentiate between land use types, such as agriculture, or forestry, accompanied by management practices, such as intensive or extensive pasture, and of the location indicator. As such, it should be possible to compare the potential biodiversity impact between products deriving, for example, from pasture in Europe and Brazil. Ecoregions have been widely used in LCIA targetting the impacts of land use on biodiversity. One problem is that ecoregions are large units, and CFs developed for ecoregions cannot capture and communicate characteristics of the surroundings of a land use. This means that for the same land use, surrounded by either a native vegetation cover or an urban area, in the same ecoregion, the results of the impact assessment would be the same if CFs for ecoregions are used.

A more refined spatial detail taking into account landscape configuration is limited to one proposal for threatened forest biomes with less than 30 % natural vegetation cover. In practice, LCA is currently unable to identify whether the land use activity contributes to perforation or dissection patterns. These two patterns are likely to occur in remote areas, and remote areas are of recognized importance to biodiversity conservation and have been lost at unpreceded rates.

Current LCA methods do not yet capture the importance of spatial context and its particular relevance for activities in remote areas. As such, LCA results cannot communicate a land use nearness to a remote, pristine, or wilderness area. Since LCA is product-oriented, if its methods to assess the impact of land use on biodiversity do not capture remoteness, it can lead to the undesired burden shifting.

In order to include an indicator that can capture perforation and dissection, a spatially explicit model is required. The most straightforward approach to do this would be to use a land cover map. A problem arises since the sole presence of an ideal or natural cover is not a guarantee for a species' survival, while the lack of natural vegetation cover may also allow the presence of other species that may depend or prefer it.

The relevance of the context, or the matrix, has been identified to be relevant for the conservation of biodiversity. Recent LCIA methods addressing land use impacts on biodiversity have a location perspective but are often limited to large regions such as ecoregions, halting the possibility of a more refined spatially explicit assessment. Landscape ecology researchers have the difficult task of developing measures for the variety of land use and habitat types; such difficulty is exacerbated when considering the global supply chain perspective brought by LCA.

Methods to assess biodiversity impacts in LCA are often derived from conservation biology, which has a different purpose than LCA. The aim of conservation, be it reactive or proactive, be it instrumental or intrinsic, is to preserve the variety of biological life. Conservation can be applied through several mechanisms, for example, through the planning and establishment of conservation areas. These conservation areas are established where there are species of conservation value because of, for example, the presence of endangered or vulnerable species in the area. The same may not be valid for LCA. Do we prevent or potentially prevent species extinction by choosing a product location that potentially causes fewer extinctions? One of the problems in answering this question lies in the different nature of conservation and its priority setting and LCA. LCA may be used for policy agenda-setting through problem identification. However, policies are not the only use of LCA, and the measurement of potential of extinction might be incoherent for other applications of LCA.

Using extinction measures, although practical, is not paramount to LCA. The use of species' number is not necessarily derived from a requirement but likely to be from the simplicity of measuring what has been measured or from the preconception that measurement has to be certain. In other words, the use of a number of species gives the impression of certainty and of a solid scientific backing to their use in LCA.

Measurements are necessary for decision making but are sometimes difficult to obtain. Measurement of biodiversity, or the difficulty in measuring it, is not an exclusive problem of biodiversity field of study, let alone of its inclusion in LCA. It is possible to measure things even if they seem hard to measure, a synthesis and guideline on how to deal with this issue are dealt with in accounting and business (Hubbard

2014). Generally speaking, the goal of measurements is to reduce this uncertainty to allow us to deal with “imperfect information” (Hubbard 2014, pp. 7–8).

The perception of measurement as a tool that does not have to provide an exact number but rather to reduce uncertainty in decision making can be useful for further development of the methodology to assess biodiversity in LCA. Measurement and the measurement of the impacts of land use on biodiversity are necessary to reduce the uncertainties in the decision making process related to a product's supply chain environmental impact. This uncertainty reduction aims to equip decision makers with more tools so they can make more informed decisions.

4 Requirements of the method

The main goal of this thesis is to propose an impact assessment method that can indicate whether a product's land use or parts of its supply chain, can have an impact on biodiversity because they take place in remote areas, potentially causing perforation or dissection.

When investigating the environmental implications of land use, it is paramount to be able to determine the location of the *land use* activity. The required level of detail would be determined by the goal and scope of the LCA, but the impact assessment method should be developed aiming to accommodate a high level of detail. This need of explicitly accounting for the location is because land use's impact on biodiversity is location bound.

The variety of land use types in a product system requires the method to assess any land use type. As such, a method should also allow the inclusion of land uses which have nearly none or low land occupation per unit of product or service but are nevertheless location bound, such as mining, roads, or railways.

LCA is an accounting tool that provides decision makers with more information about the impacts that their product has on the environment. Given the global nature of supply chains, the method should be *globally applicable*. Additionally, LCA results are presented comparatively, either a comparison of products or a comparison of different life cycle stages of the same product, also called hotspot analysis. Although a single product or service supply chain may not necessarily encompass the entire world, the ideal impact assessment method should be able to assess land use activity anywhere in the world.

By perceiving the land use in question as one of the components of the so-called matrix in landscape ecology and biodiversity conservation, it becomes clear that a biodiversity method should be able to communicate in its results relevant aspects of the landscape *surrounding* a land use. In that sense, a suitable method should be able to identify whether a product contributes to biodiversity conservation considering its spatial context.

In summary, the requirements of an ideal method for biodiversity in LCA would:

1. differentiate between land uses and land use intensities;
2. be spatially explicit, with the possibility of assessing any land use activity, including those of low land requirement per unit of product or service;
3. provide a valuation of different ecosystems, ecoregions or biomes;
4. be globally applicable; and
5. allow the inclusion of the context of the land use together with a quality indicator for the surrounding landscape.

Most of the recent methods for the inclusion of biodiversity in LCA have been developed in considering land use type and intensity, and a valuation of the ecosystems, ecoregions or biomes. The differentiation between ecoregions is not part of the scope of this thesis to avoid double counting with other existing methods.

The inclusion of context, as defined in landscape ecology, comes at the expense of the fundamental requirement of LCA, which is global applicability. Assessing products' supply chains from a strict landscape ecology point of view is impractical because of the lack of availability of globally consistent data. Therefore, simplification is necessary in order to fulfill requirements 4 and 5.

5 Method

The primary output of this thesis is a method that can be used in the framework of LCA and improve the assessment of the potential impacts that land use can have on biodiversity. The focus is to create a globally applicable method to capture the surrounding quality of a land use, requirements 4 and 5 defined in Chapter 4.

The general structure of the method consists of:

- the spatial location of a land use activity captured by geographical information systems;
- the determination of a context area outside the area of each land use activity, excluding the land use area itself, transferring the concept of landscape context and effect zones to a land use and product perspective;
- the quantification of habitats or a measure of the environmental quality on the area surrounding the land use of interest, transferring the concept of the dissection and perforation to a land use perspective;
- if a measure of environmental quality is used as an indirect indicator for the habitat configuration pattern, then a conversion from this measure to their contribution to dissection and perforation must be performed.

The detailed structure of the method with the values and the data that will be used in this thesis will be presented in section 5.1. The detailed development of the method leading to the creation of a Perforation Potential will be presented in section 5.2, followed by a description of the integration of the Perforation Potential in LCA in section 5.3.

5.1 Structure of the method

The following subsections will present: the data that will be used, how the extent of the context area will be defined, which indicator for environmental quality will be used, and the intermediate steps needed for the conversion from this measure to a Perforation Potential. A schematic drawing of the general structure is presented in Figure 15.

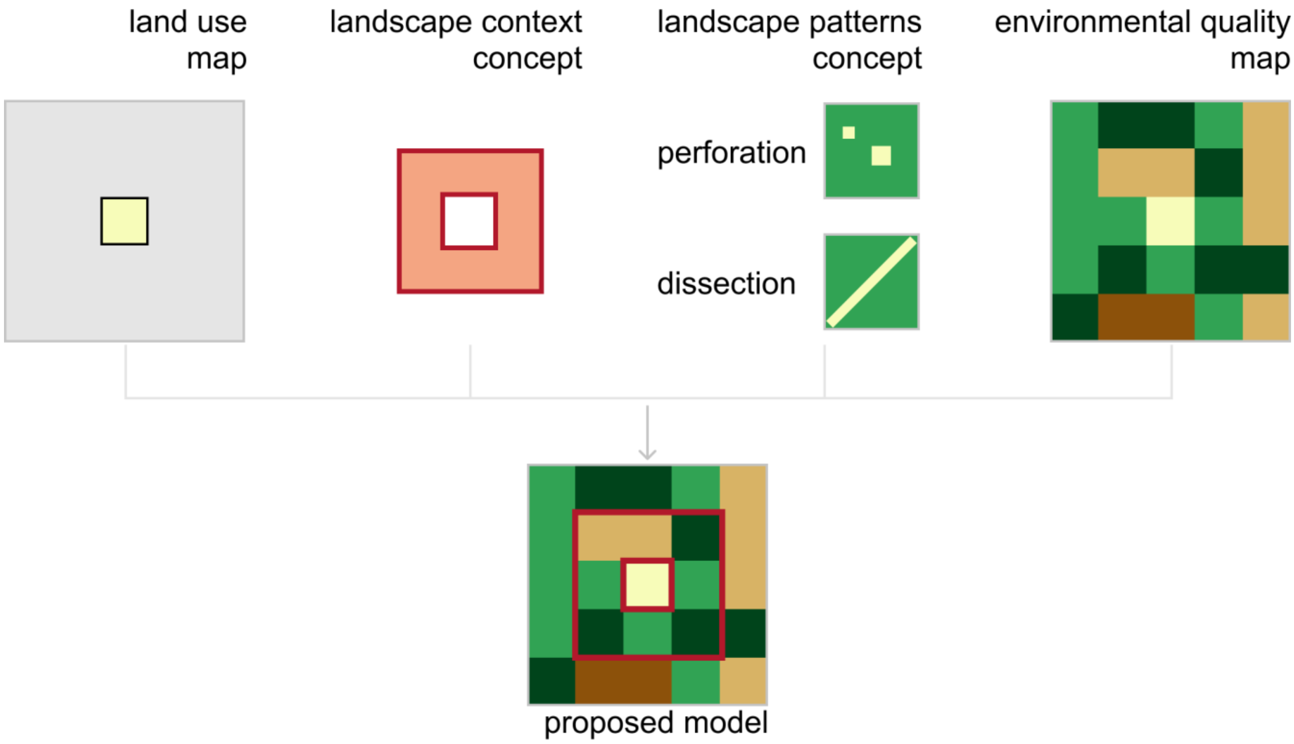


Figure 15 The method combines a land use map, landscape context and pattern's concept, and a habitat or environmental quality maps.

For all geospatial calculations, ArcGIS desktop 10.3 (Environmental Systems Research Institute, ESRI) will be used, hereafter referred to as ArcGIS.

5.1.1 Land use

In order to assess land use, the first data requirement is a map of the land use location and its boundaries. Land use datasets spanning the whole world will be used in order to demonstrate the global applicability of the method. The major land cover modifications on the environment, namely cultivated land, urban areas, transport infrastructure, and resource mining were selected as input data. Specifically, quarries and mines data were extracted from OpenStreetMaps (OSM 2018), and for cropland, pastureland, built environment, roads, and railways, the data used here will be the same as those used in the Human Footprint maps, made available by Venter et al. (2016b). Table 1 presents the land use data sources, a short data description, and its reference year.

Table 1 Land use data details.

Land use type and data source	Data description	Reference year	Data type
Quarries and mines (OSM 2018). Extracted using *overpass turbo* tool (Raifer and Olbricht 2018)	Data from Open Street Maps, data description “quarry”.	Extracted 2018	Vector
Cropland (Venter et al. 2016b)	Derived from GlobCover Land Cover V2.3, European Space Agency (Arino et al. 2012).	2009	Raster
Pastureland (Venter et al. 2016b)	A spatial dataset that combines agricultural census data, and satellite data (Ramankutty et al. 2008).	2000	Raster
Built environment (Venter et al. 2016b)	Calculated using annual average brightness from the Defense Meteorological Satellite Program Operational Line Scanner (DMS-OLS) (Elvidge et al. 2009).	2009	Raster
Roads (Venter et al. 2016b)	Map of major roads, resolution of about 500 m (Center for International Earth Science Information Network and Information Technology Outreach Services 2013).	2000	Raster
Railways (Venter et al. 2016b)	Map of railways (National Imagery and Mapping Agency 1997).	1990	Raster

5.1.2 Context area

To capture the environmental quality in a land use’ surroundings, an area to spatially represent its spatial context will be determined based on the landscape ecology principles of the *landscape context* surrounding a patch. The surrounding landscape of a patch can be coarsely determined by the demarcation of a defined area which borders a habitat patch on all sides, and exclude the patch itself (Collinge 2009, p. 105). Here, the term *context area* will be used to describe an area surrounding a land use of interest, with the term being a reference to *landscape context* from landscape ecology brought to a product perspective.

Transferring landscape patterns into a product perspective

In the fragmentation model proposed by Forman (1995, p. 407) and reproduced in Figure 8 on page 19, perforation and dissection are characterized by a non-habitat surrounded by habitat. This model was proposed from a landscape ecology point of view, while in this thesis, the focus is to characterize the context area instead of the landscape itself.

Considering the land use of interest as the non-habitat, this land use perforates or dissects when the land use is the element perforating or dissecting the landscape. Transferring this concept to a product perspective, it can be said that a land use perforates when it is surrounded by habitat. This is schematically drawn in Figure 16.

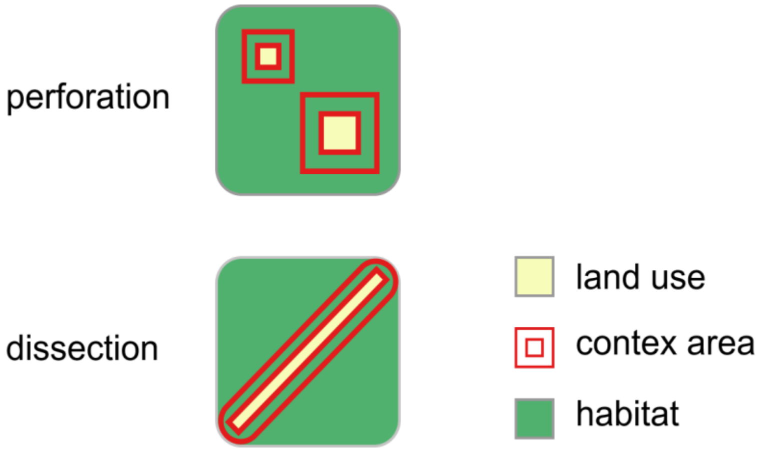


Figure 16 Land use contributing to perforation and dissection patterns from a product perspective.

To which extent, or how far from the borders of a land use should be considered to be the surrounding of a land use has to be determined for this thesis. The definition of the context area border is the focus of the next subsection.

Context area border definition

The context area proposed here is derived from the concept of effect zones, which are the effects that are beyond the spatial feature causing that impact. An effect zone is species-specific (e.g., frogs can react differently than birds to the presence of a road), activity-specific (the same bird species can react differently depending on the land use type), intensity-dependent (more or less traffic on the road), and can also depend on the geography, e.g., down or upslope, vegetation density, down or upwind.

Even knowing that effect zones are activity and species-specific, conservationists have made generalizations, namely the Roadless areas (Ibisch et al. 2016) and the Intact Forest Landscapes (Potapov et al. 2008). Those are schemes that aim at the creation of areas designated for the conservation of biodiversity and have been described in detail in section 2.8.2 (on page 23). These schemes have used a distance of 1 km from selected human land uses as a general indicator for the limits of the effects of human influences. In both these schemes, the authors assume that beyond 1 km from the selected land use activity, it no longer affects biodiversity.

For this thesis, the objective is not to determine the effects of land use in the surrounding landscape but rather to determine a surrounding area that can be considered its spatial context. The Roadless areas and the Intact forest landscape schemes provide the scientific justification for the use of a 1 km distance for the creation of the context. In this thesis, the use of a fixed distance of 1 km to define the context area of a land use implies that points beyond this distance are no longer considered part of the land use's context. The implication of different distances for the creation of the context area will be discussed in subsection 5.2.4 Discussion on modeling choices, starting on page 92. In short, the determination of the context area's distance is derived from the concept of these effect zones, but context areas, as defined here, are not effect zones per se.

Geospatial analysis steps for the creation of context areas

In geospatial analysis, the creation of an area within a fixed distance around a spatial feature is called a buffer, described on page 10. A schematic representation of a buffer for a generic circular feature is shown in Figure 17.

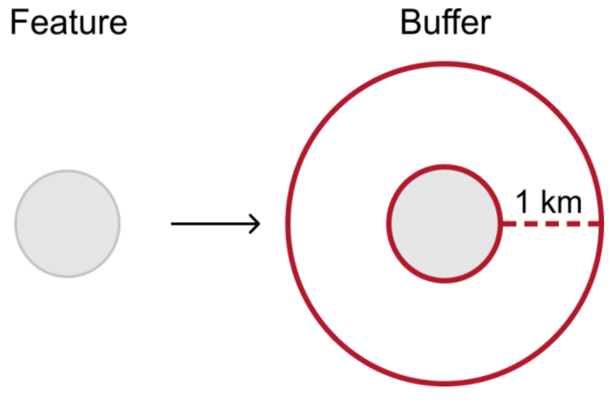


Figure 17 Illustration of a 1 km buffer outside a generic feature.

For global datasets in vector format, a large number of context areas is expected and can require long processing times. The polygons of the buffer's geometry will be simplified using the ArcGIS tool *simplify* with a distance offset of 50 m. By removing relatively extraneous vertices while preserving the essential shape of each polygon, it eases the computational calculations.

If two features are less than 2 km apart, the buffer zones will partially overlap each other. Areas between two land use features less than 2 km from each other would be accounted for in two buffer zones, resulting in double counting of that area overlapped by two buffers. To ensure that the buffer zones are only accounted for once, the buffers will be merged using the ArcGIS tool *dissolve*. If two features are less than 1 km from each other, the buffers will also partially overlap the land use feature itself. To fulfill its goal of investigating the area surrounding a land use, the buffer zones must not contain the land use itself. Therefore, the land use area will be subtracted from the buffered areas, eliminating the land use feature from the buffer zones using the ArcGIS tool *erase*. These steps result in a *context area* (Figure 18), which here is a 1 km buffer zone surrounding the land use, dissolved, and excluding the land use itself.

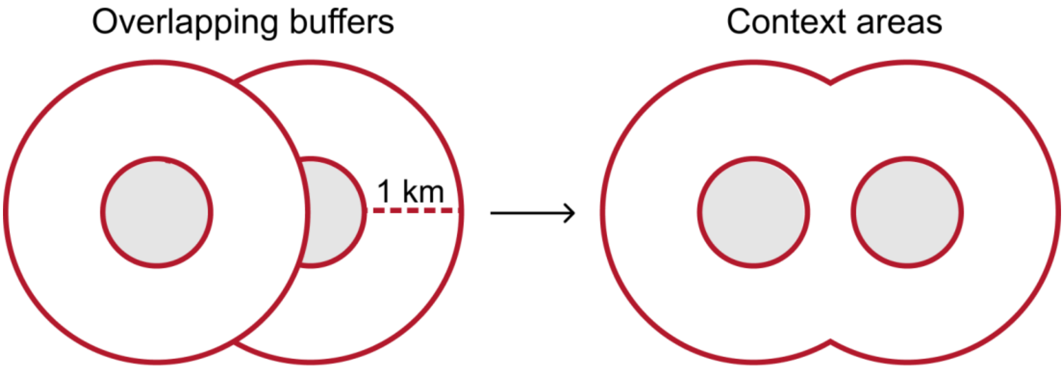


Figure 18 Schematic representation of the creation of a context area showing features less than 2 km apart.

For raster data, the context areas will be created following the same principle. For raster data, for each land use, a new layer, expanded to one raster cell (1 km), will be created using the ArcGIS tool *raster calculator*. Then, the land use layer is subtracted from the expanded raster, leading to conceptually consistent results as for a vector layer, i.e., a surrounding area which does not include the land use being investigated.

For raster data, the context areas are not independent features, being one continuous set of cells, not generating overlapping buffers. Raster's context areas will be converted into vector using *raster to polygon tool*, and then aggregated into the continuous neighboring context areas of the same land use (Figure 19). This step generates results that are consistent with the vector data's individual context areas.

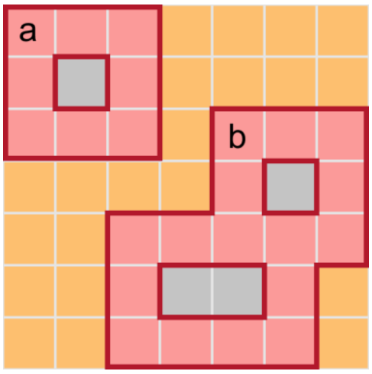


Figure 19 Raster data grouped by distinct continuous context areas ‘a’ and ‘b’.

Spatial data for roads and railways are often represented by GIS by line features, i.e., they do not contain a width measure. However, the data representing roads and railways used in this thesis are in raster format. Therefore, the same procedure as raster data described for vector has to be applied. In order to aggregate roads and rails as in Figure 19, it would be necessary to determine where a road or railway starts and ends. Aggregation of roads and rails as distinct continuous areas, as in Figure 19, can be meaningful for a specific study in which either the interest is to assess all roads in a region or particular routes. For the global datasets used, this aggregation is not conceptually plausible. Because of that, for roads and railways, the data will not be converted into vector format and will not be grouped as in Figure 19.

Exclusion of “buffer islands”

For both raster and vector, the presence of relatively small areas that are not the land use in question but are entirely engulfed by the land use of interest creates a “buffer island”. These should also be excluded from the analysis because they do not represent a context area in itself. For both data types, small areas that are surrounded by the land use itself will be excluded from the analysis, graphically represented in Figure 20.

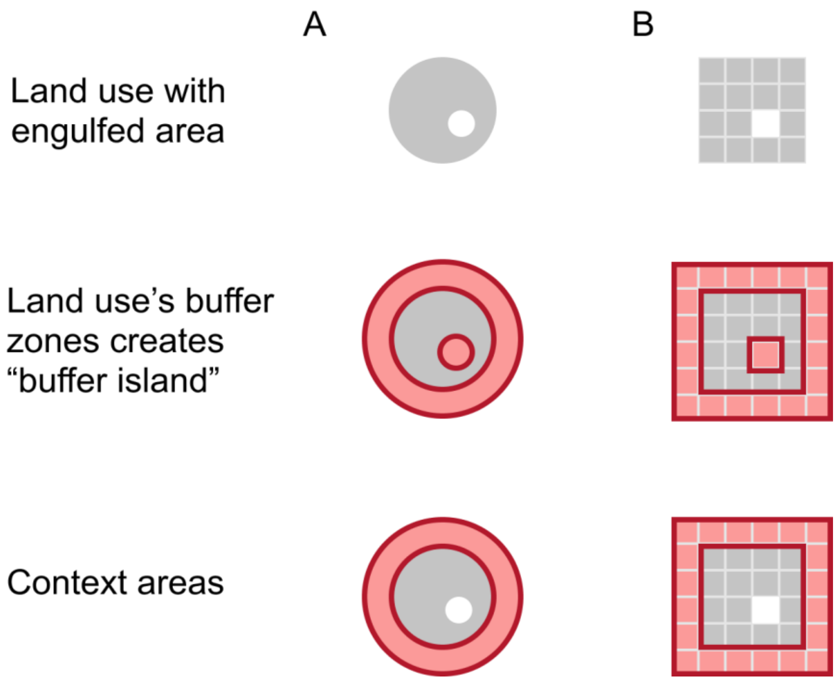


Figure 20 Illustration of land use with an engulfed area and final context area for (A) vector and (B) raster data.

For vector data, because of the 50 m simplification of the buffer areas, the minimum area of a buffer is 3 km^2, as opposed to 3,14 km^2, which would be the area of a 1 km radius circle. For raster layers, the smallest individual land use is a 1 km^2 cell, resulting in a context area of 8 km^2. Therefore, context areas smaller than 3 km^2 for vector data and 8 km^2 for raster data will not be considered to be a context area per se, but rather an area engulfed by the land use and will be excluded from the analysis.

5.1.3 Habitat indicator

The study of species is subjected to several shortfalls described in section 2.5, and as it has been demonstrated in the literature review chapter, a habitat is species-specific. Consequently, a worldwide applicable method would require habitats all over the world to be mapped. Such data is not currently available. Additionally, habitats of some species may overlap, leading to a valuation problem similar to that of species accounting. For example, if two habitats surround a land use, are they more or less critical than if only one habitat is present? Should these habitats be valued according to the value of the species? Such valuation is part of other impact assessments and is not addressed in this thesis.

In order to provide a solution to the problem of the lack of tools that can identify the potential that land use has to perforate or dissect, an approach that takes into account human pressures is suggested here. Human pressures and its cumulative effects on biodiversity have been described in subsection 2.8.3 and 2.8.4. In this thesis, the map of cumulative pressure HFI (Venter et al. 2016b) of 1 km resolution at the equator will be used as an indicator for habitat presence, meaning that the lower the human pressure, the more likely it is to host natural or semi-natural habitats.

Calculation of average HFI in context areas

The resulting context areas of the cropland, pastureland, built environment, road, and rails will coincide with the raster cells of the HFI. For both raster and vector, the context area will overlap more than one raster cell from the HFI. The average values will be obtained using ArcGIS tool *zonal statistical*; see details under heading Zonal Statistics (on page 11), in section 2.3 Geographic information systems. Zonal statistics will be applied to all land uses, with the exception of roads and railways, since their context areas are not grouped in distinct areas. A visual representation of the land use, context area, overlaid on the HFI map is presented in Figure 21.

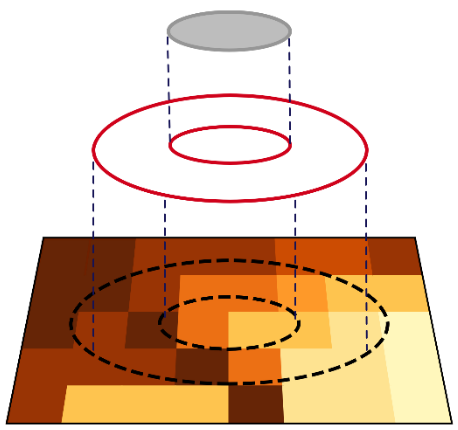


Figure 21 Schematic visualization of a land use, its context areas, and the HFI map. The HFI average values are calculated for the dashed area (the context area).

For vector data, using the native resolution of the HFI to calculate the zonal statistics would result in any raster cell-center that is not inside the context area to be uncaptured, see Figure 7 on page 12. To avoid this problem and ensure a more refined and coherent quantification against land use of quarries and mines, smaller cell sizes will be used. The ArcGIS function *snap raster* will be used to ensure that the generated cell size is aligned to the original raster. Figure 22 is a visualization of the output of raster cells captured by the zonal statistics for one context area of a mine using native and smaller cell size.

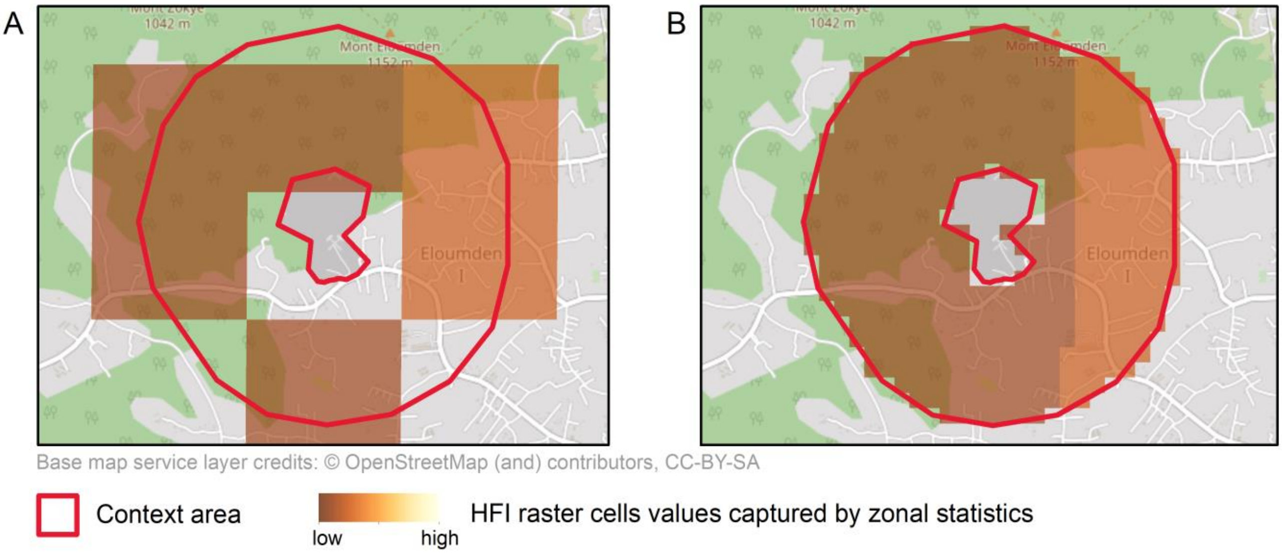


Figure 22 Visualization of raster cell values captured by zonal statistics function using (A) the native and (B) a smaller cell size.

The zonal statistics for the full dataset of quarries and mines will be calculated with a 50 m cell size. This cell size is considered to be sufficiently coherent to the shape of the context area without requiring excessively lengthy processing times.

5.1.4 Conversion of HFI into Perforation Potential

This thesis aims to determine if a land use contributes to perforation and dissection-like patterns. From a land use perspective, if an area of habitat surrounds a land use, it can be said that the land use potentially perforates or dissects the habitat. Given the absence of a habitat measure applicable to the whole world, an alternative indicator will be used, as previously described in section 5.1.3.

In LCA, if a low emitting process is used in high quantities, it can have a high contribution to the emission profile of that product. Regardless of how much of a products' portion supply chain takes place in a highly degraded area, it does not cause perforation or dissection. For that reason, a linear conversion encompassing the full

0 to 50 spectrum of the HFI, would defeat the purpose of the method. This conversion can be understood analogously to the global warming potential used in carbon footprints, for which certain pollutants cause more global warming than others, and not all airborne emissions have a greenhouse effect. The HFI value at which perforation and dissection may occur will be established through the conversion of the HFI into a Perforation Potential. This conversion from HFI into a Perforation Potential requires intermediate steps, which are the focus of this subsection.

Land use area and context areas ratios

Some land uses are continuous large areas. The creation of the context is fixed at 1 km, independent of the size of the land use itself. As a result, a smaller land use site will have a much greater context area per land use area ratio than larger land uses. A land use feature with the same shape will have a decreasing ratio of context area for greater land use areas. The context area and land use ratio were calculated and presented in Table 2.

Table 2 Land use types' characteristics.

Land use type	Land use area [km^2]	Land use area* [%]	Context area [km^2]	Context area per land use area ratio
quarries and mines	33.109	0,02	349.758	10,56
roads	10.028.197	7,48	17.410.060	1,74
rails	2.556.057	1,91	3.104.975	1,21
cropland	18.334.494	13,68	11.477.017	0,63
pasture	31.746.509	23,68	5.838.454	0,18
built environment	2.503.973	1,87	1.266.558	0,51

*calculated using the total terrestrial area of 134.064.386 km^2 of the HFI map.

Quarries and mines have the lowest share of land use area among all the land use types, but the highest ratio of context area size divided by the land use area size. This means that among the investigated land uses types, quarries and mines are expected to be more coherent with the perforation pattern when compared to cropland pastures or built environments. This serves as a justification for the intermediate steps verification and valuation, explained in the following paragraphs, to be applied using the case of quarries and mines.

Verification and valuation steps

In trying to understand a possible relationship between perforation and human pressures in the surrounding of a land use, some questions can be raised:

- Are there purely perforating land uses?
- Does a high ratio of original vegetation cover and low HFI characterize a perforation scenario?
- Does a low ratio of original vegetation cover and high HFI characterize a non-perforation scenario?

To build knowledge and understanding of the landscape configuration in the context areas to answer these questions and to establish the relationship of the HFI and the land use potential to perforate, two independent steps will be carried out: verification and valuation. Both steps consisted of the visual inspection of randomly selected context areas, using supporting layers of geospatial information. The main objectives of these steps are presented in Table 3.

Table 3 Verification and valuation steps summary.

Step	Selected context area	Step objective	Supporting maps
Verification	HFI average 0	Verification of the existence purely perforating land use.	Aerial imagery base map, GlobeLand30, OSM base map, ecological land units map, ecoregion borders, and livestock intensity map.
Valuation	Depending on average HFI and forest cover. Forest biomes only	Building knowledge about pressures in the surroundings of a land use.	

For both verification and valuation steps, land use sites will be selected randomly to avoid bias, e.g., for larger or smaller sizes, or sites closer to each other, but ultimately to allow each individual context area to have the same chance of being selected. The context areas' unique identification numbers will be selected using the random number generator function *random.sample()* from Python 2.7.8.

For both verification and valuation steps, an aerial image readymade base map available in ArcGIS will be used as the primary resource for the assessment along with the OpenStreetMaps base map. If more information is judged necessary, other maps will be used to aid in the assessment: Ecological Land Units map (ELU) (Sayre et al.) which provides information on vegetation cover at a more refined scale than the ecoregion or biome maps, a livestock intensity map (Robinson et al. 2014), and the GlobeLand30 land cover maps (Chen et al. 2015).

In the *verification step*, the context areas with HFI = 0 will be inspected for resemblance with perforation. The verification step consists of the visualization of 30 context areas with HFI of 0. As a Human Footprint of 0 indicates no mapped human pressures, a context area with HFI of 0 is expected to display a landscape configuration that resembles perforation. The absence of human pressures in the surrounding of a context area, HFI = 0, will be verified in this step. In other words, the goal of this step is to find out if purely perforation-like configuration exists.

For the *valuation step*, each selected context area will be given a value depending on its resemblance with perforation configuration. The perforation and dissection are two processes of landscape modification in which the non-habitat is mostly surrounded by habitat, see Figure 8 on page 19, and are brought to a land use perspective within this thesis.

The valuation step is carried out for forest biomes based on the general assumption that forest is the desirable land cover of forest biomes, and because its natural land cover, forests, is widely captured by land cover maps. Biomes such as savannas have multiple vegetation types such as trees, scrubs, and grasses (Jibrin 2013), a combination that would be more difficult to determine using land cover maps or aerial imagery.

Quarries and mines' context areas that are in a forest biome will be selected using ArcGIS by overlaying them with the forest ecoregions and biomes boundaries from Olson et al. (2001). The amount of forest cover in each context area will be calculated using ArcGIS zonal statistics' function with the raster input layer GlobeLand30 with reference year 2009 (Chen et al. 2015). Using ArcGIS, the forest area will be calculated by the count of grid cells from the 30 by 30 m raster cells from GlobeLand30 that overlap the context areas. The amount of forest divided by the context area size, measured using Mollweide equal-area projection in ArcGIS, result in the ratio of the forest cover in each context area.

For each inspected context area, a score from 1 to 3 will be given: 1 meaning that it does not resemble a perforation configuration, a value of 2 if a perforation like configuration pattern is visible in parts of the context area, and 3 if the configuration resembles a perforation pattern in most of the context area. A schematic drawing of the valuation scale is presented in Figure 23. The valuation range from 1 to 3 was chosen to avoid confusion with other values ranges such as 0 to 1 used in biodiversity contribution parameters (Lindner 2016, p. 81), or 0 to 100 used by HII (Sanderson et al. 2002).

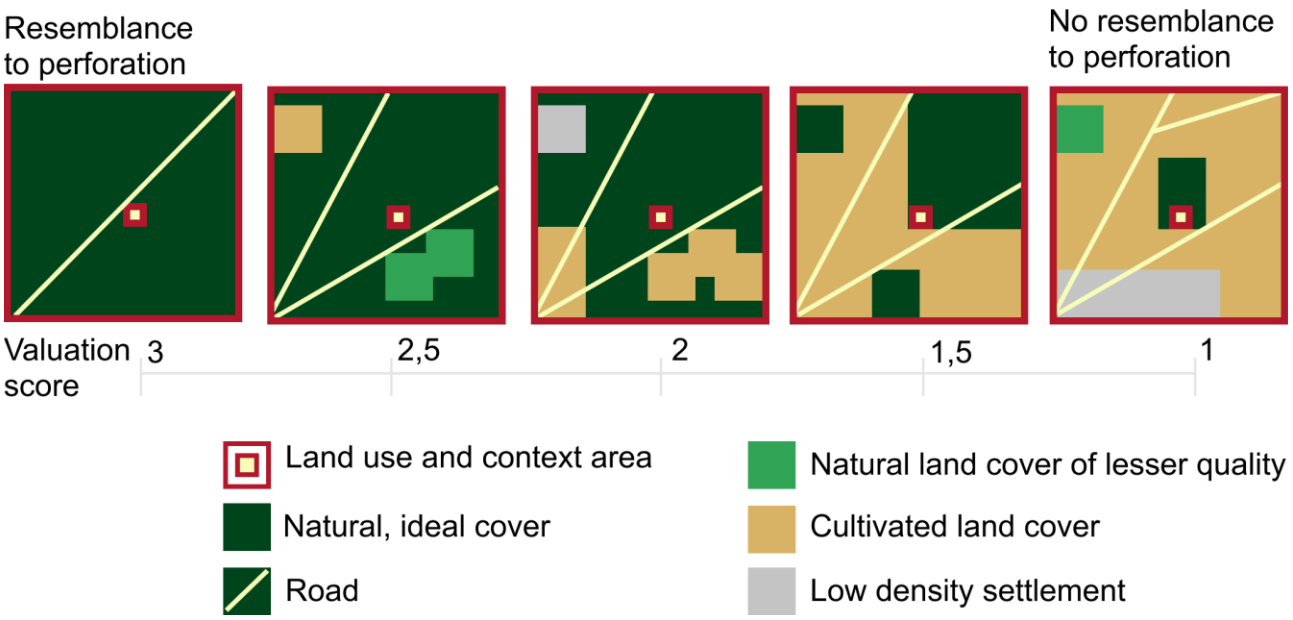


Figure 23 Valuation scale. Scores range from 1 to 3 depending on the resemblance to perforation.

In the valuation step, the context areas will be grouped according to the forest cover ratio and their average HFI. Context areas with more than 60 % or less than 30 % of the original cover will be selected based on the percolation threshold (Desmet 2018) and on the relative contribution model from Forman (1995, p. 409) (see Figure 9). For the values of HFI, the classification of HFI in the pressures classes proposed by Venter et al. (2016b) was defined for integer values (values of 0; 1 to 2; 3 to 5; 6 to 11; and 12 to 50), while the HFI calculated for context areas are averages and rounding is not desired. As an alternative, the context areas will be grouped in a similar classification: HFI ≤ 1; 1 < HFI ≤ 2; 2 < HFI ≤ 6; 6 < HFI ≤ 11; and HFI > 11. To limit the number of select areas, four valuation groups are defined (a, b, c, and d) and are summarized in Table 4.

Table 4 Context areas for valuation, grouped according to HFI and forest cover ratio.

<table>
<tr><th>Group</th><th>HFI</th><th>Forest cover ratio</th><th>Justification</th></tr>
<tr><td>a1</td><td>HFI ≤ 1</td><td rowspan="4">above 0,6</td><td rowspan="4">These are context areas for which perforation is expected because of the low HFI value and high forest cover.</td></tr>
<tr><td>A2</td><td>1 < HFI ≤ 2</td></tr>
<tr><td>a3</td><td>2 < HFI ≤ 6</td></tr>
<tr><td>a4</td><td>6 < HFI ≤ 11</td></tr>
<tr><td>b</td><td>HFI ≤ 5</td><td>below 0,3</td><td>Context areas in this range are expected if surrounded by pastureland.</td></tr>
<tr><td>C</td><td>5 < HFI ≤ 11</td><td>below 0,3</td><td>Several context areas in this range are expected.</td></tr>
<tr><td>D1</td><td rowspan="2">HFI > 11</td><td>between 0,6 and 0,9</td><td rowspan="2">Context areas in this range can exist, e.g., in case of a context area in an urban area but with forest cover.</td></tr>
<tr><td>D2</td><td>above 0,9</td></tr>
</table>

Context areas with forest ratio higher than 0,6 and average HFI up to 11 are part of the group a divided into groups a1, a2, a3, and a4 according to the HFI values, for which ten sites each will be selected. Specifically, context areas with HFI ≤ 1, form group a1; context areas with 1 < HFI ≤ 2, form group a2; context areas with 2 < HFI ≤ 6, form group a3; and context areas with 6 < HFI ≤ 11, form group a4. Context areas with average HFI up to 5 and forest cover ratio below 0,3 are part of group b, and ten sites will be selected. Context areas with average HFI between 5 and 11 and forest cover ratio below 0,3 form group c, for which also ten sites will be selected. Context areas with HFI above 11 and forest cover area ratio above 0,6 form group d, divided into groups d1 and d2, with ten sites with forest cover up to 0,9 forming group d1, and ten sites with forest cover above 0,9, forming group d2.

5.2 Development of the method

The previous section (5.1) described the structure of the method that will be applied. Firstly, the calculations of the human pressures in the context areas for the different land uses are carried out. Then the ratio of the area of the land use and the context area is calculated for quarries and mines' context areas, and the HFI converted into the Perforation Potential. A discussion on the implication of modeling choices will be described in section 5.2.4.

5.2.1 Calculation of HFI in context areas

The steps proposed in 5.1 (Structure of the method) are applied to the land uses described in Table 1, namely: quarries and mines, roads, railways, pastureland, built environments, and croplands. An example of the HFI in the context areas of the land use types is presented in Figure 24. Darker color represents lower HFI because these are areas where perforation and dissection are expected since lower HFI indicates low human pressures. Figure 24 is an extract of the HFI raster layer for the context areas of the different land uses, showing the values of the individual raster cells.

The results of the average HFI calculated for the context areas of all land use types will be presented as a histogram of frequency and as a world map. The focus is on HFI values up to 6, as these are areas of lower human pressures. In the case of roads, results are also presented for HFI values of 8 because of the roads' indirect effects that reach beyond the road itself. For roads and railways, the results of the HFI are not averaged by distinct context areas, and the values presented are the values of the individual raster cells.

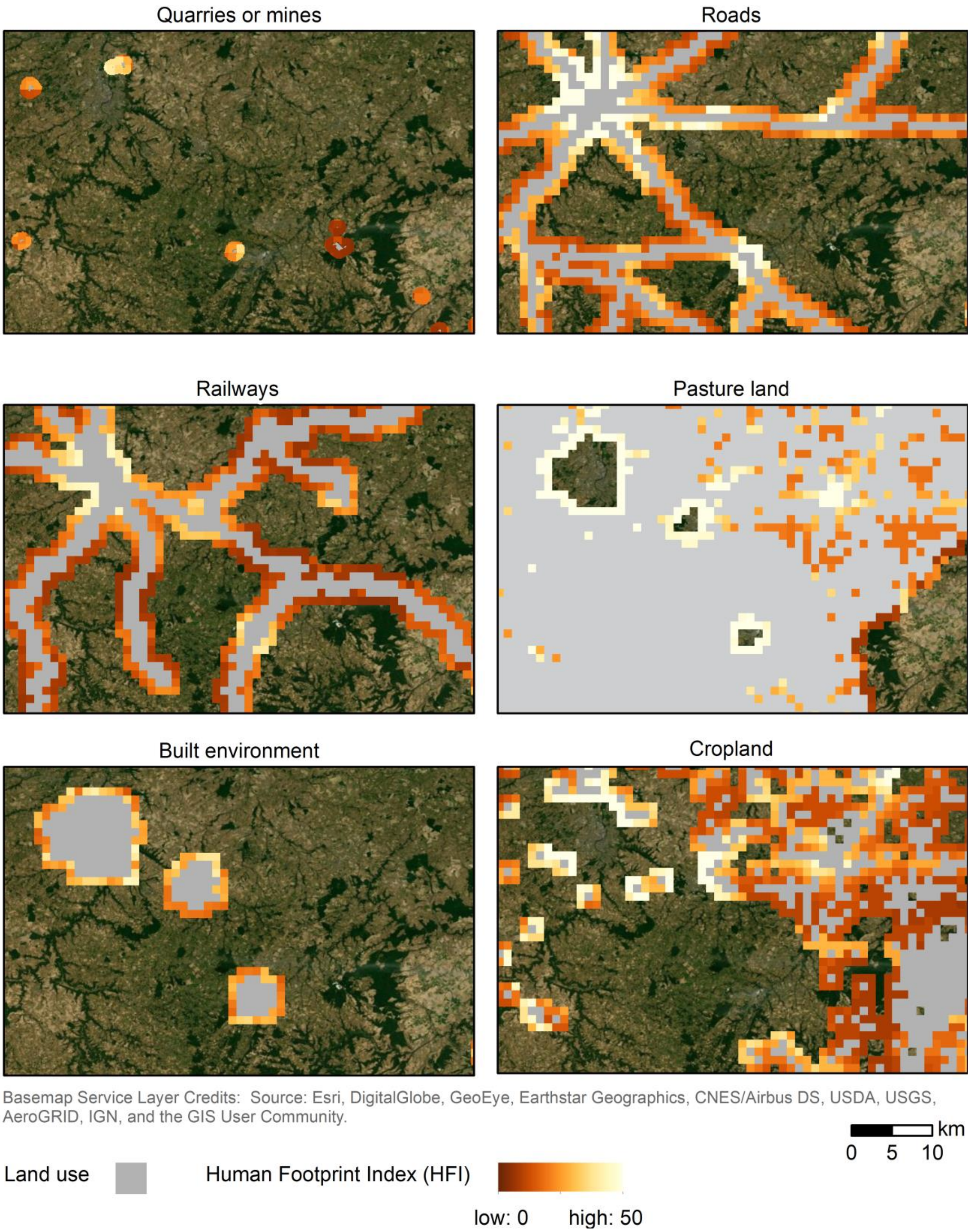


Figure 24 Maps of the Human Footprint Index on different land uses' context areas for the same location.

Quarries and mines

The dataset for quarries and mines contained 102.646 individual locations world-wide. The dataset was extracted from OpenStreetMap (OSM 2018) in March 2018. They represent an area of land which is used for surface mineral extraction such as stones, gravel, sand, and clay, or a surface mine for coal or ore (OSM 2019). The example of a context area for a mining site is presented in Figure 25.

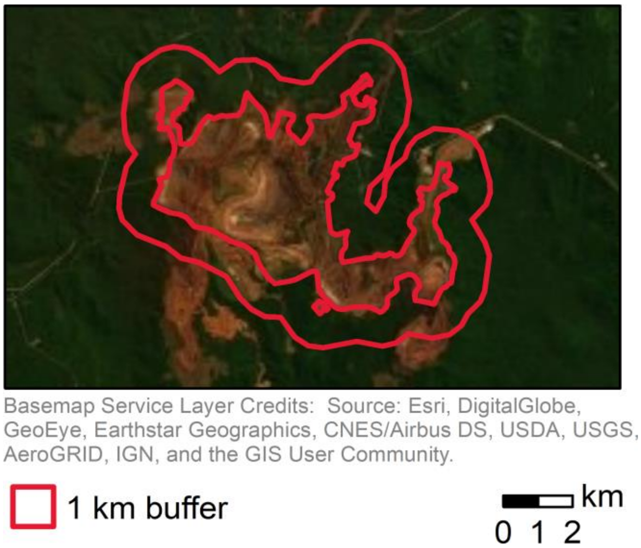


Figure 25 Example of a mineral extraction site with a 1 km buffer zone.

The quarries and mines' buffers had its geometry simplified and the overlapping buffers were merged, as explained in the Method chapter, see Figure 18 on page 49, resulting in a total of 59.400 context areas. Small areas entirely engulfed by the land use were excluded from the analysis as they were not considered to be a context area, as detailed under the heading Exclusion of "buffer islands" on page 50, reducing the number of context areas to 55.690. These steps are illustrated in Figure 26.

The HFI is available for most of the world except Moldova and small islands, mostly in the Pacific Ocean. The exclusion of context areas in these locations further reduced the number to context areas to 55.508. The average values of the HFI inside of each context area were separated in bins of equal value from 0 to 50 to construct a histogram (Figure 27).

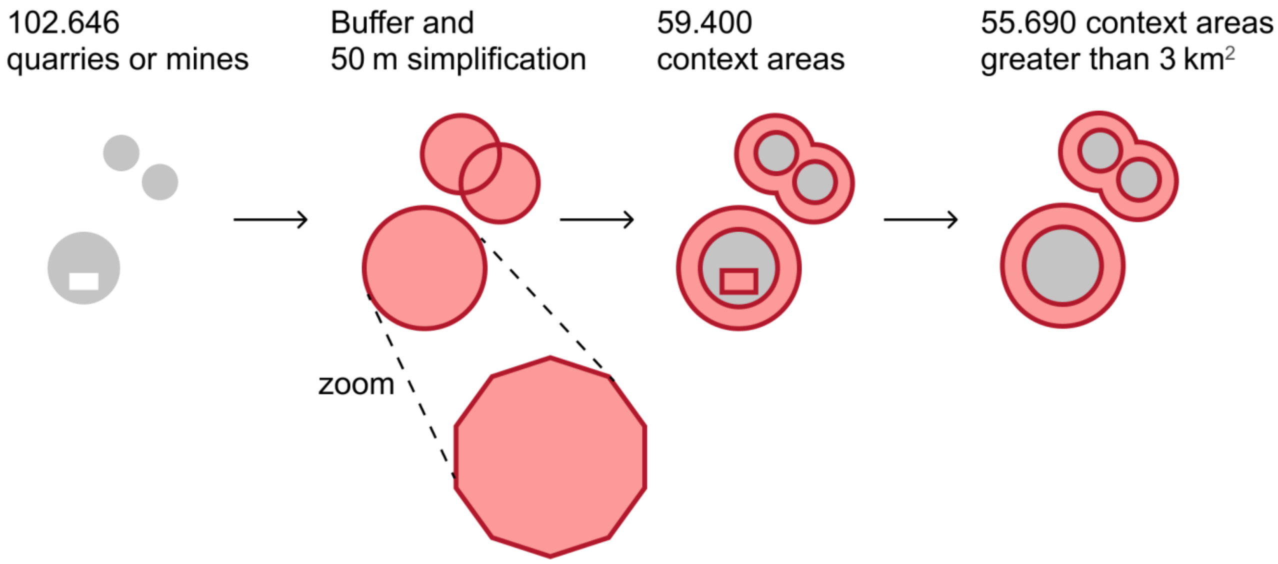


Figure 26 Steps of the calculation procedure for quarries and mines. It includes the buffer creation, simplification, creation of context areas, and selection of areas greater than 3 km^2.

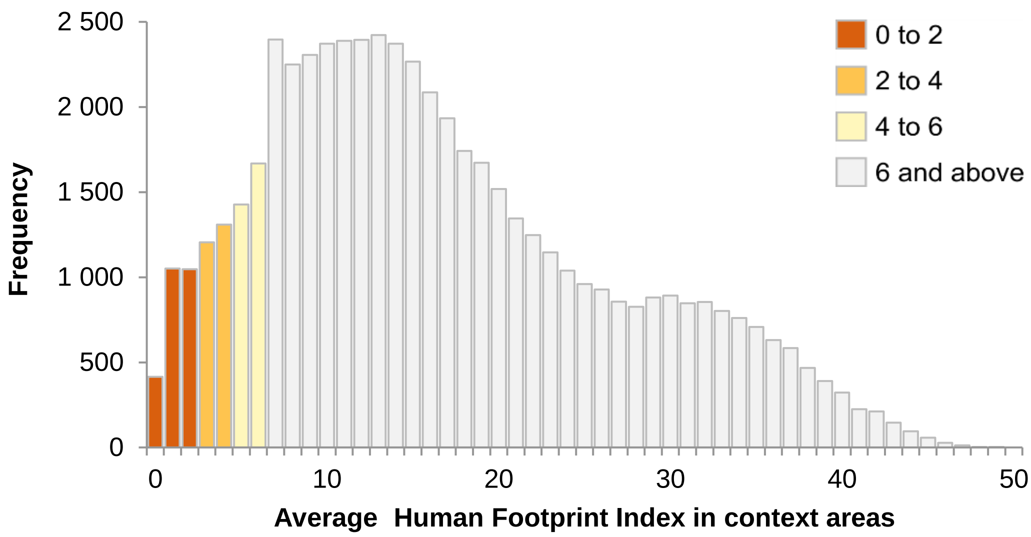


Figure 27 Histogram of the frequency of the average HFI in each quarry or mine's context area.

Of all quarry or mines context areas, less than 5% had an HFI up to and including 2, context areas with an average HFI up to 4 accounted for 9 %, while 15 % had HFI up to 6.

Quarries and mines with low HFI in the context areas were mostly found in the border of Canada and the United States of America, in the North of Brazil and Russia. Figure 28 is a map with the location of the quarries or mines with HFI up to 6.

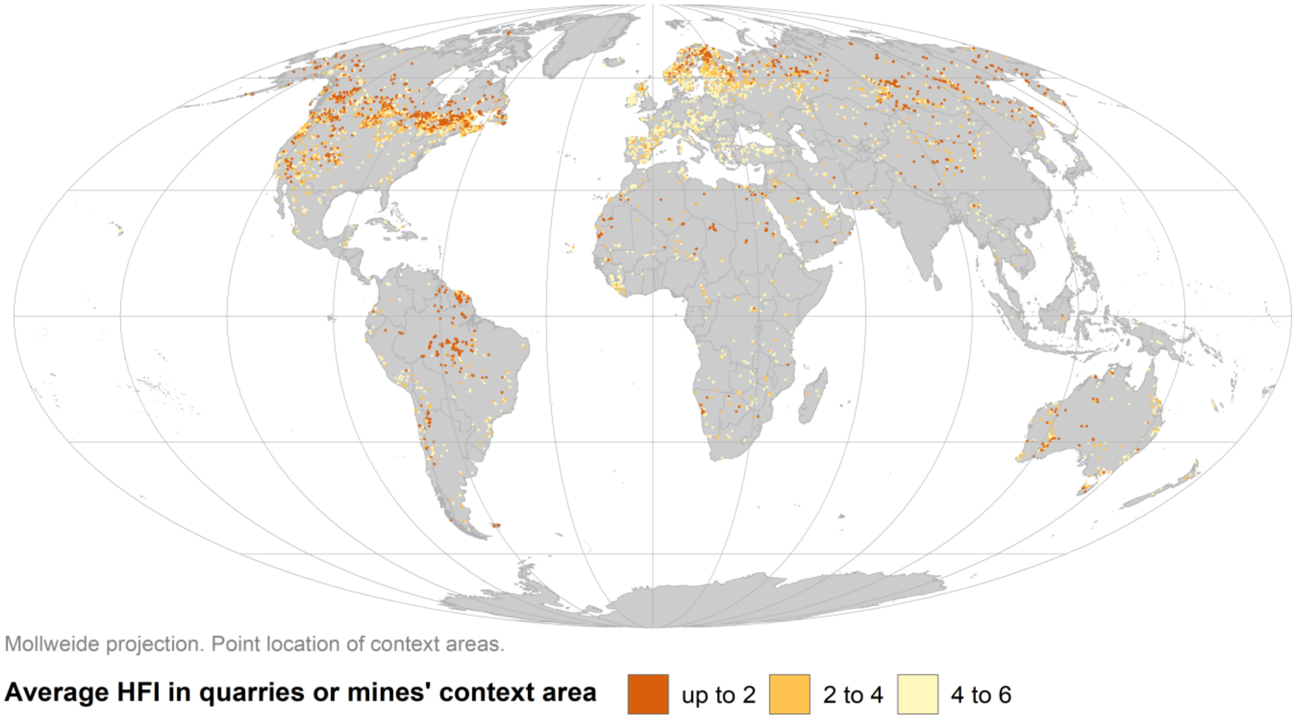


Figure 28 World map of quarries and mines with HFI up to 6 in their context area.

Roads

The input data for roads used here are 1 km^2 raster cells spanning 500 m from each side of the road. The context areas were created through the expansion of the road raster to one raster cell; a visual example is given in Figure 29, where the raster for road extent is overlaid on a base map showing the road's linear feature. The context areas for roads were not aggregated into continuous areas and the values are presented for each individual raster cell of the extended raster, or the context area.

The HFI of the road context areas' grid cells, (i.e., each grid cell for the HFI map directly surrounding the road raster) of 4 or below accounted for 14 % of the total context areas, HFI less or equal to 8 accounted for 49 %. Because roads context areas also have an HFI which is influenced by the road area itself (the HFI accounts for a road influence beyond the road itself), an HFI of 4 in a grid cell of the road's context area could mean that there is no other human pressure in that area, except the indirect effect of the road.

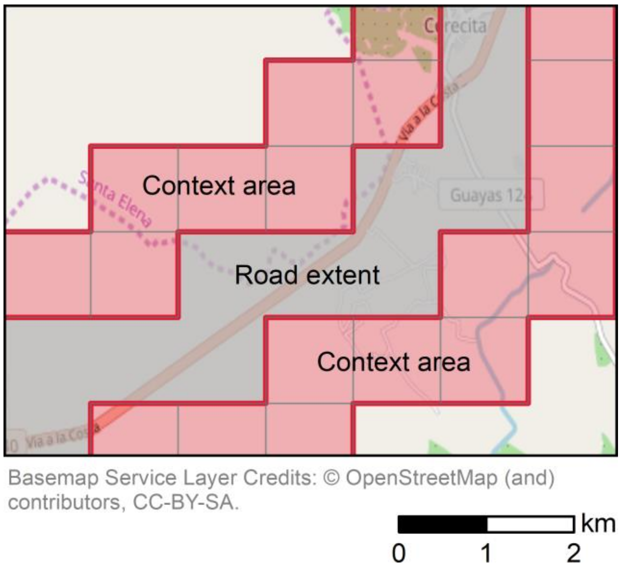


Figure 29 Map showing an example of the major road extent in raster format and the generated context area.

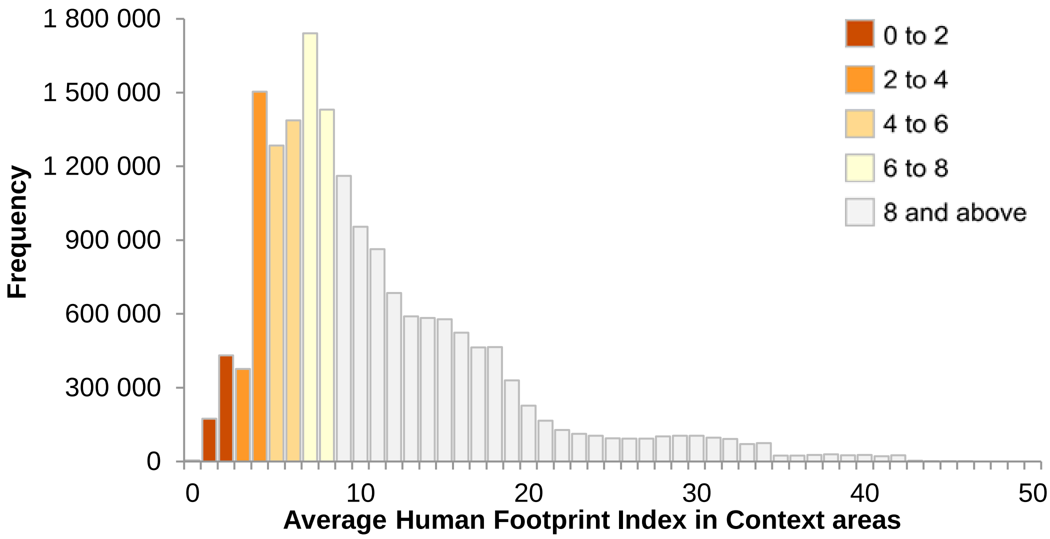


Figure 30 Histogram of the frequency of the average HFI in the roads' context area grid cells.

The HFI of roads near urban areas was relatively high, but the value quickly decreases around roads that connect those urban centers, see the map for the land use roads in Figure 24. In many locations, the surrounding of roads is dominated by agricultural land (cropland or pasture), which individually does not present a very high cumulative pressure.

The roads with lowest HFI values in their surroundings were found mostly in Canada, Russia, the north of Africa, and in Australia. A map is presented in Figure 31 to provide a visualization of the location of the areas with low HFI.

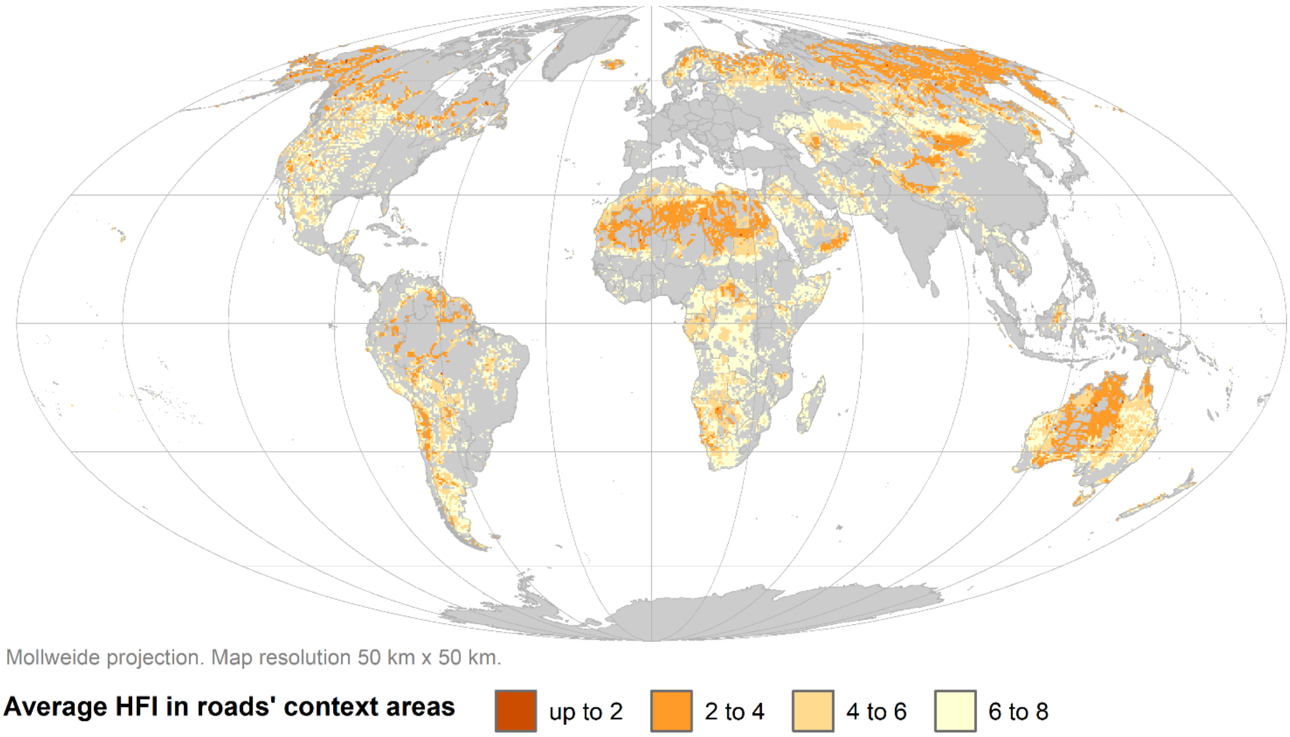


Figure 31 World map of roads' context areas with HFI up to 8.

Railways

The input data for railways used here are 1 km^2 raster cells spanning 500 m from each side of the railways. In the HFI, railways' pressures do not have an effect beyond that of the railway raster itself (no indirect effect). Also, the context areas for railways were not aggregated into continuous areas and the HFI values are presented for each individual raster cell of the extended raster, or the context area.

For railways, the values of the HFI in the context area up to and including 2 accounted for 9 % of the total, HFI up to 4 accounted to 17 % of the total, while values up to 6 accounted to 26 % of the total railways' context areas worldwide. Figure 32 is a histogram of the frequency of the HFI in the context areas of railways.

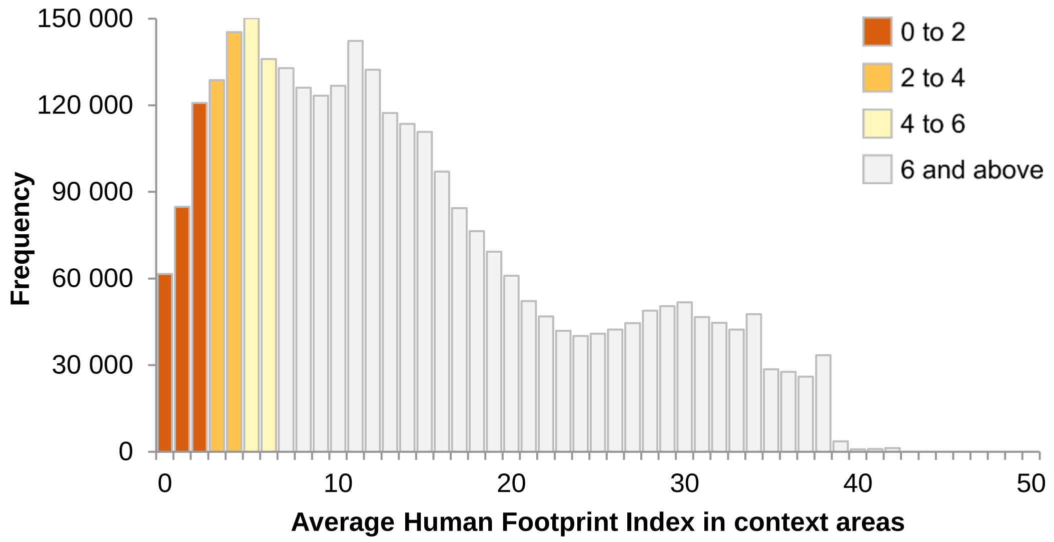


Figure 32 Histogram of the frequency of the average HFI in railways' context areas grid cells.

Railways were distributed in highly populated areas of the world, for example, Western Europe, the eastern part of the United States of America and Canada, Argentina, India, and South Africa. The railways' context areas with the lowest footprint were mostly concentrated across Canada and Russia (Figure 33).

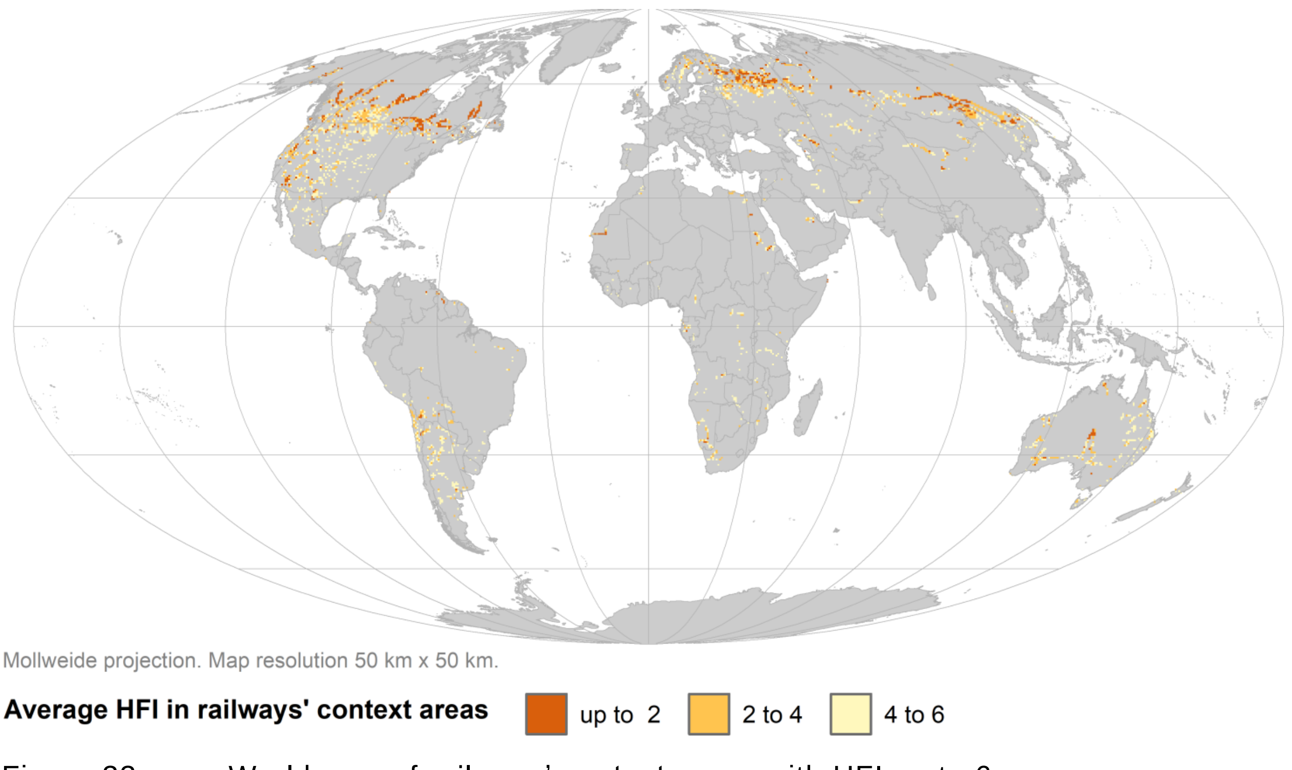


Figure 33 World map of railways' context areas with HFI up to 6.

Pasturelands

The pastureland's context area with HFI up to and including 2 accounted for 5 % of the total, HFI values up to 4 comprised 9 % of the total, HFI up to 6 represented 13 % of the pastureland context areas (Figure 34).

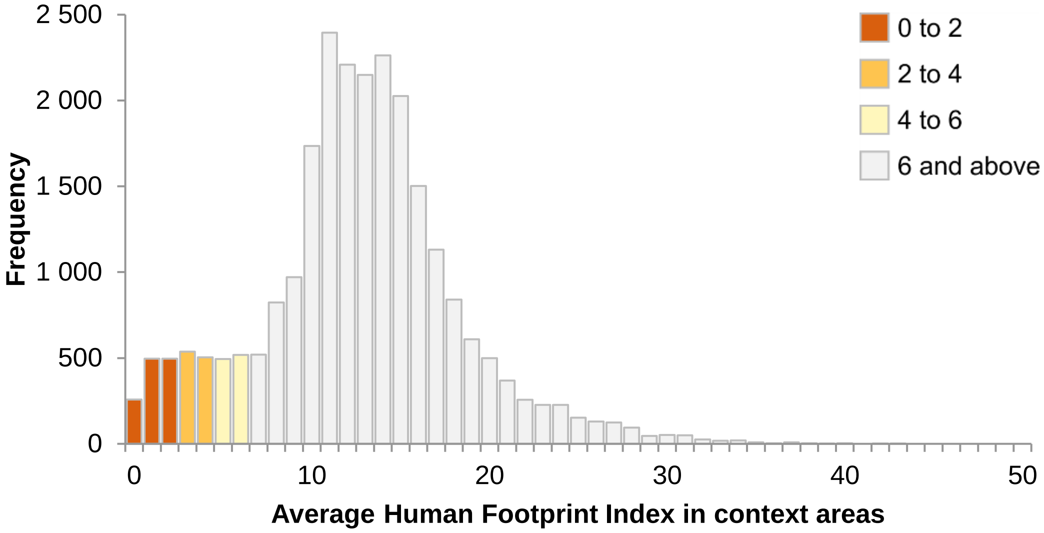


Figure 34 Histogram of the frequency of the average HFI in pasturelands' context areas.

Pastureland is the single most extensive land cover in the world. Pastureland's total mapped area was calculated using ArcGIS and accounted for 24 % of the total terrestrial area. Pasturelands with low HFI in the context areas were mostly distributed on the western side of North America, north and south-west of Africa, Asia, and Australia. A visual display of the pastureland context areas with HFI values of up to 6 is presented in Figure 35.

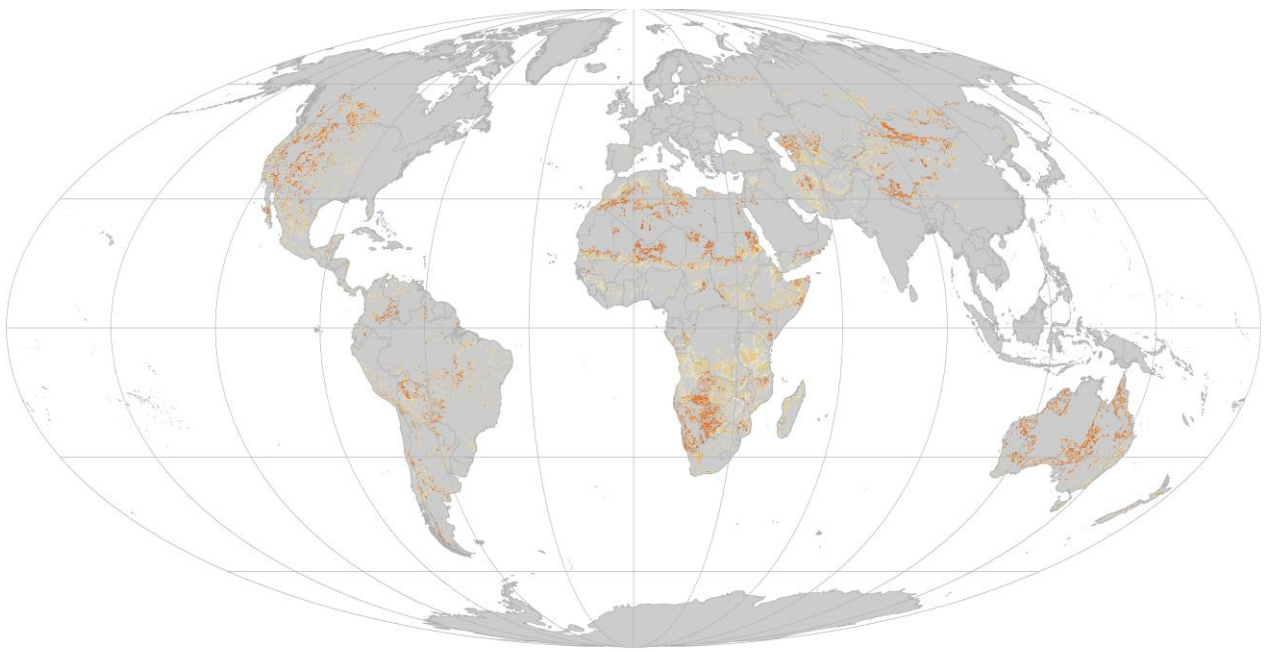


Figure 35 World map of pasturelands' context areas with average HFI up to 6.

Built environments

From the total 31.552 built environments' context areas, an HFI up to and including 2 was found for six locations, HFI up to 4 accounted for 0,23 % of the total (78 locations), and HFI up to 6 accounted for 1,25 % of the built environments context areas. A histogram is presented in Figure 36. The high value of HFI in built environments context area is because this land use type is rarely isolated from other human pressures accounted in the HFI.

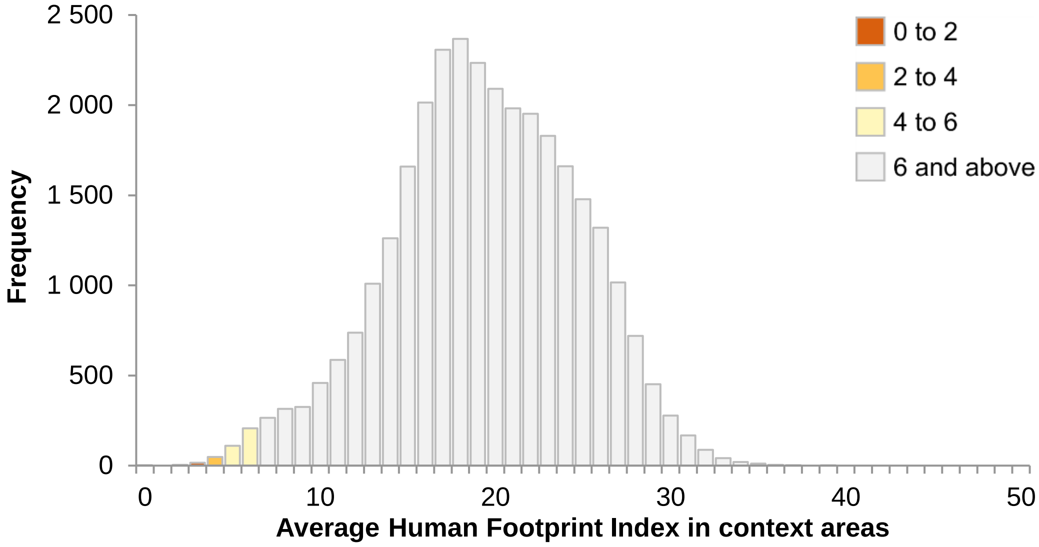


Figure 36 Histogram of the frequency of the average HFI in built environments' context areas.

As it can be observed in Figure 36, very few built environments areas are surrounded by areas of low HFI. Those are located mostly in Russia, Canada, and the north of Africa (Figure 37).

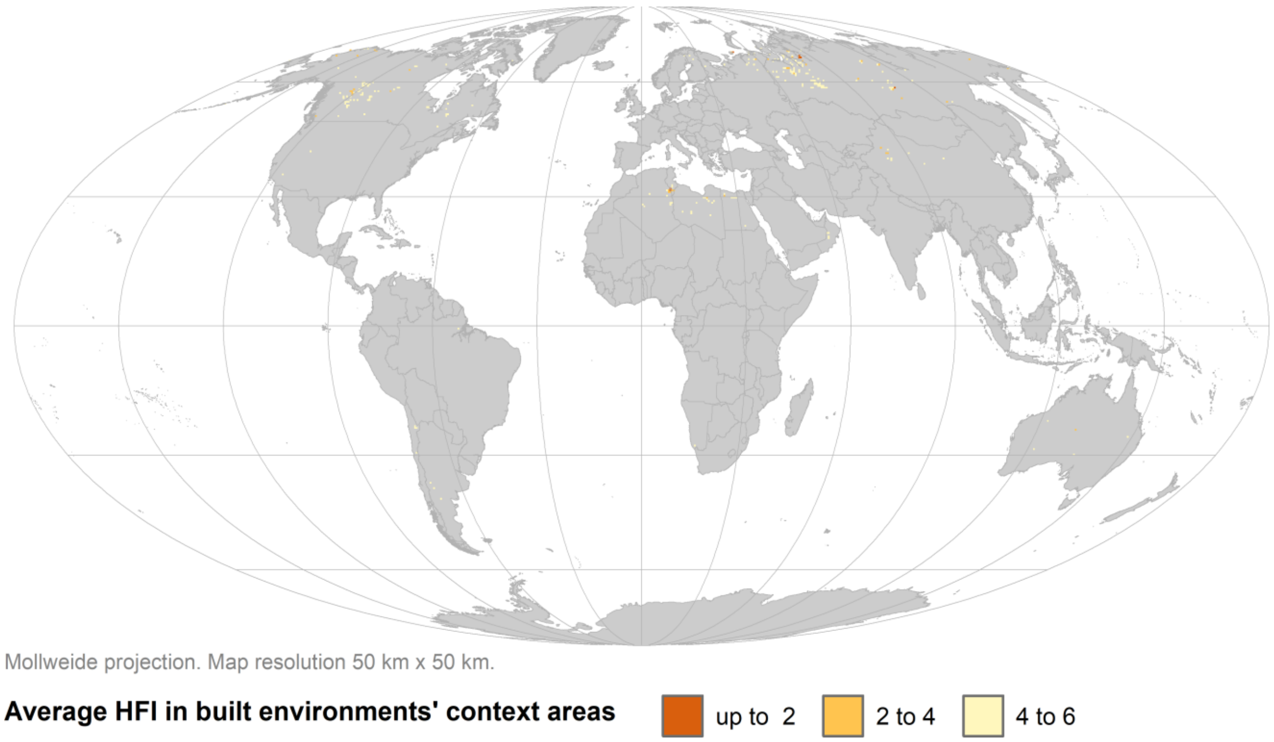


Figure 37 Built environments' context areas with average HFI up to 6.

Croplands

Context areas with HFI up to and including 2 accounted for 14 % of the total, context areas with HFI up to 4 being 31 % of the total, and up to 6 adding to 50 % of the total (Figure 38).

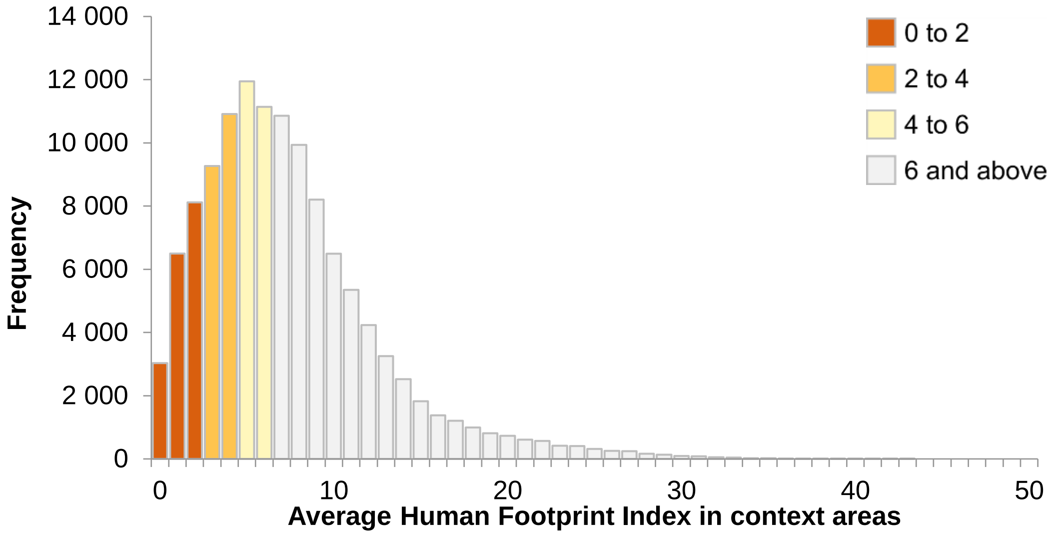


Figure 38 Histogram of the frequency of the average HFI in croplands' context areas.

Croplands' context areas with the lowest human footprint were mostly found in central regions of the United States of America and its border with Canada, in the center of Brazil, the south border of Russia, South East Asia, and in the south-west and the south-east of Australia. A map displaying the cropland's context areas with HFI up to 6 is presented in Figure 39. One of the largest continuous cropland sites spanned from the Northeast of Brazil to Argentina.

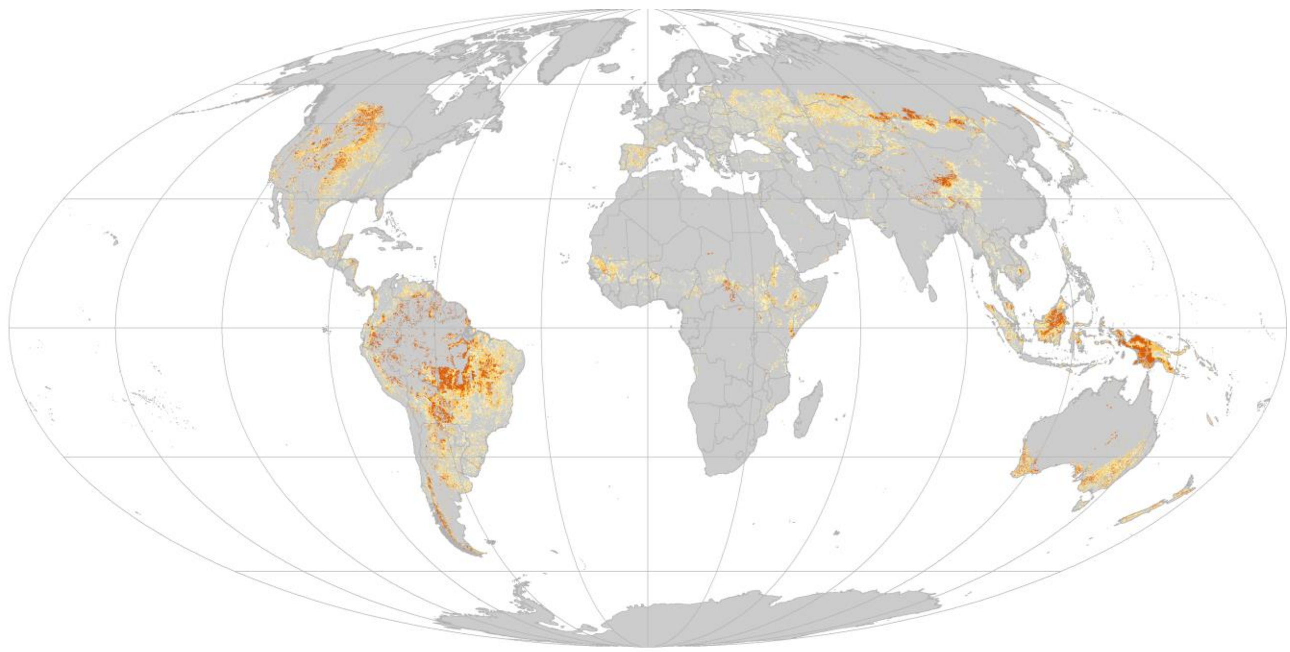


Figure 39 Croplands' context areas with average HFI up to 6.

5.2.2 Verification, forest cover in context areas, and valuation

In order to use the calculated HFI to identify areas of low human influence as an indicator of potential perforation in LCA, the HFI needs to be converted into a Perforation Potential as perforation or dissection patterns are not expected to happen in the full HFI range. However, there is no predefined relationship between the HFI and a Perforation Potential. The intermediate steps for the establishment of this relationship are the focus of this subsection.

Verification

The aim of applying this step is the verification of the existence of perforation-like configurations, specifically trying to identify existences of purely perforating land uses, and whether HFI = 0 indicates no pressure in the surrounding of a land use. The verification steps described in the subsection Verification and valuation steps on page 55 were applied, see also *verification* in Table 3 (page 55).

A total of 415 quarries and mines' context areas had an average HFI equal to 0. The verification step consisted of the visualization of the sites with the aid of the OSM base map, ESRI satellite imagery, and ELU, confirming that most of those sites were isolated from any mapped human pressures. The verification was carried out for 30 randomly selected sites.

For five sites, no quarry or mine was visible. For four context areas, no visible human pressures were visible in the context areas, but in one of these cases, the extraction site was near a river. In all other context areas, at least one road, track, or airport was visible. In six cases, a dedicated road or track leading to quarry or mine was visible, and also in two of these six cases, the context area partially overlapped an airport. Quarries or mines alongside a road or track were found in 19 cases, but the track or road were not always mapped on OSM. The results from the visualization for each of the 30 randomly selected sites are detailed in Appendix A.

These visualizations revealed that a purely perforating configuration is uncommon. Therefore a major outcome of this verification step is that it supports the assessment of perforation and dissection patterns together. This observation is not surprising since a road, rail, or waterway is required for the transport of the extracted goods.

The existence of visible roads, not captured by the HFI is justified because only major roads have a score in the HFI, and the dedicated roads or track leading to these sites are not major roads. Despite the average HFI of 0, forest plantation with clear-cut areas and tree rows were identified in five context areas, and also roads were visible. Had those utility roads been given a pressure score in the Human Footprint, they would increase the value of the HFI in the context area, resulting in it not being zero.

The 30 verified sites represent 7% of all quarries and mines that have an average HFI equal to 0. The sample size was sufficient not only to fulfill the goal of the verification step but also brought more understanding about unmapped pressures.

Forest cover in context areas of quarries and mines

The forest cover in each context area was calculated using the land cover map of 30 m resolution GlobeLand30 (Chen et al. 2015) and divided by the context area size. The values of the forest fraction in the context area, together with the calculated HFI, will be used for the grouping of the context areas that will be used in the valuation step.

Only quarries or mines' context areas that were entirely located in terrestrial and forest biomes were selected. For example, if a part of the context area was on the ocean, or if the context areas were partially located in a forest and in a non-forest biome, these context areas were excluded from the assessment. From a total of 55.508 context areas of quarries and mines that met the criteria for assessment for the HFI (see heading Quarries and mines on page 61), a total of 38.301 were entirely within the forest biomes boundaries defined by Olson et al. (2001).

The GlobeLand30 data is provided as map tiles, and at the joining border of adjacent tiles, there was overlap, which is more pronounced in northern parts of the globe. A forest cover in a context area in these overlapping zones would be accounted for on both tiles and result in the double-counting of the forest amount. Context areas in forest biomes which intersected more than one GlobeLand30 tile were excluded. This step further reduced the number of context areas to 37.819.

A total of 11.758 context areas had a forest cover ratio higher than 0,6. These represent 31 % of the quarries or mines' context areas in forest biomes, while 19 % had a forest cover ratio of more than 0,75, and for 8 % of the context areas, the forest cover and area ratio was higher than 0,9. A map is presented in Figure 40, showing the location of the quarries and mines' context areas with a high forest cover worldwide.

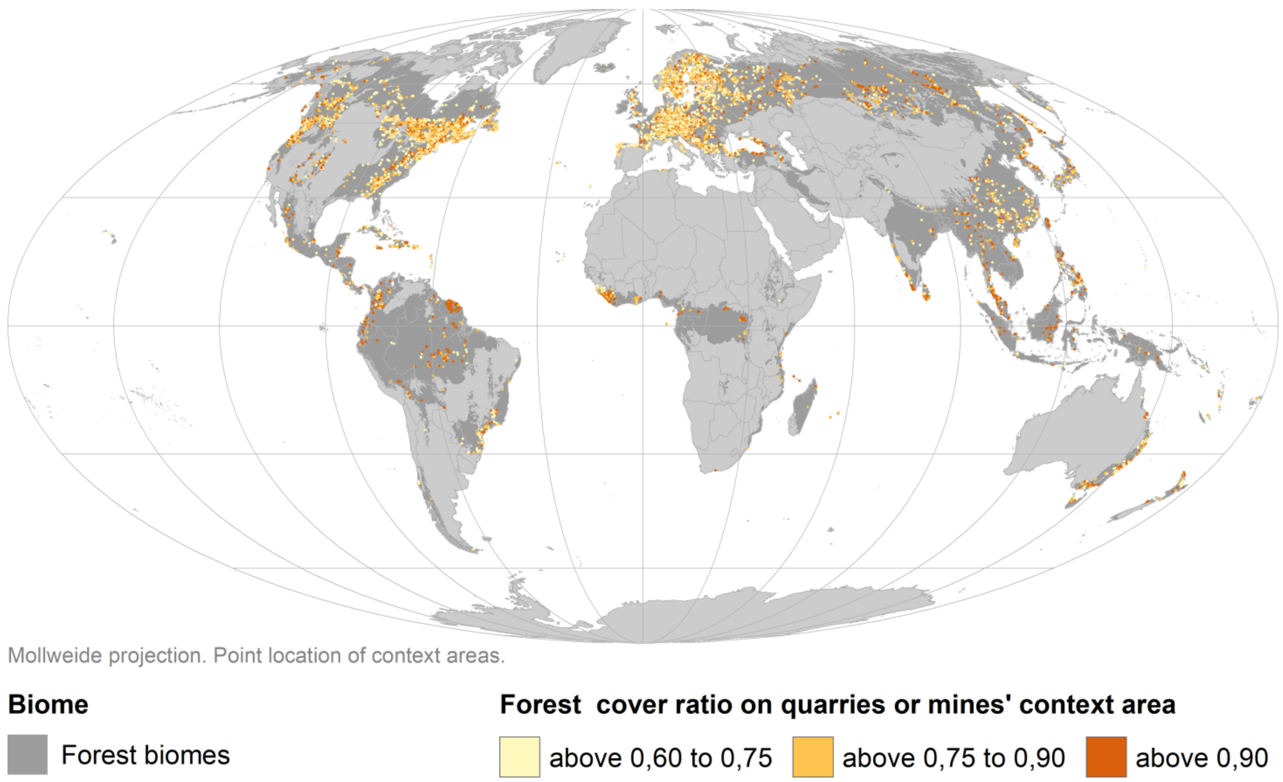


Figure 40 Quarries or mine’s forest cover per context area ratio higher than 0,6.

In this subsection, the steps for the calculation of forest ratio in quarries or mine’s context areas were described. This subsection is an intermediate step that will be used as one grouping criterion of the valuation step.

Valuation

The valuation step described in the subsection Verification and valuation steps on page 55 was applied, see also *valuation* in Table 3. This step aims to provide a better understanding of the relationship of the HFI and perforation and dissection patterns in the context areas. The valuation step was carried out for a selection of context areas of quarries and mines, grouped depending both on the HFI and on the forest cover ratio in their context areas. The groups were described in Table 4, on page 58, and an indication of groups a, b, c, and d is presented in Figure 41. A total of 14.482 context areas of quarries or mines matched these grouping criteria. The valuation was carried out for a total of 80 sites. The sites were selected using a random number generator, and their location is shown as a world map in Figure 42.

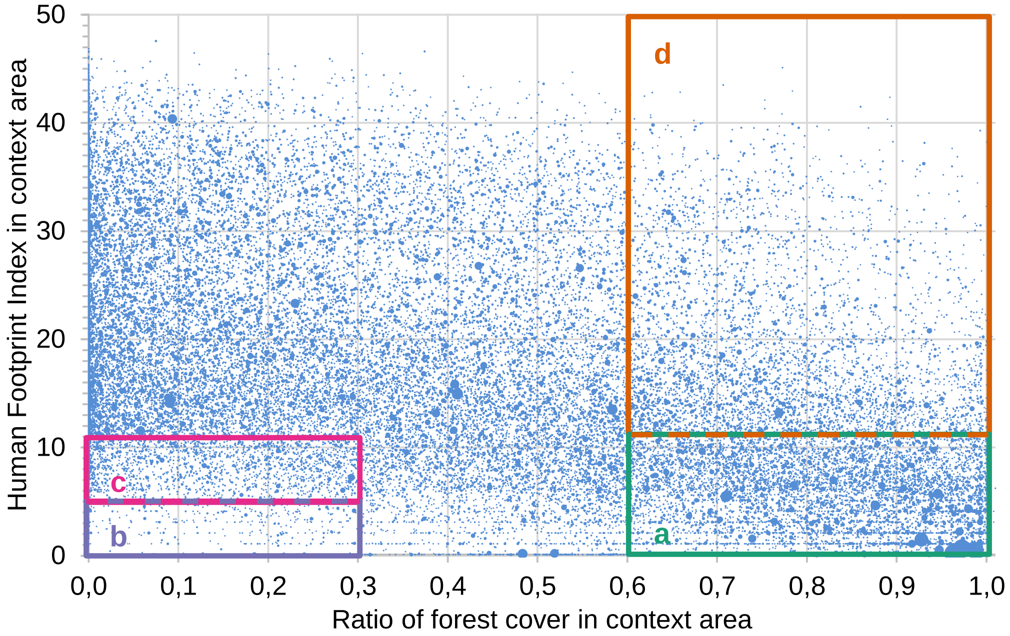


Figure 41 Scatter plot of the ratio of forest cover in the quarries or mines' context areas (x-axis) against HFI (y-axis), highlighting the valuation groups. Larger sizes represent larger context areas.

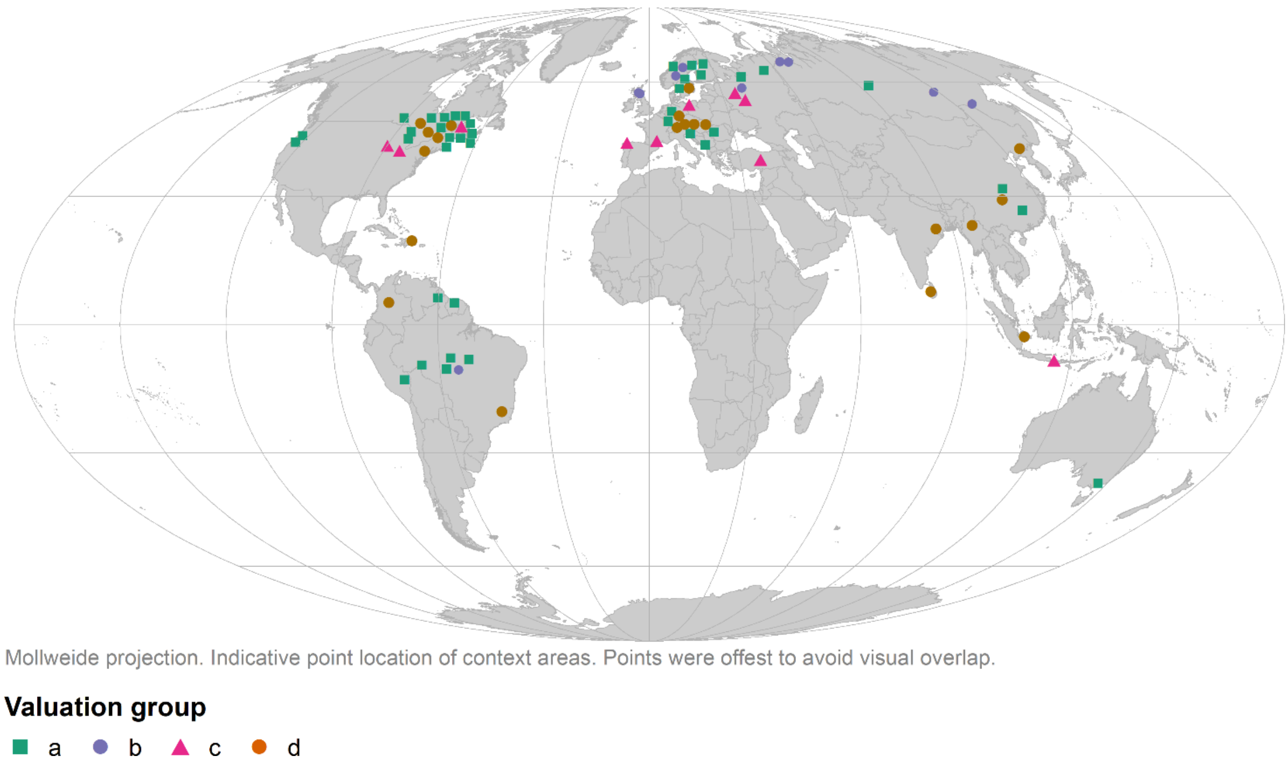


Figure 42 World map of the context areas selected for valuation.

Each selected context area was visualized with the aid of supporting maps and valuated with scores from 1 to 3 according to their similarity to a perforation or dissection patterns (see the illustrative scale on Figure 23, page 57). A value 3 is assigned to the highest resemblance to a perforation pattern and value of 1 assigned to a fragmentation-like pattern. A summary of the results of the valuation step is presented in Table 5.

Table 5 Summary of results and observations for valuated sites.

Group	Group average valuation score	Group	Group average valuation score	Summary of observations
a1	2,85	a	2,60	Overall similarity with perforation and dissection pattern.
a2	2,40			
a3	2,60			
a4	2,55			
		b	2,20	Low vegetation cover ratio and low HFI were due to the: presence of water bodies, coarseness of ecoregion boundaries, inconsistent capture of land cover by GlobeLand30 or HFI's cropland layer.
		c	1,20	Quarries or mines mostly surrounded by cropland.
d1	2,15	d	1,95	Variety of configurations. Forest plantation, trees planted in rows, palm tree plantations, vegetated areas with well defined signs of human presence.
d2	1,75			

The following paragraphs will provide an explanation of the results of the valuation step as well as other observations concerning the quality of the data used. Detailed results for each valuated context area are presented in Appendix B.

Group a: high vegetation cover (above 60 %) and HFI up to 11

For the groups a1, a2, a3, and a4, a total of 40 context areas were selected for valuation. From the selected sites, 19 were valuated as resembling peroration and given a valuation score of 3. These sites were mostly surrounded by forest; some were located along or at the end of a visible road, track or trail. There were 12 context areas which were valuated with 2,5 mostly due to the existence of non-forested patches. Seven sites received a valuation score of 2. Two context areas were valuated with 1,5 because of the presence of forest cover. No context in this group was valuated with score 1. The average valuation score in this group was 2,60. Two examples are presented in Figure 43.

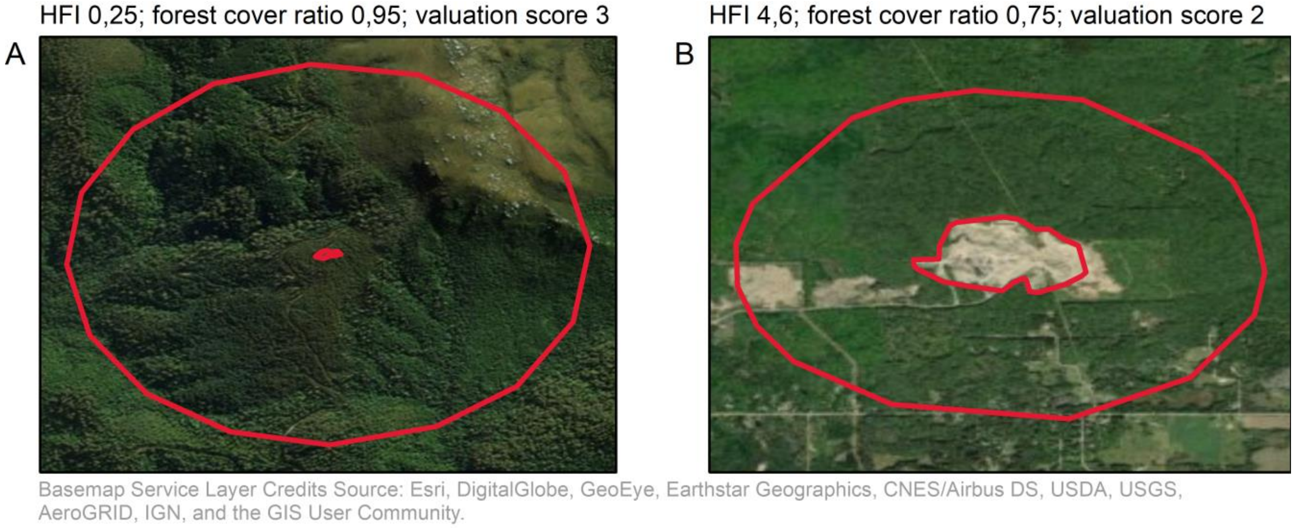


Figure 43 Example of valuated sites: group a1 (A) and group a3 (B).

A concentration of larger context areas is noticeable in the highlight of the group a in Figure 41 on page 75. Six context areas have an area greater than 100 km^2, HFI below 2, and forest cover ratio of more than 0,9. These context areas were located in Suriname and the Peruvian Amazonia. In these context areas, there were very few pressures captured by the HFI, and the presence of pressures such as roads only take place in a small part of the context area, having little influence on the average HFI and in the ratio of forest cover.

Group b: low vegetation cover (below 30 %) and HFI up to 5

The individual pasturelands' pressure score ranges from 1 to 4, depending on its intensity. Therefore, the existence of context areas with low forest cover and low HFI is expected if the context area is surrounded by pastureland. Differently from expected, only one site was entirely surrounded pastureland, the visual assessment of sites in this group also revealed other reasons for the presence of sites with low vegetation cover and low HFI.

In some cases, although the biome is a *forest biome*, the land use was surrounded by a naturally treeless landscape in the far north of the globe within a few hundred kilometers from the border of the *tundra biome*. Other ecoregion inconsistencies were swamps or flooded areas, and natural sparse vegetation cover. In the cases that the vegetation resembled to be natural, the context areas were valuated with a score of 3.

In some cases, other quarries and mines in the context area were not captured by the OSM, but the absence of vegetation was captured by the GlobeLand30's forest layer. The uncaptured quarries or mines become part of the context area, and since their land cover is not forest, they lead the forest cover ratio to be lower. The presence of water bodies leads to a reduced value of the ratio of forest cover in the context area. Also, in two sites, the context area was dominated by cropland; however, it has not been captured as cropland by the HFI map. Two examples are given in Figure 44.

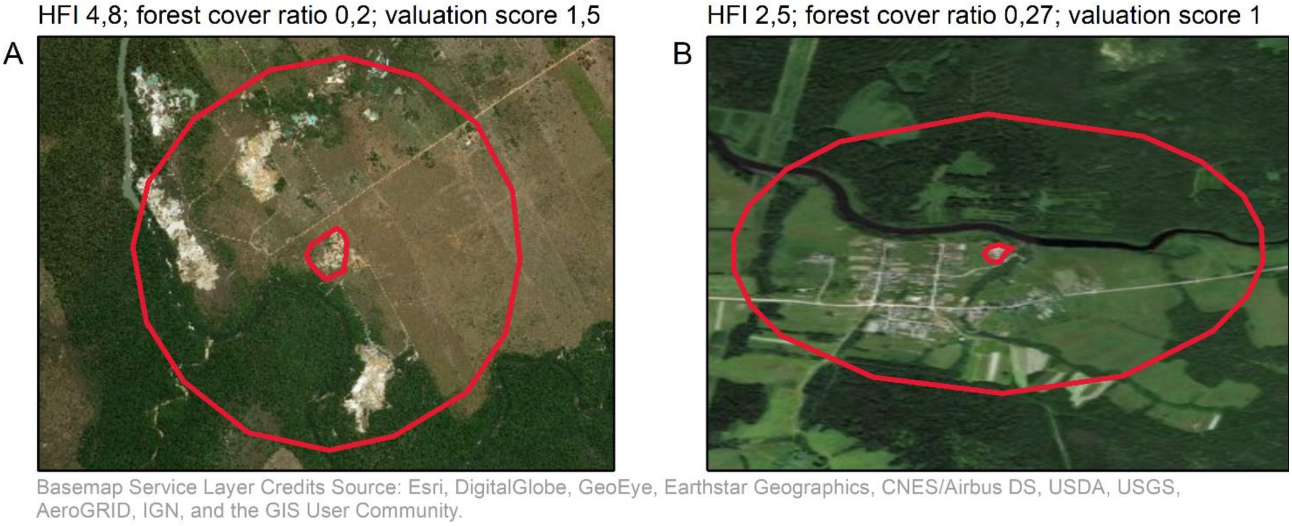


Figure 44 Example of two valuated sites in group b: the context area (A) has uncaptured mining sites and (B) the cropland or pasture and settlement were not captured by the HFI pressure maps.

In the absence of other pressures, a land use surrounded only by low-intensity pasture could be classified as perforating if the grazing land provides habitat for species of conservation value. Here, a conservative approach was taken, and for the site surrounded by low-intensity pastureland found as part of this valuation step in this group, this configuration was considered as not similar to a perforation pattern and given a valuation score of 1.

The average valuation for all the context areas in this group was 2,20. An update of the pressure layers of cropland and built environment using a more recent or finer resolution dataset would increase the values of the HFI in the context areas. Such an update would increase the HFI value of these context areas, resulting in some of these sites not being part of this valuation group.

Group c: low vegetation cover (below 30 %) and HFI between 5 and 11

The context areas in this group were mostly surrounded by cropland, cropland mosaics, fragmented patches of natural forest, highly modified landscapes, and low-density settlements. The patterns of eight context areas resembled more that of fragmentation than that of perforation, receiving a score of 1. Two context areas were valuated with score 2. From these two context areas, one seemed to hold naturally bare land with some croplands, and for the other, there were human settlements scattered among tree vegetation, croplands, and palm tree rows among dense natural-looking vegetation, despite being entirely mapped as cultivated land in the GlobeLand30.

Areas with HFI between 5 and 11 and vegetation cover below 30 % had an average valuation score of 1,2. Two examples are given in Figure 45.

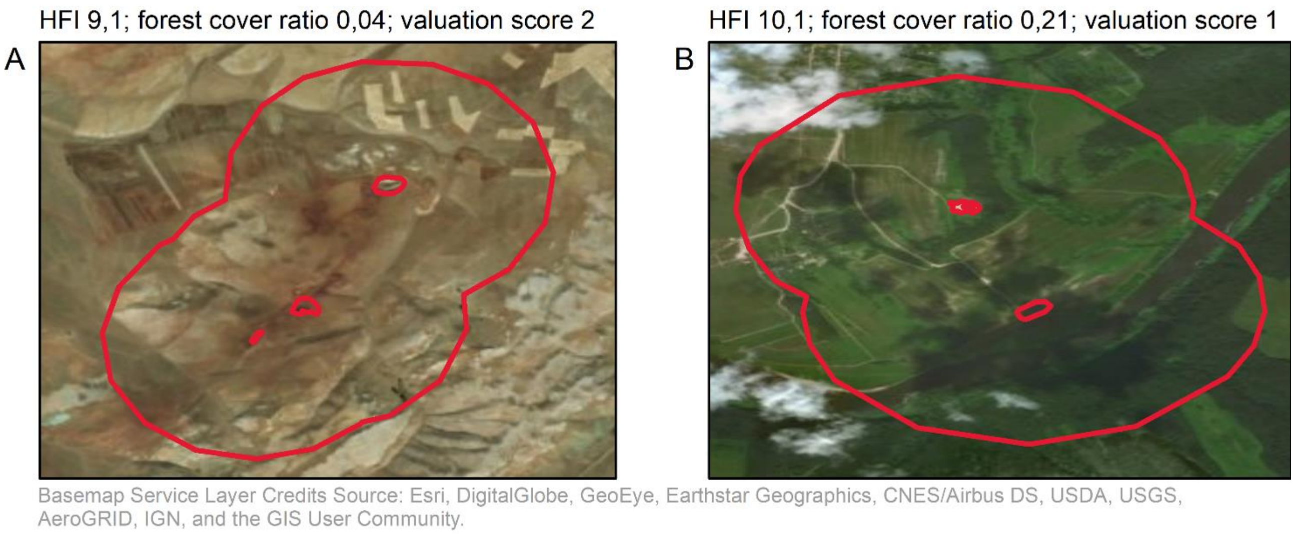


Figure 45 Example of two valuated sites in group c: (A) naturally bare land and cropland in the context area, and in (B) the context area was dominated by cropland.

Group d: high vegetation cover (above 60 %) and HFI above 11

The landscape in this group presented a variety of configurations, from visible palm tree plantations, tree plantations with visible rows and tracks through the forest, vegetated areas with signs of previous human driven landscape alteration, or vegetated areas with patches of highly modified land. Population density, nightlights, or roads outside the buffer zone caused the higher values of the HFI. This observation indicates that despite the high vegetation cover, the context areas are subjected to human pressures that are not due to land cover modifications. One site in group d2 had an HFI 31 and forest cover ratio 0,97, and the discrepancy was due to a mosaic of cropland, forest, and built environment captured by the HFI being only captured as forest by GlobeLand30. The context areas with high vegetation cover and high human pressure had an average valuation score of 1,95. Two examples are given in Figure 46.

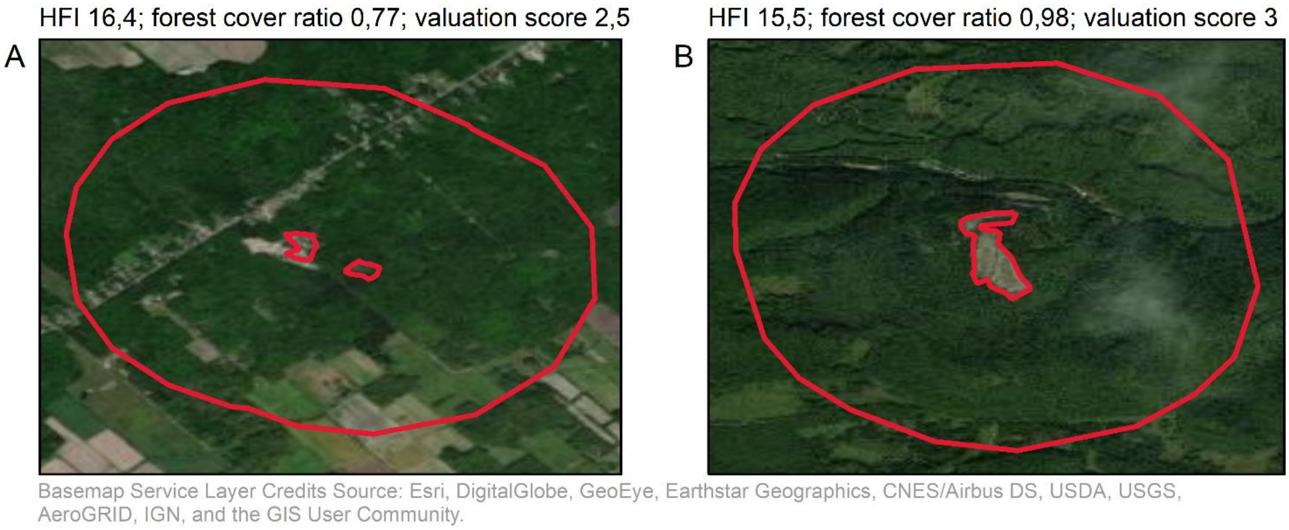


Figure 46 Example of a valuated site in group d1 (A) for which the higher HFI was due to both the indirect effect of roads, and population density; and in group d2 shown in (B) for which the HFI was due to high population density.

Summary of valuation step results

The highest resemblance to perforation and dissection configuration was observed for group a1 (areas of low HFI and high forest cover) and had a valuation score of 2,85. The lowest resemblance to perforation was found for group c (areas that have an overall high HFI and low forest cover), with an average valuation score of 1,2, having most of the mining site surrounded by cropland.

The major outcome of the valuation step is that it supports the use of a cumulative pressure indicator instead of only considering original land cover. The use of HFI allows the analysis to go beyond the simple quantification of the amount of original land cover type in the context area.

Quarries or mines in areas with overall high human influence but with high forest cover in their surroundings were observed in the valuation step. This result suggests the need to separate the human pressures in two categories: pressures that have a land cover different from the original and pressures that are not related to a modification of the original cover.

Another conclusion of the valuation step is that the use of ecoregions borders and the determination of the original cover, such as forest cover for forest biomes can be inadequate, especially in context areas near a biome border. For the purposes of this thesis, this outcome is evidence of the advantage of using a cumulative pressure map, instead of biomes or ecoregions borders and its ideal cover as an indicator for habitats.

5.2.3 Conversion to Perforation Potential

The objective of this subsection is the establishment of the conversion of the HFI into a potential of perforation for a land use context area in order to create an indicator that can be used to support the decision making process about a land use's potential to perforate. This conversion will be developed using the knowledge gained through the verification and valuation steps in combination with literature.

To use the human pressures measured in the surroundings of a land use as an indicator of perforation this relationship has to be established. Human pressures are captured by HFI as a composite index that includes roads, rails, navigable waterways, population density, nightlights, built environment, cropland, and pasturelands. One of the outcomes of the valuation step was the need to disaggregate the HFI into two categories: pressures that modify the land cover and those that do not modify the land cover. Human pressures will be grouped into *modifying* and *non-modifying* pressures, depending on whether they directly alter the physical structure of the land or not.

The HFI pressures categorized as land cover modifying pressures are cropland, pastureland, and built environment. These pressures do not overlap, i.e., for each raster cell only one of these pressures may exist. Roads and railways are pressures that modify the land cover, but at 1 km resolution, these pressures can overlap the modifying pressures of cropland, pastureland, and built environment. Therefore, roads and railways will be categorized as non-land cover modifying pressures along with navigable waterways, nightlights, and population density.

Land cover modifying parameters contributions

The general model proposed by Forman (1995, p. 409), reproduced in Figure 9, on page 20, is used as a starting point to the establishment of the relationship of land cover modifying parameters and their contribution to perforation. The model indicates the relationship of habitat remaining and their landscape contribution. If the curve proposed by Forman (1995) is strictly used as a potential to perforate, this means that the potential to perforate and dissect decreases with the absence of original land cover type. The general model of Forman (1995) as a potential to perforate and dissect is presented in Figure 47.

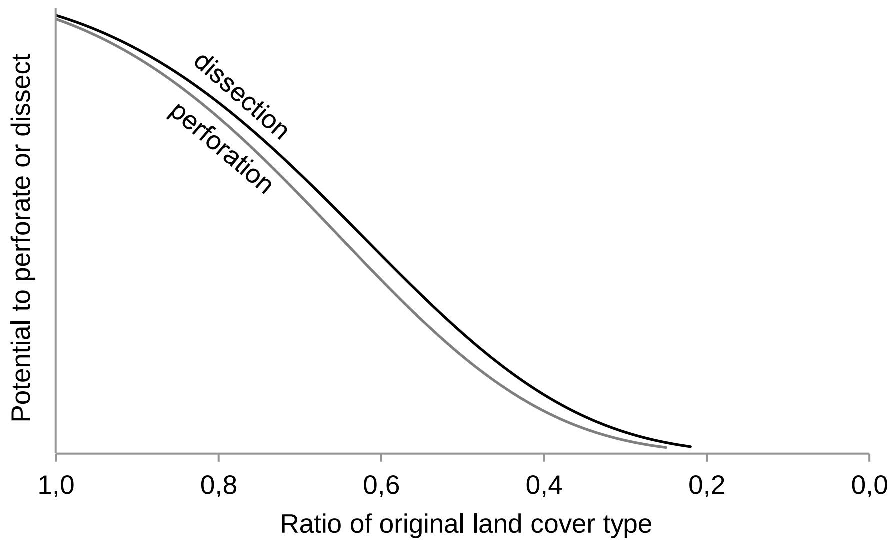


Figure 47 General model of the relative contribution of perforation and dissection proposed by Forman (1995) as a potential to perforate and dissect.

The presence of HFI pressures that modify the land cover (namely cropland, pastureland, and built environment) will be used to represent the absence of natural habitat. By assuming that the absence of land cover modifying pressures represents the original land cover type, the HFI land cover modifying pressures can be used as input to the general model proposed by Forman (1995, p. 409), schematically represented in Figure 48. This assumption is conceptually sound, as these are the major anthropogenic land cover types worldwide, with the plausibility of this assumption being further explored in Appendix C.

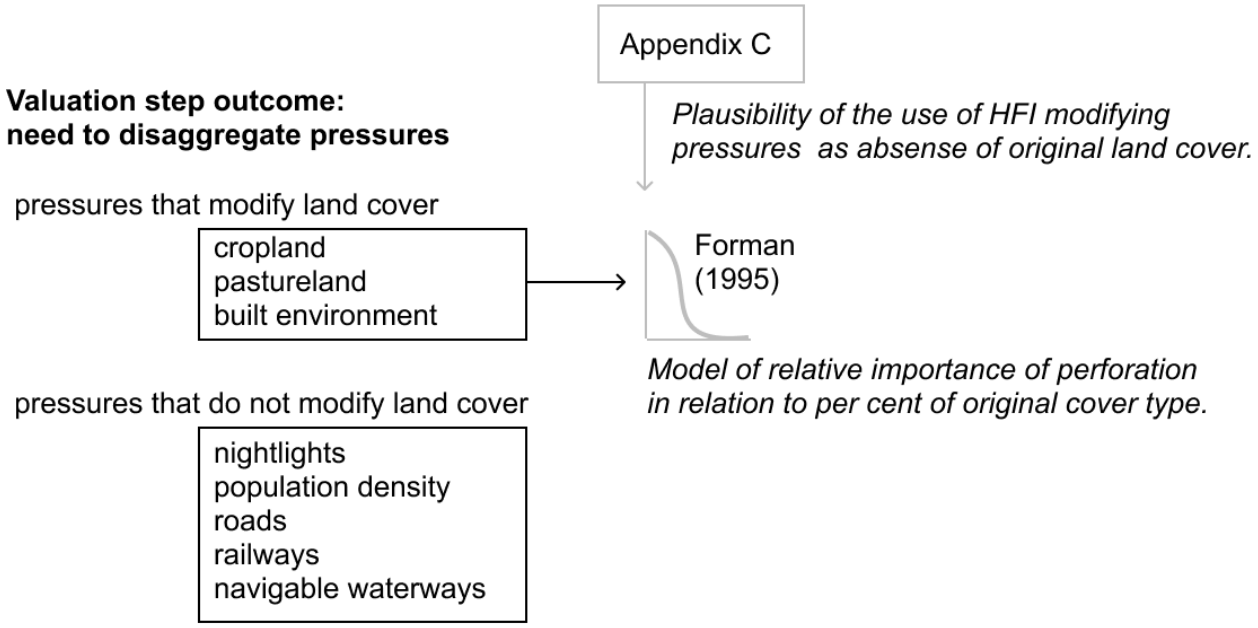


Figure 48 Representation of the steps leading to the use of land cover modifying pressures from the HFI as the absence of original land type in the model proposed by Forman (1995).

The general model of Forman (1995, p. 409) represents a distinct negative relationship of a curve, which starts with a high contribution and declines with the absence of original land cover type, but the author did not provide an equation. In order to quantitatively apply this model as a contribution to perforation, this curve has to be translated into an equation.

The overall shape of the curve proposed by Forman (1995, p. 409) is similar to the cases of a parameters’ negative contribution to biodiversity presented by Lindner (2016), see Figure 13 on page 35. The curve proposed by Forman (1995, p. 409) is neither as steep as the *immediate* curve nor as resilient as the *negative with resilience* curve presented by Lindner (2016), being approximately in between.

Lindner (2016, p. 81) provided examples of constants that can be applied to the normal distribution curve to create typical contribution curves. The intermediate values between the constants of the *immediate* and *resilient* types of negative contributions provided by Lindner (2016) were calculated and are presented in Table 6.

Table 6 Contribution curves constants provided by Lindner (2016, p. 81), and values calculated for an intermediate curve.

	Negative, immediate	Negative, with resilience	Negative, intermediate
exponent (α)	2	3	2,5
width (σ)	0,25	0,35	0,3
x-shift (β)	0	0	0
y-shift (γ)	0	0	0
x-stretching (δ)	0,5	1	0,75
y-stretching (ε)	1	1	1

Figure 49 shows the curves obtained by applying the constants of Table 6 to equation 1 in the section Biodiversity contribution method, starting on page 34.

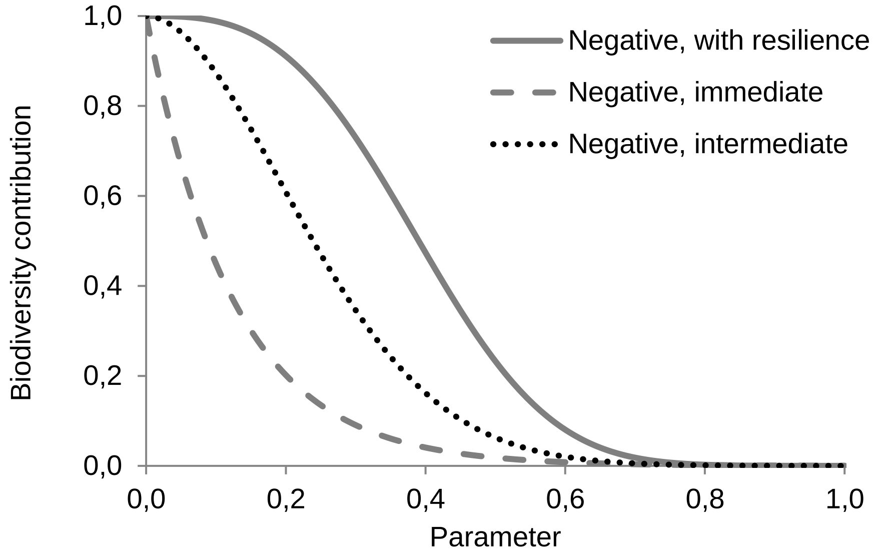


Figure 49 Relationship of a generic parameter and its contribution to biodiversity. Immediate and resilient contributions were provided by Lindner (2016, p. 81).

In the general model proposed by Forman (1995, p. 409), reproduced as a potential to perforate and dissect (in Figure 47, page 82), dissection and perforation still occur, although almost minimally when there is 40% of original land type, and there is no contribution to perforation when there is only 20% original cover left. In terms of modified cover, this means that there is some perforation contribution to perforation when there is 60% of modified land cover type and no contribution when 80% of the area is a modified land cover type. The constants for the intermediate curve were adjusted to generate a curve that fit these criteria, and the proposed curve is presented in Figure 50.

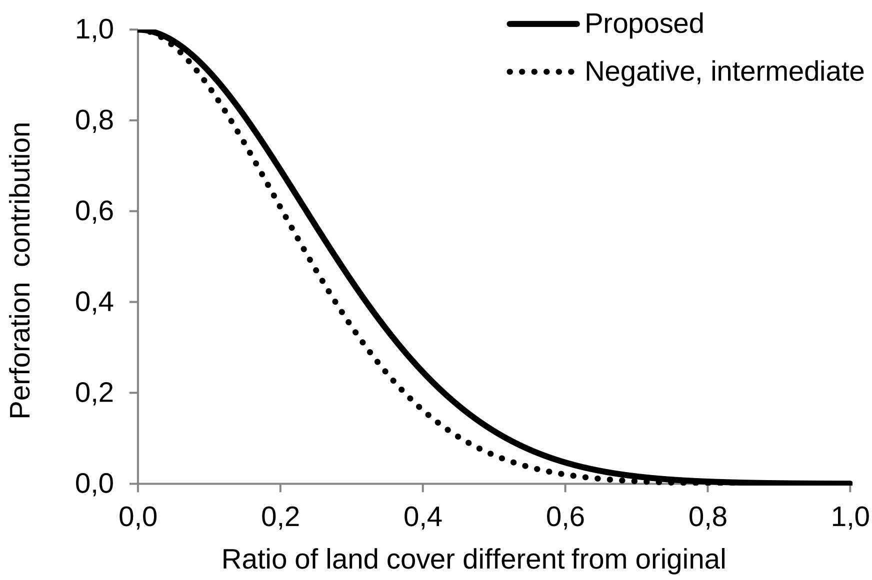


Figure 50 Relationship of the ratio of land cover that is different from original (x-axis) and perforation contribution (y-axis). The proposed curve was created by adjusting the constants of the intermediate negative contribution curve.

The constants used for the proposed contribution curve are: exponent (α) 3,5; width (σ) 0,45; x-shift (β) 0; y-shift (γ) 0; x-stretching (δ) 0,55; y-stretching (ε) 1. The implication of this choice will be explored in subsection 5.2.4 Discussion on modeling choices, under the heading Conversion to Perforation Potential, starting on page 96. These constants, when applied to e.q. 1 result in:

$$y = e^{-\frac{\left|\left(x^{0,55}\right)^{3,5}\right|}{2 \times 0,45^{3,5}}} \qquad [\,] \qquad (3)$$

Where y is the contribution of the parameter x, here ratio of modified land cover, to perforation and dissection.

A schematic representation of the literature sources backing the construction of the proposed curve for the contribution land modifying pressures to perforation is presented in Figure 51.

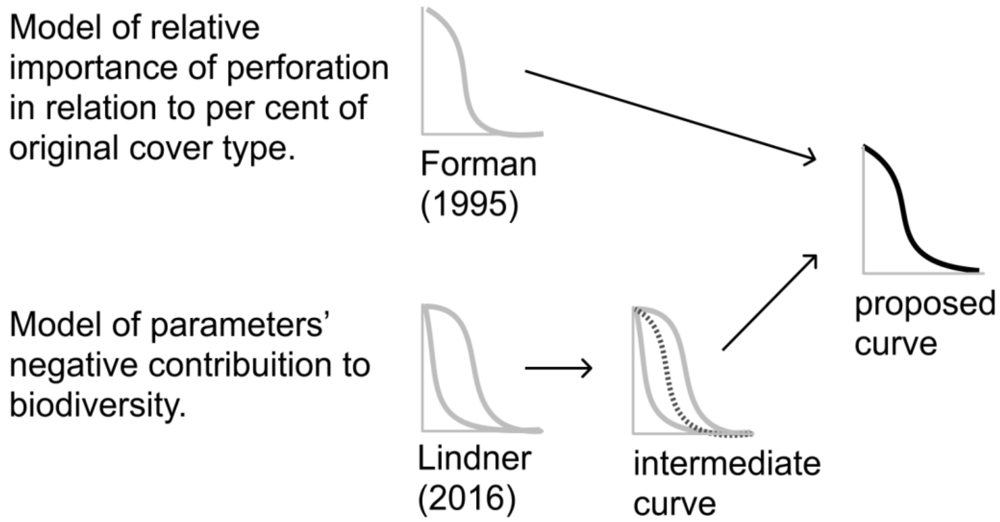


Figure 51 Proposed curve to represent the contribution of land modifying parameters to perforation, using the model proposed by Forman (1995, p. 409) and by Lindner (2016).

In the general model of Forman (1995, p. 409), the percentage of original land cover type is used. If strictly applied as a contribution to perforation, the presence of pressures of either built environment, pastureland, or cropland, would represent an equal potential to perforate. However, it is arguable that the type of land cover modifying pressures in the surroundings of a land use influence the land use's potential to perforate.

In quantifying the human pressures on the environment, Venter et al. (2016b) ascribed different pressure scores depending on the type of pressure. Specifically, the HFI gives a score of 10 for built environment, 8 for cropland, and 1 to 4 for pastureland depending on the pasture intensity. The values of these pressures, HFI_{mod}, will be used as the parameter for the contribution of the modifying pressure to perforation. The HFI_{mod} is converted into parameter x_A, from 0 to 1, with zero meaning no pressure, and 1 maximum pressure, by dividing the HFI_{mod} by the maximum possible value of 10. With this scale, an area of built environment (HFI value 10) represents the maximum value of this parameter, $x_A = 1$, while an area without any land modifying is $x_A = 0$. Applying x_A to equation 3 for y_A:

$$y_A = e^{-\frac{\left|\left({x_A}^{0,55}\right)^{3,5}\right|}{2 \times 0{,}45^{3,5}}} \qquad [\,] \qquad (4)$$

Where y_A is the perforation contribution of the parameter x_A, being x_A the average HFI_{mod} scaled [0,1] in a context area. As such, the perforation contribution combines the general model of perforation and dissection contribution of Forman (1995, p. 409) and the weight of different land cover modifying pressures captured by the HFI. In this way, the different pressure values proposed by Venter et al. (2016b) are preserved, meaning that not only the absence of habitat is included, but also the type of modification is taken into account. The resulting curve is shown in Figure 52.

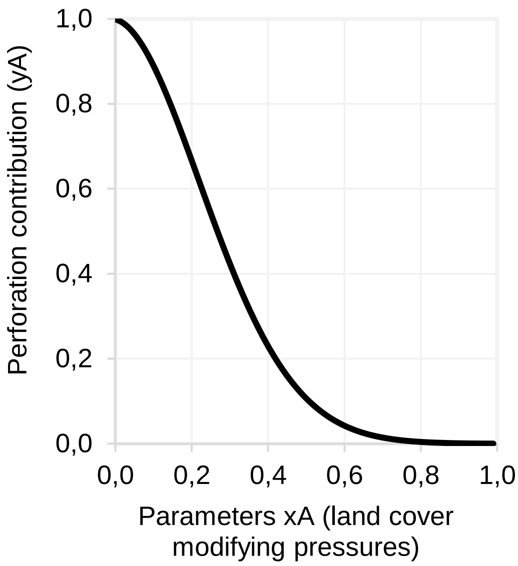


Figure 52 Land cover modifying parameter x_A relationship to the perforation contribution y_A.

Land cover non-modifying parameters contributions

Navigable waterways, population density, and nightlights were categorized into the non-modifying pressures category. Road and rails physically modify the land cover structures, but in the HFI maps, they overlap other land covers and pressures because of the HFI resolution and the indirect effects of roads. Therefore, these two pressures will also be categorized as land cover non-modifying pressures. For the avoidance of doubt, the categorization of the railways and direct effect of roads as non-modifying pressure is solely due to the 1 km resolution of the input maps.

The maximum value for the pressures of roads, rails, navigable waterways, population density, and nightlights, or $HFI_{non\text{-}mod}$, is 40 and was scaled from 0 to 1 (x_B). A context area with the highest $HFI_{non\text{-}mod}$ of 40, is $x_B = 1$, while the absence of non-modifying is $x_B = 0$.

The contribution of the $HFI_{non-mod}$ to perforation will be translated as a linear relationship using the cumulative values of the individual HFI pressures. The justification is the HFI itself since higher HFI values indicate higher pressures. In other words, a land use surrounded by an area where there is little or no land cover non-modifying pressures is potentially more damaging to biodiversity. The linear relationship between x_B and y_B is shown in Figure 53.

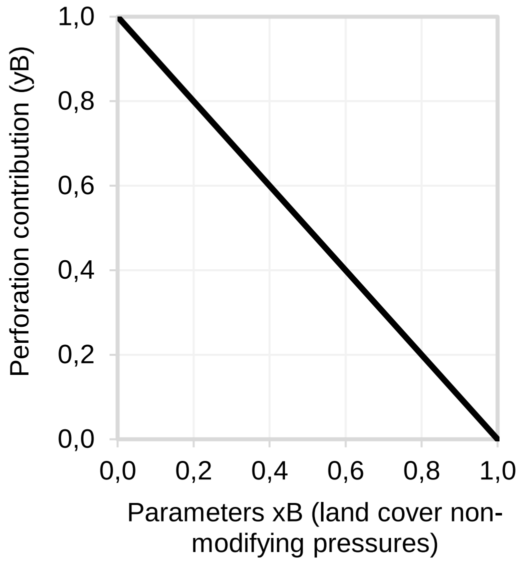


Figure 53 Land cover non-modifying parameter x_B relationship to the perforation contribution y_B.

The equation of the linear relationship between x_B and y_B is simply

$$y_B = -x_B + 1 \qquad [\,] \qquad (5)$$

Where y_B is the perforation contribution of the scaled land non-modifying pressures, x_B.

Perforation Potential

This thesis transfers the concept of perforation from a landscape ecology perspective to a land use perspective. The goal is to identify land uses that take place in remote areas without the use of strict hard borders of wilderness or intact areas and without the need for defining habitats or ideal land covers.

Here, the Perforation Potential is defined as a continuous scale from 0 to 1. A Perforation Potential of 0 indicates that the neighboring area of the land use is subjected to human pressures meaning that the land use does not perforate its surroundings. A Perforation Potential of 1 indicates that the land use's context area is under very little human pressure and has the maximum potential to perforate.

To characterize a high perforation scenario, pressures that modify the land cover and pressures that do not modify the land cover must be absent or low. The two contributions y_A and y_B are combined using the method proposed by Lindner (2016). The author suggested that when both parameters are needed, their relationship is characterized by an AND operator, see Figure 14 on page 36.

Following equation 2, multiplying of y_A (equation 4) and y_B (equation 5) results in the Perforation Potential y_{AB}:

$$y_{AB}(x_A, x_B) = \left(e^{-\frac{\left|\left(x_A^{0,55}\right)^{3,5}\right|}{2 \times 0,45^{3,5}}} \right) \cdot (-x_B + 1) \qquad [\,] \qquad (6)$$

Where x_A and x_B, are respectively, the average values of HFI_{mod} and $HFI_{non\text{-}mod}$ scaled [0,1] in a land use context area, and y_{AB} is the Perforation Potential of the land use. The Perforation Potential is graphically represented in Figure 54.

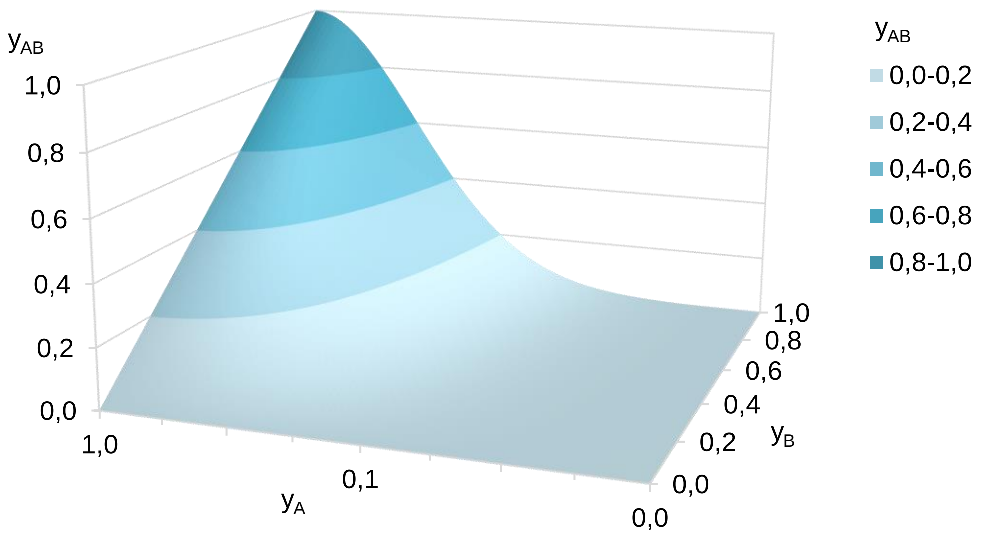


Figure 54 Relationship of land modifying (y_A) and non-modifying (y_B) contributions' relationship to the Perforation Potential (y_{AB}).

In summary, in order to convert the HFI to Perforation Potential, the land modifying and non-modifying pressures, HFI_{mod} and $HFI_{non\text{-}mod}$, were scaled from 0 to 1, resulting in the parameters x_A and x_B, and converted into the contribution y_A and y_B. The y_A and y_B values are multiplied, resulting in the Perforation Potential (y_{AB}). A schematic representation of the steps leading to the Perforation Potential is shown in Figure 55.

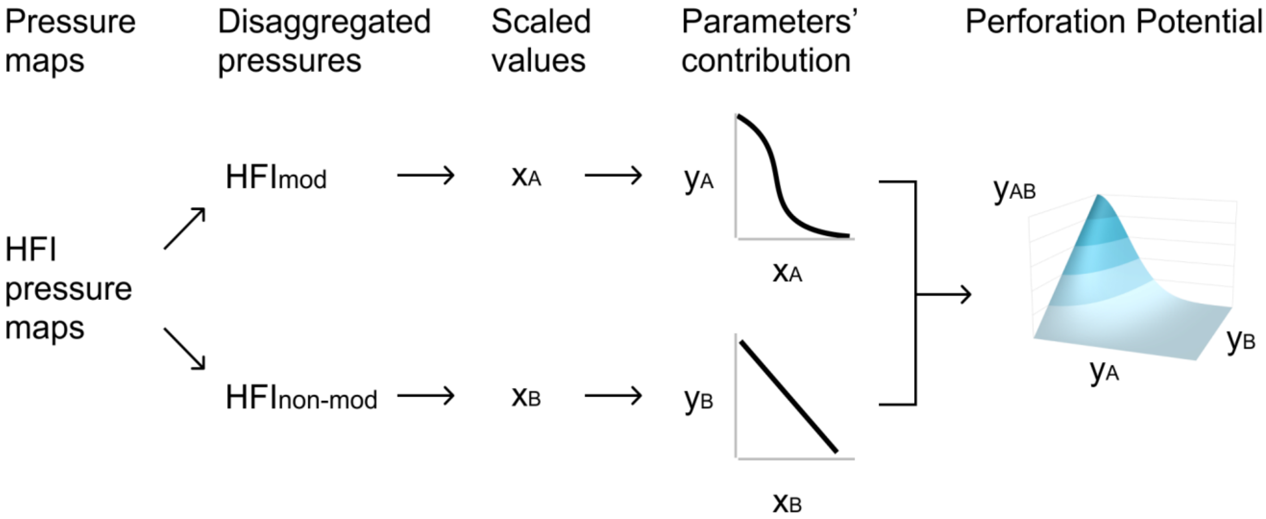


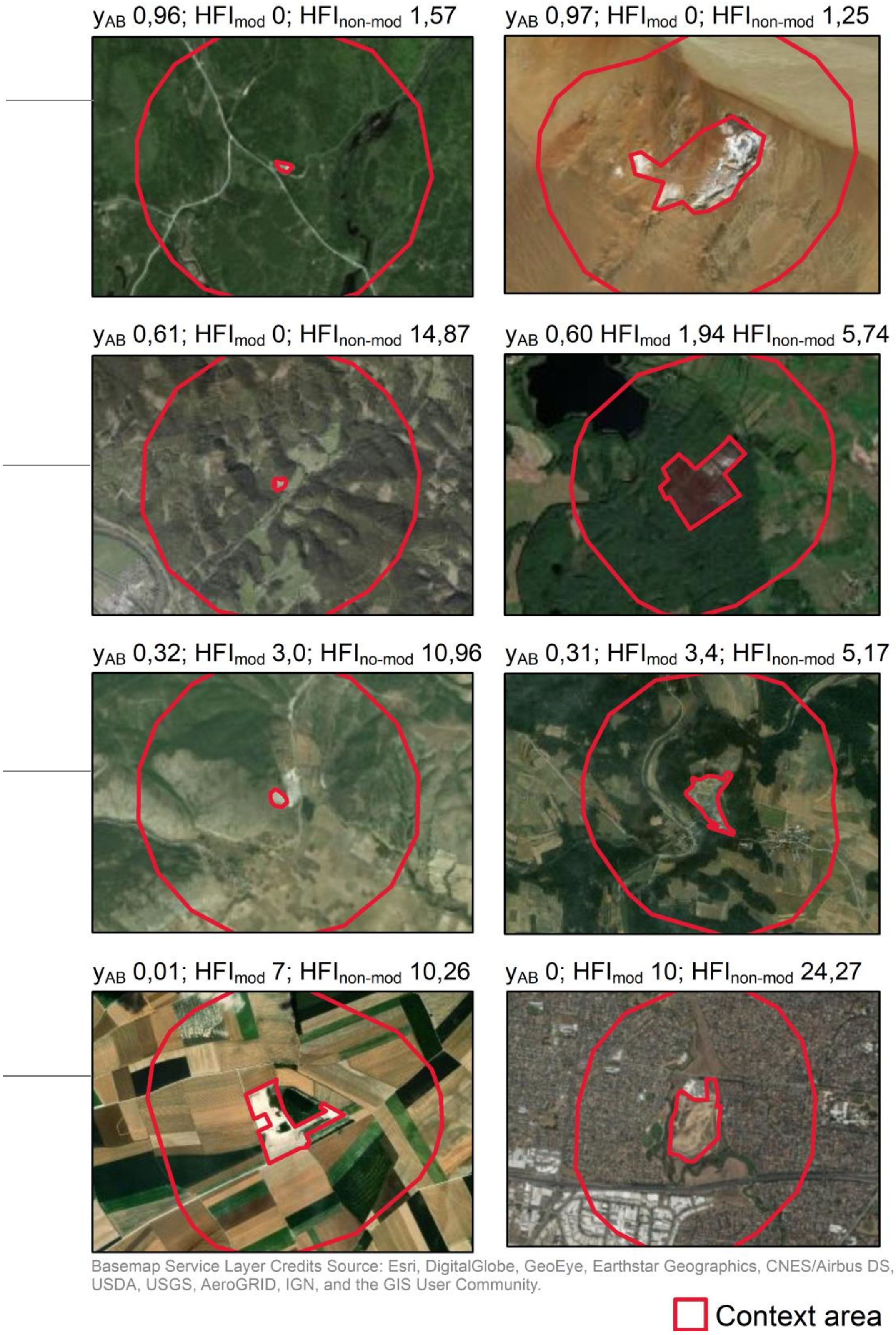
Figure 55 Schematic representation of the steps leading to the Perforation Potential.

It is important to note that the original method of Lindner (2016) uses the potential contribution to biodiversity, while here, the method proposed by Lindner (2016) is used to construct a perforation potential, which is one element causing impact to biodiversity. In other words, higher Perforation Potential indicates more damage to biodiversity.

To provide an example of the Perforation Potential, the HFI disaggregated maps, HFI_{mod} and $HFI_{non\text{-}mod}$ were created in ArcGIS, the average values calculated for quarries and mines using zonal statistics tool with a cell size of 50 m, converted into y_A and y_B, and the y_{AB} values calculated. Examples of different Perforation Potentials are presented in Table 7. High y_{AB} are found in context areas with minimal human pressures in the surrounding, and low y_{AB} are found in context areas surrounded by existing human pressures. Two mining sites of similar y_{AB}, one surrounded by forest cover and one by mountainous bareland, were intentionally selected to demonstrate that the Perforation Potential is independent of the type of ecosystems.

Table 7 Perforation Potential (y_{AB}) scale with examples of quarries and mines' context areas. Where HFI_{mod} ranges from 0 to 10 and $HFI_{non\text{-}mod}$ ranges from 0 to 40.

Perforation Potential (y_{AB})
1,00
0,95
0,90
0,85
0,80
0,75
0,70
0,65
0,60
0,55
0,50
0,45
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00



The Perforation Potential applied to all context areas of quarries and mines is presented as a map in Figure 56. By using HFI, it is possible to characterize every individual land use site, here quarries and mines, in relation to the amount of human pressures in its surroundings. The Perforation Potential brings the concept of perforation to a land use perspective worldwide without the use of hard borders to define ecoregions or the need to determine an ideal or natural land cover type.

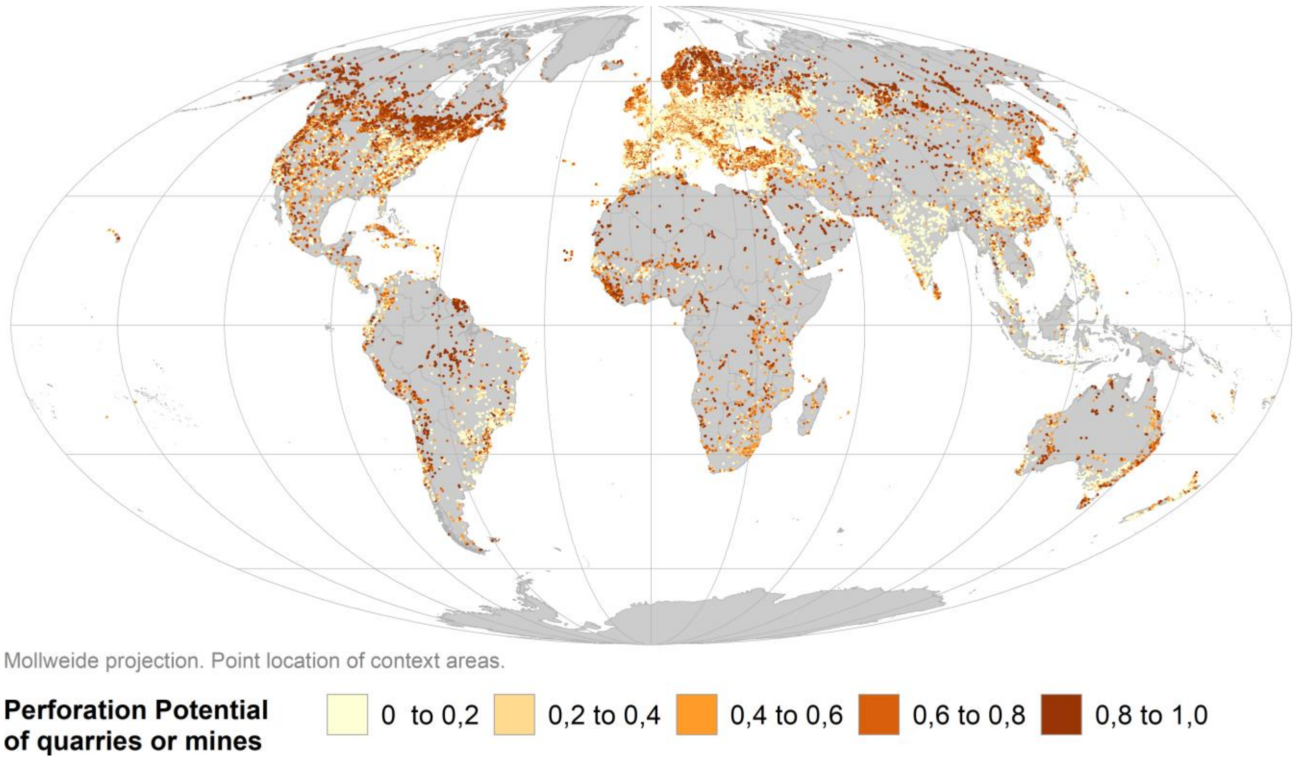


Figure 56 Map of the Perforation Potential applied to quarries or mines.

5.2.4 Discussion on modeling choices

LCA is a tool with the ambitious aim of describing all relevant environmental impacts associated with a product or service. In trying to describe the consequences of any anthropogenic activity, the real world is simplified in a tangible way so decisions can be made.

The focus of this thesis is to provide a method to describe if a land use activity may affect areas of potential value for biodiversity due to its remoteness or lack of human pressures. The method was developed independently from ecoregions borders, used a land use map, a buffer distance from this land use, and a map of cumulative pressures representing the environmental quality. A conversion between the environmental quality indicator and a Perforation Potential was suggested. Also, a valuation step was carried out for forest biomes. These modeling choices are the focus of this subsection.

Development of the Perforation Potential independently of ecoregions

The ecoregion border definition was identified to be the reason why some quarries or mines had a low HFI and low vegetation cover, particularly in group b of the valuation step. The topic merits more detailed clarification because ecoregions have often been used in previous methods to assess biodiversity in LCA.

Visual inspection of sites in group b with the aid of ELU map revealed that some of the context areas were mapped as sparsely vegetated by the ELU and the absence of tree cover seemed to be natural. The assumption that this sparse vegetation was a natural cover is supported by the quarry or mine being located near the border of a non-forest biome, and because the sparse vegetation in the context area was the same as the neighboring non-forest biome. In these cases, it is reasonable to attribute the unexpected low HFI and low vegetation cover to the ecoregion border definition. In such cases, the classification of biomes and ecoregions, although consistent with LCA (Koellner et al. 2013b), proved to be too coarse for the LCIA method proposed in this thesis.

Despite the efforts and advancement in regionalization, it is still unrealistic to expect that specific information about the location of every product location will be available for an LCA in the near future. Ecoregions' borders can be useful for the applicability of the LCIA, even if their quality is dependent on underlying data. However, the use of ecoregion for the construction of the impact methods itself may lead to the misleading characterization of the environmental impact for cases of incoherence found in the valuation step and mentioned in this subsection.

Land use

The land use maps used in this thesis, like any map, are a spatial representation of features in the real world. Spatial data have several sources of uncertainty. These uncertainties can be derived from for example an incomplete dataset (e.g., not all existing quarries and mines have been captured by the dataset), they can be subjected to mistakes (e.g., an incorrectly captured quarry), there can be issues with the temporal correlation when comparing two datasets. For data captured by different observers as is the case for the OSM, the data present location bias and definition discrepancies (e.g., if a mine is captured by the visual extend by one observer, or by the location of the mining company land ownership by another). Spatial data is also subjected to a mismatch in representation, which occurs, for example, in capturing a cropland area as a raster cell and is evident when different resolutions are compared, e.g., when comparing cropland data for GlobleLand 30 and that used as input to the HFI.

The valuation and verification steps leading to the creation of the relationship of the HFI to the Perforation Potential were carried out for quarries and mines, but the Perforation Potential is applicable to any land use type. The use of the developed Perforation Potential to other land use types is justified because the method for the creation of the context areas, by definition, does not include the land use itself. For land uses with large continuous extents, such as cropland, the results can be useful to indicate that the land use borders areas with a lower human footprint, potentially indicating encroachment of the land use in remote areas rather than perforation itself.

Buffer distance

The creation of context areas was defined as an equal distance buffer from the borders of the land use. A fixed distance of 1 km was not chosen arbitrarily but based on the concept of effect zones. The road ecology and conservation literature describe that most effects of human activities are within 1 km of its borders.

If adequately justified, smaller or larger buffer areas can be applied as a form of assessing the sensitivity of the buffer distance. The underlying HFI map can be resampled to a smaller cell size as it was done in the case of quarries and mines. For the input maps of other land uses used in this thesis (raster data with a resolution of 1 km), a smaller buffer size would lead to the same result, as resampling does not increase the level of detail of the underlying data.

A buffer of greater distances could be used if justified, but its implication must be observed. Take the case of a land use in a remote area of the Peruvian Amazonia.

In this case, an increased buffer distance would most likely lead to the same or very similar Perforation Potential. However, take a second case, of a building, surrounded by cropland in the 1 km buffer, and further surrounded by natural, non-used forest. In this case, a context area created with a 2 km buffer, would result in a higher Perforation Potential than when using a 1 km buffer, but it is questionable if the results of the larger context area are meaningful. From a land use perspective, in this example, the impact of a potential perforation to the natural forest should be attributed to the land use *cropland* since it is the land use adjacent to the forest as opposed to the building.

A fixed distance buffer is suggested in this thesis, but it can be questionable if varying distances according to the size of the land use could be used. Despite the understanding that a land use of large extents can be more harmful to biodiversity, the land use area size and its intensity are not part of the context, and by definition, they shall not be part of the context area. Take an example of the surrounding of a house for which its *context area* is the area that is within a specified “distance beyond its fence”. Since the context area is determined to be a distance beyond its fence, this distance is the same regardless of the size of the house. A bigger house would have a fence of greater length, and consequently, a larger context area, but its context is within the same distance from its fence. In short, the context area is delineated independently of parameters that refer to the land use itself except for its spatial boundaries, so the buffer distance should not vary with the land use size.

Remoteness

The definition of remoteness, or which areas can be considered remote, wilderness, or intact, is binary in conservation literature: an area is either remote or not. As the objective of this thesis is to quantify and allow comparison of different land uses, a strict definition of wilderness areas is very restrictive and would lead to nearly no land use to be identified as affecting wilderness. Hence, the justification of a continuous spectrum of remoteness.

The HFI has been used to demonstrate the level of human influence in the surrounding of a context area. This cumulative index for human pressures, the HFI, has been classified by its authors (Venter et al. 2016b) according to the level of human pressures. The authors categorized the pressure level using a quantile classification, and no further justification is provided. The quantile classification is problematic, as in the case of future increases in human pressures in an area of no human pressures, a recalculation of the HFI would result in higher HFI values, leading the pressure frames to be shifted towards higher values. In addition to the problem of the definition of the pressure classes of Venter et al. (2016b), using only the no and low pressure classes as an indicator of remoteness was also considered to be too restrictive for the purpose of this thesis.

Conversion to Perforation Potential

The conversion of the HFI into a Perforation Potential is fundamental for its inclusion in LCA. The simplest way of making the conversion would be a direct conversion from the HFI to a Perforation Potential. Using such a simplistic approach would mean that a context area surrounded by intensive cropland (HFI of 8) in the absence of any other pressure could be evaluated as having the same Perforation Potential as an area surrounded by native vegetation, with pressures from population density in the region and nightlights (adding to HFI equal 8). Despite the latter not characterizing a perfectly remote scenario, it is certainly arguable that both scenarios should not be evaluated as equal in terms of their disturbances to the surrounding biodiversity.

In order to capture the differences within the HFI, the index was disaggregated into pressures that modify and that do not modify the land cover. To apply this disaggregation, two maps representing HFI_{mod} and $HFI_{non\text{-}mod}$ have to be created in GIS. This choice adds one more GIS step, as opposed to the calculation of the zonal statistics of the HFI provided by Venter et al. (2016b).

The HFI_{mod} and $HFI_{non\text{-}mod}$ are scaled from 0 to 1, which is done by dividing the value of the modifying pressures and the non-modifying pressures by its maximum possible value, 10 and 40, respectively. It can be questioned whether this scaling should be done in terms of the maximum possible value or by the maximum measured value calculated for each land use type. The justification for using the maximum possible value is backed by the conceptual basis of the method proposed, in which the context is assessed independently of the land use area itself. Additionally, the purpose of the method is to be applicable to LCA, and varying the scaling range would be undesirable.

In this thesis, the relationship between the land-modifying parameters is derived from landscape ecology. The relationship was based on the general model of landscape process contribution proposed by Forman (1995, p. 409), Figure 9 on page 20, and its translation to an equation was based on the intermediate values for immediate and resilient negative contribution curves provided by Lindner (2016). The constants for an intermediate curve were adjusted to better represent the curve proposed by Forman (1995). Such approximation can open the discussion of the consequences of shifting the curve along the 'x' axis or increasing or decreasing its steepness. The implication of such variations has not been calculated in this thesis, as the overall conclusion of shifting the curve can be obtained without calculations, e.g., shifting the curve to the right would result in areas with higher values of modifying pressures to have a higher potential to perforate, and shifting the curve to the left gives the opposite result. An equation governing a curve to approximate the curve of perforation and dissection contributions suggested by Forman (1995, p. 409) can be obtained by a variety of combinations of the constants of the equation 1, resulting in a curve of similar shape, but it is not possible to test or prove which alternative is factually more accurate.

For the land cover non-modifying parameters, in this thesis, a linear relationship is proposed. The linearity between the non-modifying parameter and the contribution to perforation gives equal value to all pressures of that type. The equal value between pressures was used by Venter et al. (2016b) in the cumulative index HFI and is the justification for the linear relationship in the absence of a more refined relationship.

Valuation step

In this thesis, habitat and species-specific data were not used to represent perforation and dissection due to the lack of availability. As an alternative, the Human Footprint Index was used as an indicator of environmental quality regarding remoteness and converted into a Perforation Potential. This conversion required intermediate steps. A scale indicating spatial resemblance to a perforation pattern was applied to selected sites on forest biomes. This step could also have been applied to other biomes if habitat or the ideal land cover extent could have been confidently defined.

The valuation step, applied for quarries and mines in forest biomes, provided the knowledge and understanding leading to the creation of the Perforation Potential, but the Perforation Potential is independent of biomes or ecosystems types. The applicability of the Perforation Potential to any biome or ecosystem was shown in one example of Table 7 in which high Perforation Potential was observed in a land use surrounded by forest and another by natural bareland.

The valuation step was carried out for forest biomes through visual inspection of aerial images and other supporting maps. Other valuation techniques can be applied, such as the use of specialized software tools that calculate the level of fragmentation in an area. In the case of forest biomes, such tools could have been applied using forest cover as habitat indicator. The visual inspection carried out in the valuation step allowed the identification of areas that despite the lack of forest cover and being on forest biomes, presented natural sparse vegetation and therefore given a high valuation score. This insight was gained because visual inspections were carried out and would be unnoticed if the assessment had been carried out simply by software packages calculating the forest fragmentation on the context areas.

5.3 Integration with LCIA methods for land use and biodiversity

The environmental problem of land use in a remote area is one aspect of human activities that impact biodiversity and can be relevant to decision making on management practices. As an illustration of this application, take the example of a house in two scenarios, one surrounded by intensive cropland, roads, and nightlights (no-perforation), and one in a remote location (high-perforation). In both cases, the land use is the same. However, specific practices, or the so-called management parameter, could be more relevant depending on the scenario. For a household, one management parameter can be, for example, “the ownership or feeding of domesticated cats”. In the no-perforation scenario, a domesticated cat may not be a problem to species of conservation value because the surrounding is a highly modified environment. While for the high-perforation scenario, a house in the remote area, the ownership of cats can have an impact on biodiversity as those pets potentially feed on native birds or spread diseases to species of conservation concern. This example shows the value of including a Perforation Potential in LCA.

In this thesis, the method to identify remote areas was developed independently of other aspects, such as the valuation of ecosystems. Therefore, the Perforation Potential should be used in combination with other methods assessing the impacts of land use in order to provide meaningful support to decision making. Three approaches to the integration of the Perforation Potential with other life cycle impact assessment methods have been identified: as an independent category, as a modifier to the quality axis, and as a context parameter.

The simplest way to include this method in LCA is as an *independent impact category* side by side with another biodiversity impact category that assesses and evaluates the land use in terms of the land use itself, its location and intensity.

Another approach is to use the Perforation Potential *as a modifier* to the LCA's land use quality axis, incorporating it as an additional penalty for impacts occurring in remote areas. To use the method in this way, the units of the impact assessment method must be consistent and coherent with the use of a Perforation Potential. The method developed in this thesis, at least theoretically, can be used in combination with methods that assess biodiversity in terms of naturalness. The naturalness or hemeroby can be used as a measurement of the contrast of the intervention and the natural environment and the Perforation Potential as a modifier of that impact, giving a higher impact for high perforation scenarios.

A third option for the inclusion of the Perforation Potential in biodiversity assessment is through its use as a *context parameter* in the biodiversity contribution method proposed by Lindner (2016). The author defines that a context parameter modifies the management parameter. At least conceptually, Perforation Potential could be included as a context parameter. The result would allow different management practices to be suggested depending on the pressures surrounding a land use.

The next chapter is a practical example of an LCA of steel production where the integration of these three options will be explored.

6 Practical example: steel production

This section is a practical example of how to use the Perforation Potential in LCA. It will provide an understanding of the contribution that the developed method brings to LCA. The preference was given to a simple system and a stand-alone product which has its inputs sourced from different locations.

6.1 Goal and Scope

The selected product was steel and the goal of the assessment is to identify the potential perforation impacts of the mining necessary for the production process of steel in its supply chain. The scope of this example is cradle to gate, meaning it includes the extraction of raw material and processing.

The LCA method applied is the accounting type (also known as attributional) for which inputs and outputs are ascribed to the functional unit of a product by relating it to the unit process using average data. The steel is modeled as 1 t of steel in Germany. The analysis will be carried out for steel from iron ore, as opposed to steel from scrap metal. The functional unit is defined as “1 t of steel from iron ore, in Germany, at the production plant”. In this example, only the perforation impact is considered, no other environmental impact categories are analyzed. Land use transformation is not considered, for example, the case of a mining site expansion resulting in the conversion of native vegetation cover into a mining site.

Steel can be used in many applications, such as automotive, mechanical equipment, but its largest market is building and infrastructure (World Steel Association 2019). To understand what the functional unit could be used for in the construction industry, a steel beam will be used for illustration purposes. A steel beam type HEA 320, of 1 m weighs approximately 100 kg/m (Masteel UK Limited 2019). The dimensions of a cross section of such beam are: 310 mm section depth; 300 mm section width; 9 mm web (the thickness of the connecting vertical middle part) and 15,5 mm flange (the upper and lower horizontal part of the beam). A schematic drawing of an H-shaped HEA 320 beam is presented in Figure 57. Therefore 1 t of steel, in this case study, is roughly equivalent to ten H-shaped HEA 320 beam of 1 m.

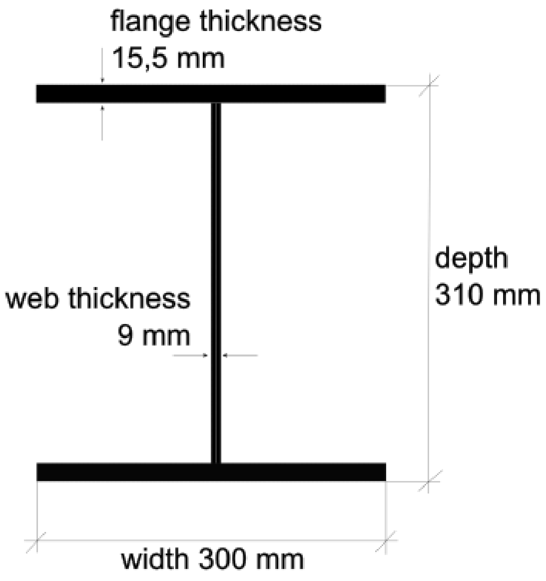


Figure 57 Cross-section of an H-shaped HEA 320 beam.

6.2 Inventory

The main inputs of steel production using a blast furnace are iron ore and pellets together with coke. Coke is produced from hard coal, also called metallurgical coal. An already existing process for the production of steel was obtained from the GaBi dataset (thinkstep AG 2019). For the German steel production, iron ore and pellets' inputs proportions are 50 % from Canada, 25 % from Brazil, and 25 % from Australia (thinkstep AG 2019). Steelmaking coal in Germany is sourced from Canada (thinkstep AG 2019). For this case study, steel was assumed to have an iron content of 95 %. Around 0.77 t of coal is required to make 0,6 t of coking coal, which is required to the production of 1 t of steel (Critical Raw Materials Alliance 2018).

For simplification purposes, rail and road transportation is not included in this case study. Since Perforation Potential is only valid for terrestrial biomes, maritime transport of the input materials to Germany is also not included. A flow chart is presented in Figure 58.

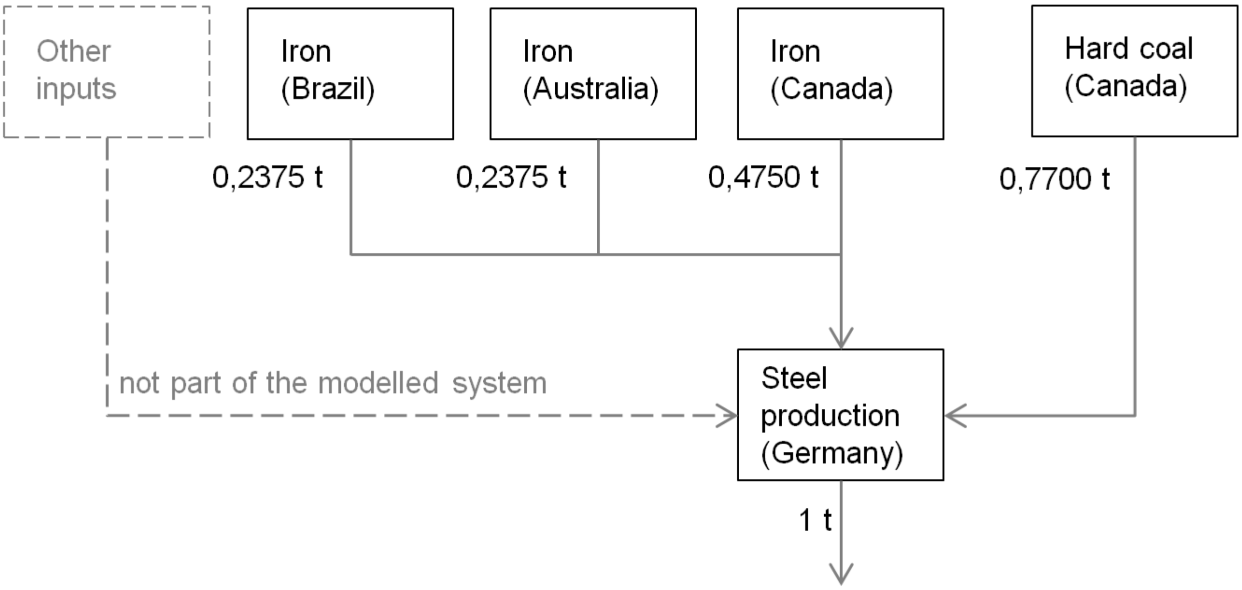


Figure 58 Flow chart of steel production (95 % iron content in the steel).

6.2.1 Extraction sites in each country

The Brazilian iron ore is sourced from two iron ore mining regions, one in the South East and one in the North region of Brazil. The South East mining region is called the “Iron Quadrangle” in the State of Minas Gerais, which is an area that produces various minerals. For this region, the active ferrous mines were located through the Mineral Resources Map of the Minas Gerais State (da Silva and Augusto 2014). For the North region, iron ore is extracted in the Carajás mine in the State of Pará (Gadelha 2019). Carajás is the example mine previously shown in Figure 25.

In Australia, iron ore is mostly extracted in Western Australia, specifically the Hamersley Province in the Pilbara region (Government of Western Australia 2018). The mapped mines in OSM in this region were selected and confirmation regarding the extracted commodity was obtained using information from OSM (2018), environmental agency (EPA 2019), and mineral databases (Hudson Institute of Mineralogy 2019).

In Canada, 95 % of the iron ore is mined in the provinces of Labrador and Quebec (Government of Canada 2018), the locations of the mines were identified using a mineral resources map (Government of Canada 2017). In 2017, 95 % of Canada’s steelmaking coal was extracted in British Columbia (Coal Association of Canada 2019), the location of the mines were also found using a mineral resource map (Government of Canada 2017).

A world map showing the mining regions of the commodities used as input in this case study is shown in Figure 59. Specific location maps of the mining sites are presented in Appendix D.

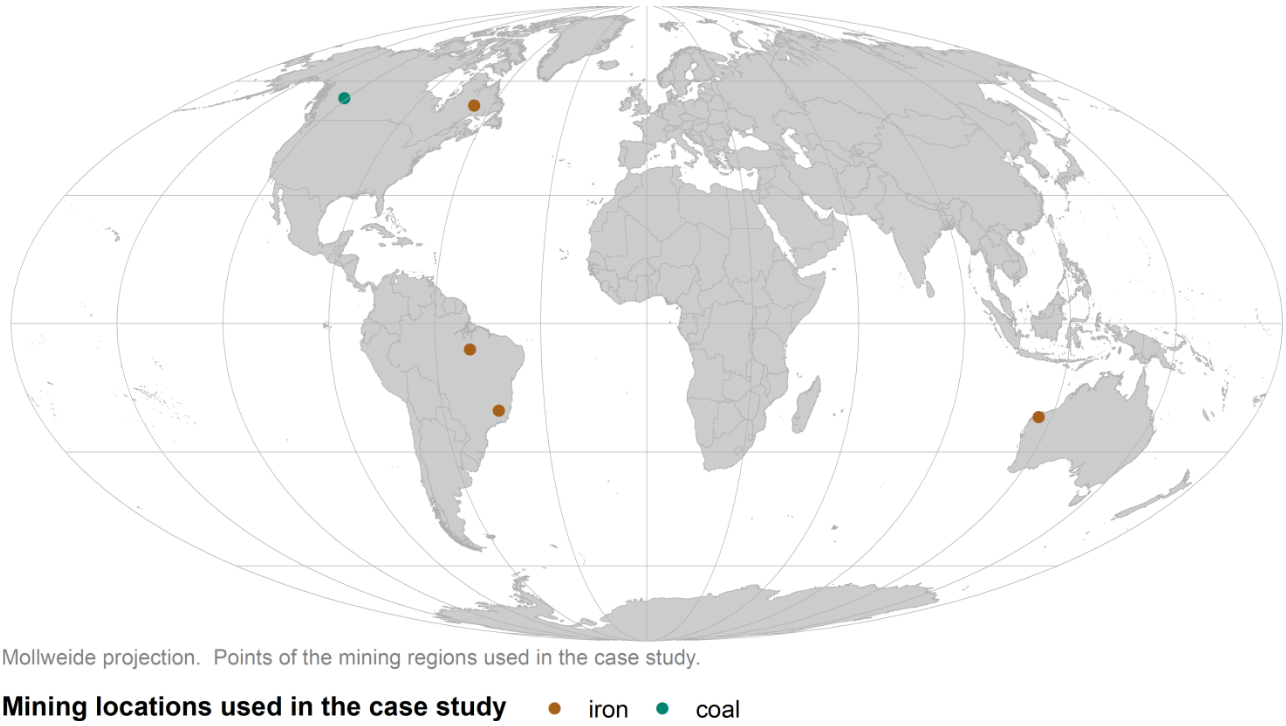


Figure 59 World map showing the general location of mining sites for this case study.

6.2.2 Inventory calculations

The mines were selected from OSM quarries according to the mining datasets described in the previous section. All relevant mines had been captured in the OSM dataset, except for some metallurgical coal and iron ore from Canada. In this case, the mines were located using the geographical coordinates from the resources map from the Government of Canada (2017) and their extent captured according to the approximated extent of the visible mined area using the imagery layer base map available in ArcGIS. The areas of the mines were calculated in ArcGIS using the equal-area projection Mollweide.

Iron ore has highly variable Fe-contents of iron carbonates and iron oxides. The production data was available per country in the World Mining Data report (Federal

Ministry of Sustainability and Tourism, BMNT 2018). The report provides “the content of recoverable valuable elements and compounds” and the data for iron was provided in relation to the Fe-content.

The national production of metallurgical coal or iron was divided by the total area of mines to obtain the annual area required for the production of each commodity. The values are shown in Table 8, and the results of the area requirement are shown in Figure 60, using a three-letter country code: Canada (CAN), Australia (AUS), Brazil (BRA).

Table 8 Iron and metallurgical coal mining areas and their annual production. Annual production data from the Federal Ministry of Sustainability and Tourism, BMNT (2018).

Commodity	Mined area (A_{mined}) [km²]	Annual production (prod) [t]	Area demand [m²/t]
coal, CAN	130	25960000	4,99
iron, AUS	265	531075350	0,50
iron, BRA	218	271275900	0,80
iron, CAN	86	25941900	3,30

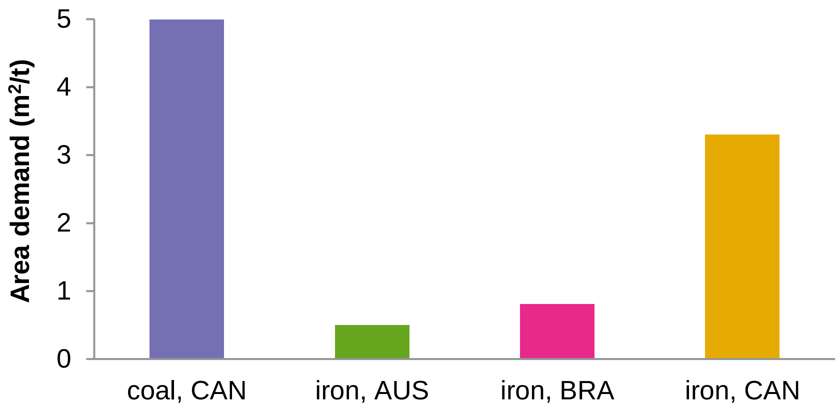


Figure 60 Metallurgical coal and iron ore area demand.

Coal and iron ore mining in Canada presented the highest area demand per ton of commodity, while iron from Brazil and Australia presented similar area demand. The total Canadian iron ore mining area is roughly 35 % of that of Brazil or Australia, but the Canadian production of iron ore in Fe-content is about a tenth of the area mined in either Brazil or Australia, making the area demand to be much higher for iron extraction in Canada.

6.3 Impact assessment

Following the steps for the creation of the context areas presented in Chapter 5, there were a total of 54 mines' context areas relevant to this case study. Following the method proposed in this thesis, the mean HFI_{mod} and $HFI_{non\text{-}mod}$ for each context area were calculated using ArcGIS tool zonal statistics. The HFI for each context area was converted to Perforation Potential (y_{AB}), according to the steps detailed in section 5.2.3 Conversion to Perforation Potential, on page 81. Here the Perforation Potential will be called PP_i, where the index *i* represents an individual context area for iron or coal. The results of each mine site are presented in Appendix D, Table D 1, and summarized in Figure 61.

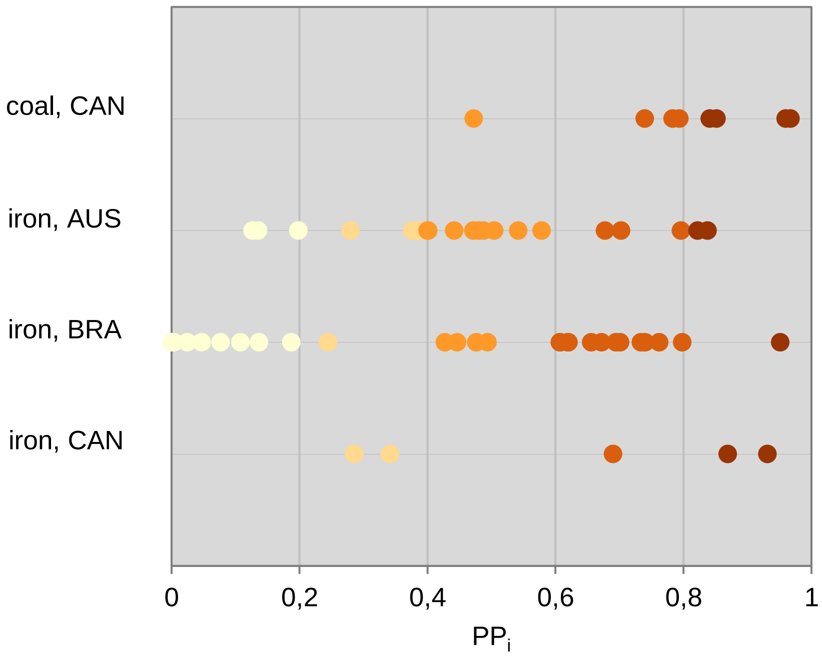


Figure 61 Visualization of PP_i for each context area for iron and coal.

The context areas vary in size, therefore for each commodity, a context area fraction ($CA_{fraction\ i}$) is calculated dividing the area of each context area (CA_i) by the total area of the context areas for each commodity in each country (CA_{tot}). The total context areas size measured in ArcGIS using Mollweide equal-area projection were: 219 km^2 for coal from Canada; 576 km^2 for iron from Australia, 517 km^2 for iron from Brazil, and 137 km^2 for iron from Canada.

$$CA_{fraction\ i} = \frac{CA_i}{CA_{tot}} \qquad [\,] \qquad (7)$$

The values $CA_{fraction\ i}$ are multiplied by their respective Perforation Potential (PP_i) to obtain a weighted contribution. The values of this multiplication are added for each commodity and country. The values are presented in Table 9 and Figure 62.

$$PP_{CA} = \sum CA_{\text{fraction i}} \cdot PP_i \qquad [\,] \qquad (8)$$

Table 9 Values of the total context area for each commodity per country and their calculated Perforation Potential (PP_{CA}).

Commodity	Total context area CA_{tot} [km^2]	PP_{CA}
coal, CAN	219	0,7776
iron, AUS	576	0,4682
iron, BRA	517	0,4503
iron, CAN	137	0,5564

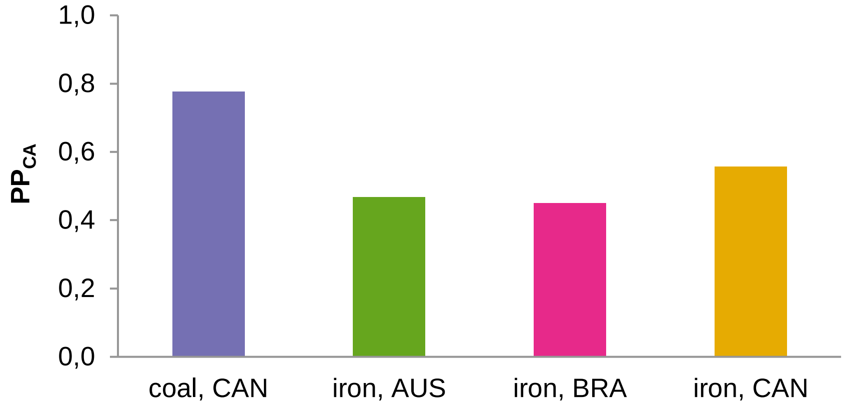


Figure 62 Perforation Potential of context areas of coal and iron ore.

The Perforation Potential has to be associated with a mining site ($PP_{mined\ area}$), and is obtained by dividing the context areas (PP_{CA}) by the inventoried mined area (A_{mined}) converted into m^2.

$$PP_{\text{mined area}} = \frac{PP_{CA}}{A_{\text{mined}}} \qquad [1/m^2] \qquad (9)$$

To associate the PP for each commodity, the $PP_{mined\ area}$ is divided by the area demand (A_{demand}). Area demand is the annual production (prod) divided by the mined area. The calculation of the PP is simply PP_{CA} divided by the annual production. The results for 1 t of each input is presented in Table 10 and in Figure 63.

$$PP = \frac{PP_{\text{mined area}}}{A_{\text{demand}}} = \frac{\frac{PP_{CA}}{A_{\text{mined}}}}{\frac{prod}{A_{\text{mined}}}} = \frac{PP_{CA}}{prod} \qquad [1/t] \qquad (10)$$

Table 10 Perforation Potential of 1 t of each steel input.

Commodity	Annual production (prod) [t]	PP_{CA}	PP per commodity [1/t]
coal, CAN	25960000	0,7776	$3{,}00 \cdot 10^{-08}$
iron, AUS	531075350	0,4682	$8{,}82 \cdot 10^{-10}$
iron, BRA	271275900	0,4503	$1{,}66 \cdot 10^{-09}$
iron, CAN	25941900	0,5564	$2{,}14 \cdot 10^{-08}$

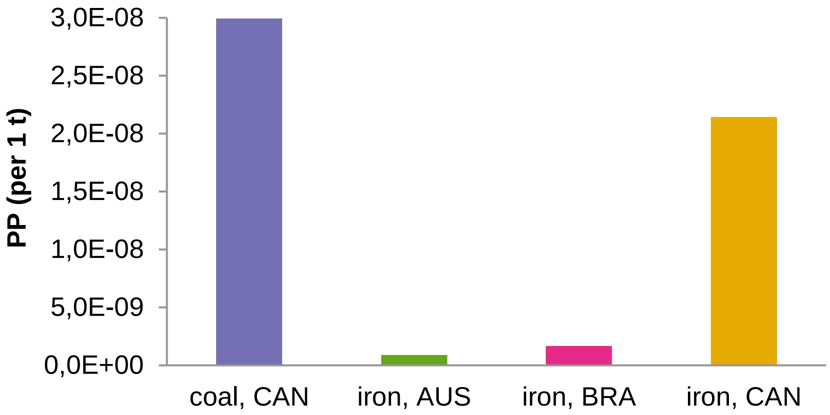


Figure 63 Perforation Potential for the production of 1 t of input.

Once the Perforation Potential has been calculated per commodity, those are multiplied by the functional unit's inputs required amount ($Input_{FU}$). The values of 0,77 t of metallurgical coal from Canada and 0,95 t of iron are used. As the iron production data per country is provided in terms of Fe-content, the proportions were applied directly: 50 % iron from Canada, 25 % from Australia, and 25 % from Brazil. The results are presented in Table 11 and as a contribution graph in Figure 64.

$$PP_{FU} = \sum Input_{FU} \cdot PP \qquad [\,] \qquad (11)$$

Table 11 Results of the calculation of the Perforation Potential per functional unit (PP_{FU}).

Commodity	$Input_{FU}$ [t]	PP per commodity [1/t]	PP_{FU}	PP_{FU} [%]
coal, CAN	0,77	$3,00 \cdot 10^{-08}$	$2,31 \cdot 10^{-08}$	68,13
iron, AUS	0,24	$8,82 \cdot 10^{-10}$	$2,09 \cdot 10^{-10}$	0,62
iron, BRA	0,24	$1,66 \cdot 10^{-09}$	$3,94 \cdot 10^{-10}$	1,16
iron, CAN	0,48	$2,14 \cdot 10^{-08}$	$1,02 \cdot 10^{-08}$	30,09
total			$3,39 \cdot 10^{-08}$	100,00

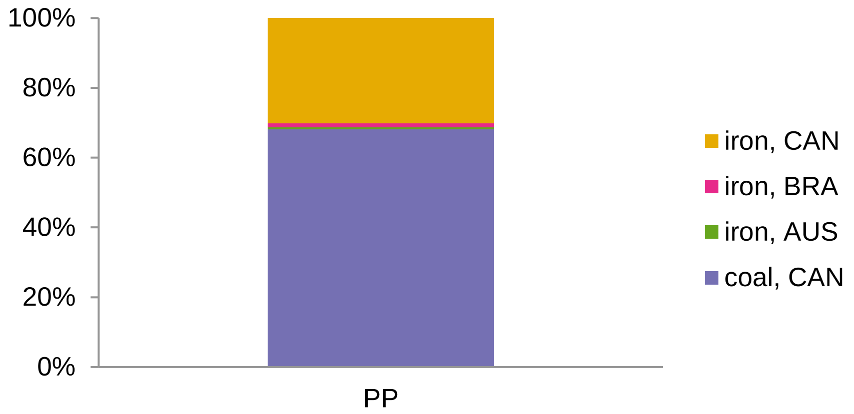


Figure 64 Contribution of the Perforation Potential per functional unit.

For this case study, coal mining in Canada is the input that contributes the most to Perforation Potential per each ton of steel. Iron from Australia and Brazil had only a minimal contribution to perforation for the investigated product system.

The iron ore from both Brazil and Australia represent a smaller share of the iron input with only 25 % each, have the lowest area demands (see Figure 60), and relatively similar overall Perforation Potential (see Figure 62) although a few individual context areas presented a high Perforation Potential (see Figure 61), resulting in a low contribution to the PP per functional unit. The Canadian iron, which accounts for 50 % of the iron in the product system, has a higher PP per ton of iron in comparison to iron from Brazil and Australia (Figure 63). For the metallurgical coal, its PP is high, meaning that the mined areas have low human pressures in its surroundings. As a result, the coal and iron from Canada are the mining activities that contribute the most to the Perforation Potential in the investigated product system.

6.4 Integration with other LCA methods

The method proposed in this thesis and applied in the case study in the previous section addresses the context aspect of a land use. It does not take into account the impact of the land occupation itself or any quantification or valuation of the region where the land use takes place. The method was designed to be used in combination with other impact assessment methods that can address other aspects related to biodiversity conservation. Three possibilities of inclusion of the Perforation Potential in LCA have been identified and are detailed in the following subsection.

6.4.1 Perforation Potential as an independent category

The case study of the steel is applied to the impact assessment method proposed by Chaudhary and Brooks (2018) to provide a practical example of the use of the Perforation Potential as a separate category. The ecoregion map (Olson et al. 2001) was overlaid on the 92 individual mines of iron and coal used in this case study. Ecoregion borders intersected some iron ore production sites in Brazil and Canada, i.e., one mining site is in more than one ecoregion. Respecting the ecoregion borders this intersection resulted in 104 mining sites. Maps of the individual mines are presented in Appendix D (Figure D 1 to D 6). The mined areas in each respective ecoregion were calculated using ArcGIS.

The sum of the mined areas was divided by the amount of iron or coal produced in each country. Data for specific mines' production was not collected, therefore the production data is related to the total mineral production in the country.

In the absence of a specific CF for mining operations in the method for assessing biodiversity footprint proposed by Chaudhary and Brooks (2018), CF for "taxa aggregated, urban intensive" in each ecoregion was multiplied by the area requirement per input and location, respecting the ecoregion differentiation (Table 12). The results of the Perforation Potential as an independent category are presented in Figure 65. The results of the impact assessment for the individual mines using the method proposed by Chaudhary and Brooks (2018) are shown in Appendix D, Table D 2.

Table 12 Summary results of the calculation of impact per functional unit (FU).

Commodity	Input per FU [t]	Biodiversity footprint per ton [PDF]	Biodiversity footprint per FU [PDF]
coal, Canada	0,77	$2{,}06 \cdot 10^{-13}$	$1{,}59 \cdot 10^{-13}$
iron, Australia	0,24	$2{,}49 \cdot 10^{-14}$	$5{,}97 \cdot 10^{-15}$
iron, Brazil	0,24	$6{,}54 \cdot 10^{-13}$	$1{,}57 \cdot 10^{-13}$
iron, Canada	0,48	$5{,}06 \cdot 10^{-14}$	$2{,}43 \cdot 10^{-14}$
total			$3{,}46 \cdot 10^{-13}$

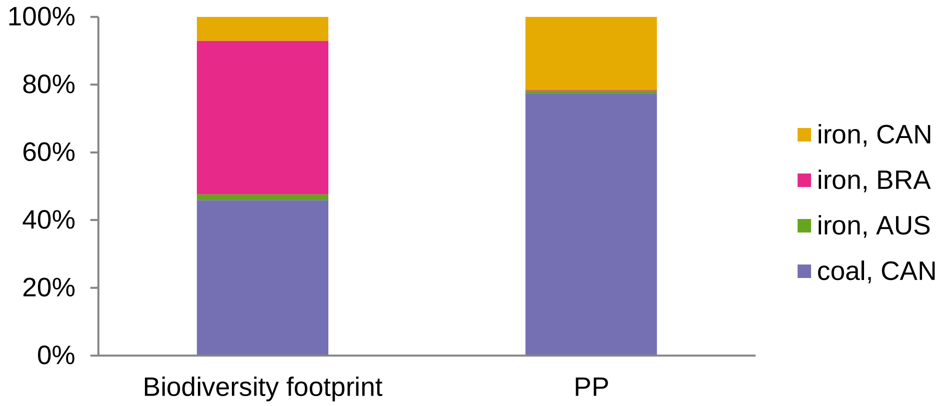


Figure 65 Contribution of the biodiversity footprint (Chaudhary and Brooks 2018) and Perforation Potential (PP) for the functional unit as two independent categories.

Results interpretation

The land use impact, calculated in terms of potentially disappeared fraction of species, is dominated by the coal mining activities in Canada and iron mining in Brazil, followed by iron mining in Canada, with Australia presenting a minimal contribution. Explicitly identifying that mining in Canada is the operation which occurs in most remote areas per unit of product is not possible by using the biodiversity footprint method of Chaudhary and Brooks (2018) alone.

The two independent categories represent different aspects of biodiversity. The land use impact method of Chaudhary and Brooks (2018) is used to indicate the impact of the land use itself. It is a measure of the decrease in the environmental quality caused by the land use in comparison to the reference state and includes a valuation of the biodiversity in each ecoregion. The Perforation Potential conveys a type of impact that is dependent on the surroundings but independent of other aspects such as land use type, ecoregion, or intensity.

By using the Perforation Potential as a separate category, it brings one more level of detail to decision makers. Using perforation as an additional category is simple, but gives no weight between the two categories. The advantage is that its simplicity and transparency gives the LCA commissioner more detailed information about its supply chain. More detailed information can allow targeted decisions in specific parts of the supply chain or suggest further investigation of improvement opportunities.

6.4.2 Perforation Potential as a modifier to an impact category

To use the Perforation Potential as a modifier to an impact category the units must be consistent. The Perforation Potential is an indicator of remoteness obtained through the quantification of human pressures. This indicator is conceptually coherent with LCIA methods assessing hemeroby, or naturalness, such as the DNP proposed by Fehrenbach et al. (2015).

The Perforation Potential is not an appropriate modifier for methods that measure the impacts of land use on biodiversity in terms of potential species extinctions such as the ones proposed by Chaudhary et al. (2015) or Chaudhary and Brooks (2018). This is because the units are inconsistent: a hypothetical mining operation with the Perforation Potential of 0,1 is expected to have less impact than another with Perforation Potential of 1, but these values do not directly translate into potential extinctions.

To use the Peroration Potential as a modifier to the DNP, the DNP is multiplied by the Perforation Potential resulting in a modified DNP (DNP_{mod}).

$$\mathrm{DNP_{mod}} = \mathrm{DNP} \cdot \mathrm{PP} \qquad [\,] \qquad (12)$$

All land uses in this case study are mining operations, considered to be the hemeroby class VII, having CF of 1 for the DNP proposed by Fehrenbach et al. (2015). In this case, the modified DNP results in identical values of the contribution assessment of land use demand. The intermediate calculation steps and the final results are presented in Table 13 and graphically in Figure 66.

Table 13 Calculation of the modified DNP.

Commodity	$Input_{FU}$ [t]	Area demand [m²/t]	Land use per FU [m²]	PP_{FU}	DNP per FU	DNP_{mod} per FU
coal, CAN	0,77	4,99	3,85	$2{,}31 \cdot 10^{-08}$	3,85	$8{,}87 \cdot 10^{-08}$
iron, AUS	0,24	0,50	0,12	$2{,}09 \cdot 10^{-10}$	0,12	$2{,}48 \cdot 10^{-11}$
iron, BRA	0,24	0,80	0,19	$3{,}94 \cdot 10^{-10}$	0,19	$7{,}53 \cdot 10^{-11}$
iron, CAN	0,48	3,30	1,57	$1{,}02 \cdot 10^{-08}$	1,57	$1{,}60 \cdot 10^{-08}$
total				$3{,}39 \cdot 10^{-08}$	5,72	$1{,}05 \cdot 10^{-07}$

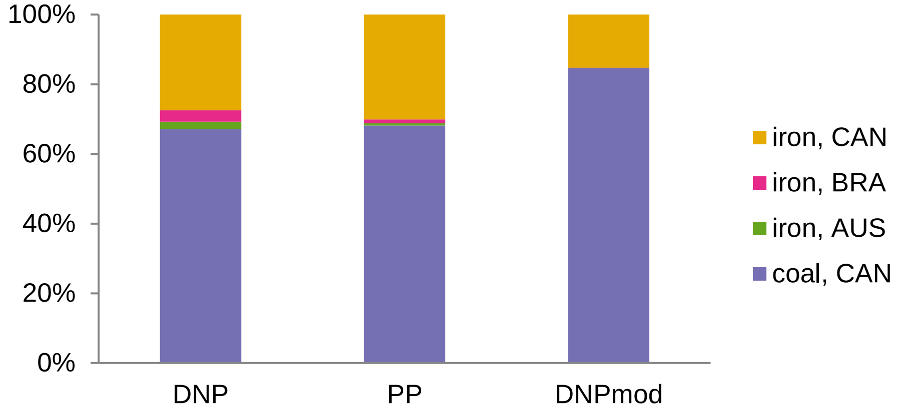


Figure 66 Contribution analysis for DNP, Perforation Potential, and modified DNP.

Results interpretation

The dominance of coal mining in Canada observed in both Perforation Potential and the DNP impact category is exacerbated in the modified DNP. This is because coal mining is the most area demanding process per functional unit. This same contribution is observed for the DNP since all land uses have the same distance from naturalness in this case study because all of them are mining operations.

The mining operations in Brazil and Australia do not appear in the contribution analysis of the modified DNP because of the low area demand of these processes and the input amount (0,24 t each as opposed to 0,47 t for iron ore from Canada and 0,77 t coal). The drawback with this approach is, the use of only Perforation Potential, DNP, or modified DNP does not provide any valuation of different biomes or ecoregions.

6.4.3 Perforation Potential as a modifier for a management parameter

A biodiversity contribution function for mining operations has to be defined in order for the method proposed by Lindner (2016) to be used. Such a function has not yet been established. The development of such a function requires dedicated research and is beyond the scope of this case study application.

Despite the unavailability of the biodiversity function, constraints to the inclusion of the Perforation Potential to the method proposed by Lindner (2016) can be discussed. A biodiverse area with high amounts of habitat may provide an influx of biodiversity to perforating areas. If the assessment is based on species richness on the land use patch, a land use surrounded by a remote area will be perceived as more desirable. This would result in a positive biodiversity contribution to be attributed to a potentially perforating land use. However, the higher biodiversity on the plot would be caused by the quality of its surroundings, rather than by the land use management practices of the land use.

7 Evaluation

In Chapter 4, on page 42, the requirements for the ideal method to assess biodiversity in LCA have been described. In this section, the proposed method is evaluated against these requirements.

Differentiation between land uses and land use intensities

The method developed in this thesis can be applied to different land uses. The calculation of the HFI in the context area of major land use types, mostly defined by distinct land covers was calculated: cropland, pastureland, urban areas, railways, roads, and quarries or mines. This exemplification demonstrates the method's applicability to different land uses. Other land uses can also be applied without any foreseeable constraints. The calculation of the Perforation Potential can also be applied to any land use type, using HFI disaggregated into HFI_{mod} and $HFI_{non\text{-}mod}$.

The model can be applied to any land use, including those of minimal area requirement per unit of product. The method was exemplified for road and railways, but it can also be applied to other uses such as transmission lines.

The differentiation of land use intensity has not been demonstrated. However, its inclusion can be achieved by a more refined distinction of the land use type. For example, instead of calculating the Perforation Potential to pastureland, the values can be calculated, for pastureland of low, medium, or high intensity, noting that intensity classes, or land use classes per se, are also not paramount to the application of the method.

The method differentiates the land use types through its spatial borders but does not give any weighting between land use types. This is incorporated through its combined use with other LCIA methods that already incorporate this aspect.

Spatial explicitness

The foundation of the model proposed in this thesis is the location perspective, hence fulfilling the spatial explicitness requirement. By using spatial data for the land use, the model characterizes the potential of a land use to contribute to perforation in its location. In that way, it does not generalize the land use type by any other factor such as grid, country, or ecoregion. Such generalizations can be applied for implementation purposes for the use in LCA software.

Ecosystems, ecoregions or biomes differentiation

The weighting of the ecosystem, ecoregion, or biomes has not been included in the proposed method. This choice was intentional and an integral part of the method for two reasons: to avoid double counting with other impact assessment methods and to allow the evaluation of the context to be explicit and independent.

In the case study for steel production, the method was applied as an independent category for the impact of land use side by side with a method that takes into account the type of land use as well as the valuation of ecoregions. Therefore, demonstrating that it is possible to use the method in combination with other impact assessment methods and differentiate between ecoregions or biomes and quantification of differences of the land use in the quality axis of the LCIA framework.

Global applicability

It is possible to apply the method worldwide fulfilling the global applicability requirement. The global applicability was demonstrated by the calculation of the HFI score in context areas of land uses for the entire globe. A limitation derives from the availability of land use data. In the case study, some mines had not been previously mapped by the OSM, but their locations were identified obtained through a bottom-up approach, i.e., by national datasets as opposed to a previously pre-mapped global dataset, and their spatial boundaries captured. Global applicability constraints can arise for land uses that have not been already globally consistently mapped.

Inclusion of the context

The method proposed in this thesis brings to LCA the ability to explicitly identify activities in remote areas. This method transfers landscape ecology concepts to LCA to allow the assessment to include a measure of the quality of the surroundings in the environmental profiling of products.

Overall evaluation

In summary, the method proposed in this thesis fulfills the requirements for the assessment of biodiversity in LCA presented in Chapter 4:

1. differentiate between land uses and land use intensities: the method developed in this thesis can differentiate between land uses. Land use intensities can be captured as a distinct land use type;
2. be spatially explicit, with the possibility of assessing any land use activity, including those of low land requirement per unit of product or service: the basis of the method is the location perspective, and applicability to major land use types has been demonstrated;
3. provide a valuation of different ecosystems, ecoregions, or biomes: the method does not provide a valuation of ecosystem, ecoregions, or biomes. In the method proposed in this thesis, perforation has the same value in all remote areas because the method was designed to be used in combination with other methods. Application in LCA in combination with another method that includes a valuation of ecoregions has been demonstrated;
4. be globally applicable: the method is globally applicable and has been applied to land uses worldwide; and
5. allow the inclusion of the context, together with a quality indicator for the surrounding landscape: the method's main focus is the incorporation of the spatial context of a land use activity. It quantifies the quality of the surrounding of a land use.

8 Synopsis

The wide variety of life forms and the preservation of biodiversity is the focus of several research fields. Human activities have altered terrestrial ecosystems for millennia, and the current dominance of humans in nearly all areas of the world is a significant concern for the preservation of biodiversity. Researchers have identified that not only the amount of natural habitat but also its configuration is essential to the conservation of biodiversity.

Life cycle assessment is a standardized tool that aims to support decision making from a product perspective, considering not only the impact of a product but of its entire supply chain. Its holistic approach also prevents burden shifting. Life cycle assessment can treat different environmental problems independently, and one environmental problem which has been the focus of a segment of the method developers is the impacts that land use can have on biodiversity.

The framework for the inclusion of the impacts of biodiversity in life cycle assessment established that a land-occupying activity may decrease the environmental quality of that land and also prevents it from reaching a higher, ideal, natural, or semi-natural state. Several approaches to measure this quality level have been proposed. The methods are based on biodiversity and conservation science, but often use a biodiversity measurement, such as species richness. Such approaches have inherent problems due to our limited knowledge of the variety of life, problems in species classification, and the inevitable valuation or weighting of species.

The modification of landscapes alter or destroy habitats, and can pose barriers to species movements. From that angle, landscape ecologists have studied the effects of what is called fragmentation, an umbrella term that refers to habitat modification processes and habitat patterns. Only one life cycle impact assessment method has proposed a quantitative spatial approach to the inclusion of landscape configuration, but the method was specifically designed for areas of low amounts of natural vegetation remaining, leaving a gap in the approaches to the assessment of land uses that take place in areas of high habitat amount. Such areas are subject to landscape fragmentation types known as perforation and dissection, which occur when a non-habitat patch is surrounded by habitat.

Wilderness or remote areas are relevant for biodiversity conservation from either an instrumental or intrinsic value point of view. Their preservation is the focus of pro-active conservation schemes. These schemes highlight the importance of preserving areas that have no or very little human influence. Given the lack of human influence, these areas would be characterized by high habitat amounts, hence subject to perforation and dissection if land use exists in those areas.

Life cycle assessment lacks a method which allows the explicit identification of land uses in remote areas, which can potentially contribute to perforation and dissection. Therefore the method proposed in this thesis aims at filling this research gap by assessing the quality of the surrounding of a land use taking into account: 1) a land use map, 2) a context area, and 3) the existence of habitats in the context area. Details of these three aspects are explained below:

1) Because *land use* is location bound, a map of the location of the land use is a requirement of the model proposed. The method was developed to be applied to any land use, be it those often used in life cycle assessment such as urban areas, cropland, and pasturelands, but also to land use types which have a relatively low land use requirement per unit of product such as mining sites, roads, and railways.
2) The concept of *context* is derived from landscape ecology, and is an area outside the study area, but excludes the area itself. Here, the study area is the land use area. The determination of the context of land use is derived from the literature and was fixed to 1 km. The scientific justification for the 1 km was based on two proactive conservation schemes.
3) One barrier for the assessment of perforation and dissection patterns in life cycle impact assessment is that habitats are species-specific. By being species-specific, the construction of a method to assess these configuration types would require data on all existing habitats. Instead of trying to approach it from a species habitat approach, the use of *human pressures* was proposed as an indicator of the presence of habitats. In this thesis, the Human Footprint Index was used as an indicator. The full spectrum of the Human Footprint rages from 0 to 50, with 0 representing no human pressures and 50 being the value of the highest cumulative human pressures.

The aforementioned steps were applied to the land use types that form the majority of the anthropogenic land uses in the terrestrial ecosystems. Land use types assessed here were built environments, which is a representation of urban areas, pastures, and croplands, representing the agricultural land, major transport infrastructure, captured by the inclusion roads and rails, and quarries and mines have also been investigated. For each land use type, a context area of 1 km outside its borders was created and the average value of the Human Footprint Index was calculated within the context areas.

The results showed that very few urban areas had a low Human Footprint in its surroundings. Pasturelands with low Human Footprint were scattered in Africa, concentrated in the western part of North America, found in Mongolia, and Australia. Croplands with low Human Footprint in its surroundings were found in the central part of the United States of America and its borders with Canada, in the central part of Brazil and Bolivia, along the southern border of Russian, South East Asia, New Zealand, and in the south-eastern and south-western parts of Australia. Roads with the lower Human Footprint in their surrounding were found longitudinally across Canada, Russia, and the north of Africa, and latitudinally across Australia. Railways with low Human Footprint in the context areas were mainly found in Canada and Russia. Quarries or mines with low Human Footprint were scattered around the world but mostly concentrated in Amazonia, Canada, and across Russia.

The Human Footprint average values calculated for the context areas represent the intensity of anthropogenic pressures in the surrounding of the land uses. In this thesis, the Human Footprint is used to indicate if the area potentially perforates or dissects. The relationship between human pressures and the Perforation Potential had to be established, requiring intermediate steps. These steps were applied to quarries and mines.

Context areas of quarries and mines with a Human Footprint of 0 in the context area were selected for verification of the existence of purely perforating land use configurations. The verification consisted of visually inspecting aerial images of 30 randomly selected sites. Despite those sites being considerably isolated from other pressures, this verification step showed that a purely perforating configuration is rare or unlikely when assessed from a product perspective. Any human activity for the extraction of goods, e.g., a mining site, will need a road, rail, or waterway for the transport of the goods. The Human Footprint value of 0 in the context area was found because the transport infrastructures leading to these extraction sites were not captured by or are not part of the Human Footprint map, being, e.g., local and utility roads.

A validation step was carried out to provide a better understanding of the configurations inside the context areas of the quarries and mines in forest biomes, 80 context areas were randomly selected. The context areas were separated into four main groups (a, b, c, and d). The groups were created depending on Human Footprint values in the context area and the amount of forest cover. Each of the selected context areas was inspected against supporting geospatial information, such as aerial images, base maps, land cover maps. Each site was valuated with a score from 1 to 3. The value of 1 was given if the visual inspection of the context area did not resemble a perforation or dissection resembling a fragmented landscape. A value of 2 was given if some parts of the context area had a configuration similar to perforation and dissection. A value of 3 was given to sites that resembled perforation and dissection configuration in most of the context area.

The results of the valuation exercise provided important learning outcomes. Context areas in the group with high forest cover and low Human Footprint presented several areas with similarity to perforation and dissection. The visualization of areas with low Human Footprint and low vegetation cover showed that in some areas, the low vegetation cover was due to the presence of water bodies, the inconsistency of the cropland land data used, as well as the borders of the ecoregion. The latter was observed when the context areas were relatively close to a tundra biome, for which the non-forest vegetation cover appeared to be natural; in these cases, a high valuation score was attributed. Context areas with low vegetation cover and low Human Footprint values contained mostly areas surrounded by cropland and was the group with the lowest average valuation score. Context areas for which, despite high vegetation cover, were subjected to high human pressures presented mixed configuration with, for example, forested areas intercepted by roads, tracks, and trails. One outcome of this valuation step was the need to assess pressures that modify the land cover such as cropland or pastureland separately from pressures such as nightlights or population density.

To establish the relationship between Human Footprint and perforation or dissection, the HFI pressures were disaggregated into pressures that modify and pressures that do not modify the land cover. The contribution of the HFI's disaggregated pressures and their potential contribution to perforation and dissection were derived from literature. Also, it was considered that both pressures must be low in order for the perforation to be considered high. Therefore, to calculate the Perforation Potential, the average values of the land modifying and non-modifying pressures for each context area were scaled, and then multiplied.

To provide a concrete example of how this method can be applied in life cycle assessment, a case study was carried out. The production of 1 t of steel from iron ore was selected as a case study. The system was modeled using the iron ore and metallurgical coal import origins and ratios for Germany, focusing on the mining activities for iron ore and coal. The mining locations were obtained using global and national datasets or environmental agencies' data. The amount of iron ore and coal produced per country was obtained from an international report of mineral resources. The Perforation Potential in the context area for each input and country was divided by the total amount of product in that country. The Perforation Potential of each input was multiplied by the required amount of input in the product system. When the values were calculated for the required quantities in the case study, coal and iron from Canada dominated the Perforation Potential impact.

The interpretation of the case study result is that for the modeled 1 t of steel, the Canadian mining inputs were the ones that take place in areas with low human pressures. As such, these mining activities are most likely to contribute to perforation like landscape pattern. In order to understand the impact of the land use itself to assess the decrease in quality of the land use activity, its intensity, and weighting according to ecoregions, the proposed method has to be used in combination with another impact assessment method. Three approaches have been identified: 1) as an independent impact assessment category, this is the most straightforward and most transparent approach, 2) the use of the Perforation Potential as a modifier to an existing biodiversity impact category, as an additional penalty to the impact category provided the biodiversity being measured are coherent between the methods, and 3) as a modifier to a management parameter; for this use, the management parameter has to be defined.

This thesis proposes the explicit inclusion of a land use's context in life cycle assessment to assess the impact of land use activities on biodiversity. The method unambiguously informs whether a land use borders an area of low human pressures being applicable to any land use type. Here, the use of a cumulative index of human pressures to indicate a potential of perforation is suggested and does not necessarily require species-specific data. The method does not rely on any predefined ecosystems or biomes boundaries and can be applied to the whole world, but should be used in combination with other impact assessment method for the assessment of the impacts of biodiversity in LCA.

9 Outlook

Assessing land use and its impact on biodiversity is complex, data demanding, and value-laden. This complexity should not halt information that can be simplified to be accessible to decision makers through tools such as LCA. In this thesis, a simplified approach to identify if a land use takes place in an area of low human pressures has been proposed. The further development of the explicit inclusion of the context of a land use is the focus of this chapter.

Context area definition

The creation of the context area can be improved from a unique value of 1 km to different distances if justified in terms of the influence of a land use in its surroundings. Characteristics such as vegetation type, slope, up or downstream, and up or downwind can be used to determine different distances for the creation of the context area. Such development, however, will require a substantial amount of data and supporting research to be meaningfully applied.

Environmental quality data

Given the complexity of biodiversity assessment for a globally applicable tool, the quality of the surrounding environment was evaluated using a global map of human pressures. Other approaches can be used, for example, by the use of specific data for habitat.

The cumulative pressure map resolution of 1 km used in this thesis is sufficient to provide guidance for global assessments, but it is too coarse for the replacement of site-specific environmental impact assessment. The use of pressure maps with finer resolution or at least a more recent reference year is highly recommended.

The use of a cumulative pressure map as environmental quality can also be improved with the use of other input data, such as forestry. The land use type forestry has not been assessed despite being a major terrestrial land use type. In order to include it, further definitions of the location of used forests and forestry would have to be specified as well as its contribution as environmental pressure, but the data is not readily available.

Average values

In this thesis, the average values of human pressures in the context area were used. This is a first approach to including an explicit element of the context of the land use to a product land use's perspective. Further work can focus on an even more refined spatial perspective. For example, the inclusion of size (small or large land use) and shape (elongated or circular) of the land use, as well as the number per context area (if it is a combination of several or if it is one site).

Within the framework of the presented method, statistics such as minimum, maximum, and standard deviation can also be presented. An interesting development would be to capture differences of the surrounding quality depending on the spatial disposition of the pressures. If there is a high contrast of the pressures in opposites sides of the context area, e.g., a land use is surrounded on one side by forest and in the other by urban area, or if the pressures in the surrounding are spatially homogenous.

Explicitly characterizing the pressures within the context area is expected to be particularly valuable for elongated land uses such as roads, but also for very large continuous land uses such as croplands.

Operationalization

The success of a method is not only dependent on its scientific robustness but also on its operationalization and accessibility to LCA practitioners and commissioners. As such, impact assessment method developers face several barriers, such as the complexity of the interpretation of indicators developed and simplicity for operationalization in LCA software. In this thesis, major land use types have been investigated based on land cover data. This data can be further refined, for example, detailing the minerals or ore extracted in the mining sites. Such development, however, lies in the interface of LCI and LCIA and is a topic for future discussion and research.

Landscape change

This thesis focused on perforation and dissection patterns. However, inconsistencies between the land use types data and the aerial images were found. Inconsistency of the data for cropland and current aerial imagery suggested that these areas have been subjected to change in land cover. The implications of these temporal inconstancies are beyond the purpose of this thesis, but it brings attention to the fast pace at which landscapes are modified, highlighting the need to identify areas of low human pressures in the scope of product assessments. This observation suggests that the assessment of land cover change, as landscape processes can be valuable to future method development.

Nomenclature

The method was developed with the intent of identifying land uses that potentially contribute to the perforation of the landscapes. The concept is transferred to a land use perspective to bring the insight that at its borders, the land use could contribute to the degradation of areas of low human pressure. From a landscape ecology perspective, it is unlikely that a land use spanning an extensive area, such as a large scale monoculture, can be denominated perforation.

For large continuous land uses, the proposed Perforation Potential can serve as an indicator of the encroachment of the land use, e.g., a cultivated land bordering areas with low HFI. The identification of these areas can be valuable for environmental assessment, and should not be dismissed as a parameter to be used in LCA, although it can be questionable if *perforation* is an adequate nomenclature.

Use recommendation

The proposed method brings an explicit assessment of the land use's surroundings and is not a comprehensive assessment of the land use' s biodiversity impact. The method must either be further developed to include the impact of the land use itself or be used in combination with another impact assessment. In this way, it will evaluate the land use in terms of the degradation caused by the land use, including land use type and management practices, and include a valuation of the type of intervention on the ecosystems where the land use takes place.

Glossary

Biome is a division of the Earth's surface based on climate patterns, soil types, and the ecological community in the area (e.g., animals and plants). They are major distinctions and include, for example, forests, grassland, desert, and tundra. Biomes are much coarser than Ecoregions, *see ecoregions*.

Buffer is an area set to a specific distance created around an input feature, *see also context areas*.

Context areas are defined here as an area that surrounds the land use being investigated, excluding the land use itself. They are created by a buffer zone around the land use and can be composed of discontinuous land use patches of the same type.

Context is the surrounding of an area; in this thesis is the surrounding of a specific land use type, excluding the land use area itself.

Context parameter is a parameter that influences the outcome of a land use activity on biodiversity but is independent of the land use activity itself or its management practices.

Ecoregions are areas grouped by their distinctness of natural communities and species; the boundaries estimate the original extent of natural communities before significant anthropogenic use. Here the data source used is the one defined by Olson et al. (2001). Ecoregions are fit in within biomes. In this thesis, only terrestrial ecoregions are considered.

Feature in geographic information systems is a representation of a real-world object in a map. It carries spatial (geographical) and non-spatial (description) information.

Fragmentation as an umbrella term means a discontinued area of an organisms' preferred environment, *see habitat*. It can be caused by a natural or anthropogenic process. In this thesis, the focus is on fragmentation caused by human activities.

GlobeLand30 is a map of global land covers dataset at 30 m resolution. The dataset has an overall accuracy of 80 %. The classes are water bodies, wetlands, artificial surfaces, cultivated land, forest, shrubland (a vegetation adapted to drought or fires, often woody with small needle leaves), grassland, bareland, permeant snow and ice, and tundra. The dataset is available for the reference year of 2000 and 2010 (Chen et al. 2015) the latest was used in this thesis.

Habitat is an organism's preferred environment, or where a species lives.

Human Footprint Index (HFI) is a cumulative human pressures index; it ranges from 0 to 50 (Venter et al. 2016b), provided as a map of 1 km resolution at the equator. It is used to calculate the Perforation Potential in this thesis.

Human Influence Index (HII) is a cumulative human pressure index; it ranges from 0 to 72 (Sanderson et al. 2002), is the predecessor of the HFI.

Human pressures that do not modify the land cover ($HFI_{non\text{-}mod}$) is defined for the purposes of this thesis as the cumulative human pressures index of human pressures, HFI, that takes into account only the pressures that do not relate to land cover modifications. The $HFI_{non\text{-}mod}$ includes the pressures of roads, railways, navigable waterways, nightlights, and population density. The pressures composing the $HFI_{non\text{-}mod}$ may overlap, and ranges from 0 to 40.

Human pressures that modify the land cover (HFI_{mod}) is defined for the purposes of this thesis as the cumulative human pressures index of human pressures, HFI, that takes into account only the pressures that are a result of land cover modifications. The HFI_{mod} includes the pressures of cropland, pastureland, and built environment. The pressures composing the HFI_{mod} do not overlap, and ranges from 0 to 10.

Land cover is the physical cover of the area, usually the vegetation; it does not directly correspond to a land use. A forest land cover can be native or exotic, natural or planted, and they can be used or non-used by humans, see land use. Examples of land covers are forests, grassland, and waterbodies.

Land use is the anthropogenic activity taking place in an area, for example, sheep or cattle grazing.

Life cycle impact assessment is the step that transforms the inputs and outputs of a product system into environmental impacts.

Life cycle inventory is a life cycle step for the quantification of input and output flows of a product system.

Pattern, here, refers to the static spatial configuration of an area.

Percolation threshold in landscape ecology is the point in which further reduction in habitat abruptly reduces the landscape connectivity.

Perforation is a landscape spatial process or pattern for which non-habitat is surrounded by habitat.

Raster data are formed by regular grid cells; each pixel has an associated value.

Remote areas, here, refer to an area of low human influence, an area where, e.g., there is little or no anthropogenically modified land cover, and where humans have little or no access.

Vector refers to data that are composed of vertices and paths. In geospatial systems, they can be points, lines, or polygons.

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Appendix A

Results of the visualization of 30 randomly selected quarry or mines' context area with HFI of 0 in their context area (verification step).

Table A 1 Verification results. Point location of the center of the context area in decimal degrees in longitude (Lon) and latitude (Lat).

Context observed cover	Human presence	Comment on OSM mapping	Lon	Lat
forest, flooded vegetation, scrub or grassland	along minor road	visible quarry or mine	28,323	67,823
forest	along minor road	no visible quarry or mine	122,486	59,840
forest	along minor road	no visible quarry or mine	122,585	59,762
forest	along minor road	no visible quarry or mine	122,672	59,698
forest, sparse vegetation	along minor road, two roads	no visible quarry or mine	-122,235	53,701
forest, forest with visible rows	along minor road, two roads	visible quarry or mine, larger than captured feature	-86,523	49,956
forest	along river, no visible human pressures	visible resource extraction site	-53,183	-0,226
forest	along road	visible quarry or mine, smaller than mapped feature	-75,346	48,026
forest	along road	visible quarry or mine	-73,780	49,490
forest, sparse vegetation	along road	visible quarry or mine	-70,349	48,833
mountain, dry	along road	visible quarry or mine, unmapped quarry or mine in the context area	90,835	37,064
forest	along road visible on imagery, not mapped by OSM	visible quarry or mine	-121,998	54,528
forest	along road visible on imagery, not mapped by OSM	visible quarry or mine	-82,413	47,328
forest, forest with rows, grassland	along road visible on imagery, not mapped by OSM	visible quarry or mine	-73,574	46,678
forest, forest with rows	along road visible on imagery, not mapped by OSM	visible quarry or mine, unmapped quarry or mine in the context area	-66,238	47,100
forest, forest clear cut with rows	along road visible on imagery, not mapped by OSM	visible quarry or mine, not matching OSM mapping	-54,757	-12,295
forest, bare land patches	along road, along track	visible quarry or mine	-116,413	50,347
forest	along road, and minor road	no visible quarry or mine, site has been removed from OSM map 2019	-69,864	48,592
forest, with clearing	along road, connecting roads	visible quarry or mine	-66,466	47,217

Context observed cover	Human presence	Comment on OSM mapping	Lon	Lat
forest, flooded vegetation	dedicated road	visible bare land patch, not matching border of mapped quarry or mine	117,095	65,140
forest, patches with tree rows	dedicated road, two roads	visible quarry or mine	101,478	57,882
forest, flooded vegetation	dedicated road, air-port	visible quarry or mine	-157,837	67,106
desert	dedicated road, air-port	visible resource extraction site, resembling in situ ex-traction	-7,518	27,563
forest	dedicated track	no visible quarry or mine	-54,685	4,774
scrub	dedicated track	visible quarry or mine	127,386	-14,435
forest	no visible human pressures	visible quarry or mine	-121,918	55,152
forest, water	no visible human pressures	no visible quarry or mine	-74,786	49,508
forest	no visible human pressures	visible resource extraction site	-53,704	0,485
forest	no visible human pressures	visible quarry or mine, bare land small patches	-53,419	-0,033
forest	no visible human pressures	visible quarry or mine	-53,288	-0,132

Appendix B

Valuation results for mines and quarries' context areas depending on their similarity to the perforation pattern. Values from 3 to 1 were given to indicate similarity to perforation pattern, with 3 representing similarity a perforation and dissection pattern and 1 no similarity with perforation and dissection. See Figure 23 for visualization.

Table B 1 Valuation results for selected sites. Point location of the center of the context area in decimal degrees in longitude (Lon) and latitude (Lat).

Group	Forest cover ratio	Mean HFI	Valuation score	Comment	Lon	Lat
a1	0,99	0,00	3,0	perforation, with uncaptured mine site in buffer	-60,128	6,030
	0,99	0,86	3,0	surrounded by forest, elongated mine sites	-55,331	4,818
	0,99	1,00	3,0	small quarry, road intersection	-79,117	47,250
	0,98	0,73	3,0	surrounded by forest	-51,461	-8,087
	0,96	0,26	3,0	surrounded by forest	-65,048	-9,444
	0,93	0,50	3,0	surrounded by forest, road, no visible quarry or mine	-74,291	49,540
	0,88	0,49	2,5	well defined road and patches of non forest	-66,588	47,474
	0,84	0,00	2,5	well defined road and patches of non forest	-75,037	46,917
	0,83	1,00	3,0	perforation, unsure if quarry or mine	-122,441	43,518
	0,80	0,53	2,5	surrounded by forest and clearings of possibly recovering vegetation, track in context area	-57,099	-9,407
a2	1,00	1,35	3,0	surrounded by forest	147,013	-37,614
	0,96	1,25	2,0	some non-forested patches appear natural or recovering, with roads captured by OSM	-121,625	44,204
	0,94	1,39	2,5	surrounded by forest with dedicated road, grassland patch beside quarry or mine	54,213	63,668
	0,93	1,53	3,0	surrounded by forest	-70,555	-12,858
	0,93	1,69	3,0	surrounded by forest	94,185	58,960
	0,90	1,02	3,0	surrounded by forest	-56,661	-7,844
	0,80	1,26	1,5	water bodies, roads, low density settlement, visible tree rows	18,812	64,400
	0,77	1,73	2,0	forest and pasture patches, no visible quarry or mine	-83,179	46,305
	0,76	1,57	2,0	surrounded by forest with clear roads, grassland or scrub patches, low density housing, no visible quarry or mine	-67,121	48,329
	0,75	1,26	2,0	other quarry or mine in context area not captured in OSM, surrounded by forest and flooded areas	26,455	65,402

Group	Forest cover ratio	Mean HFI	Valuation score	Comment	Lon	Lat
a3	1,00	2,33	3,0	surrounded by forest with tracks	23,810	62,287
	0,94	3,37	2,5	forest, water body and patches of cleared forest not captured by GlobeLand30	15,622	60,180
	0,93	3,25	2,5	forest, mine or quarry along track, patch of scrub or grassland	-63,553	45,144
	0,89	5,26	2,5	forest, mine or quarry along track, patch of scrub or grassland	-71,951	46,274
	0,88	3,23	3,0	surrounded by forest along road and track	-68,202	49,860
	0,85	4,18	2,5	forest, water body and small patches of scrub or grassland and cropland	14,684	57,839
	0,85	4,06	3,0	surrounded by forest with road and track	-69,506	47,497
	0,75	4,62	2,0	mix of forest, with cropland or grassland or scrub leading to quarry	-84,203	44,331
	0,65	2,25	2,0	surrounded by forest and tree plantation and cleared forest, no visible quarry or mine	-66,886	45,570
	0,60	4,08	3,0	surrounded by forest with road and track	41,530	61,641
a4	1,00	9,82	2,5	along road with several tracks cutting through buffer	14,126	47,427
	0,88	8,69	3,0	mostly forest with tracks	19,158	42,750
	0,85	10,88	2,5	surrounded by forest and possibly recovering vegetation, with cropland and low density settlement in the west part of the context area	113,290	26,572
	0,83	7,20	3,0	surrounded by forest	-91,455	49,898
	0,82	9,29	3,0	forest with small patches of cropland along ridges	22,866	46,085
	0,81	10,74	3,0	surrounded by forest	12,375	64,439
	0,73	6,33	2,5	forest, quarry or mine along road, small cropland sites along road and river	110,743	31,778
	0,70	10,97	2,5	forest, water body, cropland and grassland along roads	-72,077	44,784
	0,64	8,86	2,0	two mapped quarry sites, eastern surrounded with cropland encroaching forest (not quarry or mine), western by forest	10,576	50,378
	0,64	9,16	1,5	two mapped quarry sites, western surrounded by cropland (not quarry or mine), eastern by forest with tracks and transmission lines	9,644	50,350

Group	Forest cover ratio	Mean HFI	Valuation score	Comment	Lon	Lat
b	0,27	4,88	2,5	forest or tree plantation not captured by GlobeLand30, large water body, patches of bare land	16,757	64,493
	0,27	0,25	3,0	remote, sparse vegetation, seems naturally sparse tree cover	118,197	57,122
	0,27	2,47	1,0	cropland and low density settlement not captured in HFI	39,207	58,500
	0,20	4,81	1,5	mostly cropland, continuous forest cover, quarries or mining sites not captured by OSM, encroaching vegetation	-54,633	-10,534
	0,19	2,97	3,0	other quarries not captured by OSM (but coherent with GlobeLand30), forested areas not captured by GlobeLand30	13,759	62,100
	0,11	0,38	1,0	mostly grassland, quarry or mine encroaching disconnected forest patch	127,040	53,737
	0,04	0,25	3,0	remote, sparse vegetation, seems naturally sparse tree cover	67,350	66,500
	0,02	3,06	3,0	remote, sparse vegetation, seems naturally sparse tree cover	66,895	66,539
	0,00	2,51	3,0	mostly rock, mountain, with sparse vegetation (ELU) seems naturally sparse	-3,935	56,666
	0,00	1,58	1,0	no and low intensity grassland with planted forest patches, valuation 3 if grassland is accepted as a habitat	-4,388	56,934
c	0,26	6,62	1,0	modified landscape, low density settlement, encroaching forest cover	37,502	56,609
	0,21	10,12	1,0	mostly cropland	36,677	54,429
	0,20	7,68	1,0	cropland mosaic	2,593	43,722
	0,18	10,11	1,0	mostly cropland and water body	-84,429	41,178
	0,17	9,15	1,0	mostly cropland	-68,374	48,472
	0,13	8,31	1,0	water body and cropland, low density settlement	15,601	53,468
	0,11	6,23	1,0	mostly cropland and water body	-89,803	42,544
	0,04	9,14	2,0	mostly cropland, surrounded by bare natural-looking land cover	36,839	38,940
	0,00	9,85	2,0	forest cover mapped by GlobeLand30 as cultivated land, visible crop and palm tree rows among dense natural-looking vegetation	115,480	-8,408
	0,00	5,98	1,0	cropland and forest patches	-7,680	43,226

Group	Forest cover ratio	Mean HFI	Valuation score	Comment	Lon	Lat
d1	0,89	11,60	3,0	surrounded by forest along road. HFI: road, low human population density and nightlights	-75,289	46,544
	0,89	12,79	2,0	surrounded by forest, road and cropland on valley. HFI: medium population density and nightlights	15,623	47,889
	0,87	16,36	3,0	surrounded by forest. HFI: high human population density and nightlights	108,794	29,038
	0,82	14,72	2,0	surrounded by forest and grassland or schrubland	85,262	22,066
	0,82	14,23	1,0	mapped as cropland by ELU, mostly palm plantation and fragmented forest	106,506	-2,938
	0,81	26,43	3,0	surrounded by forest, built environment area near buffer. HFI: human population density, nightlights, road, urban area. Urban area near the buffer	126,040	41,743
	0,77	16,40	2,5	surrounded by forest with settlement along road, cropland encroaching in south of context area HFI: indirect road, human population density	-73,993	45,095
	0,75	12,00	2,0	surrounded by forest, water body. HFI: road, high human population density and nightlights	-81,736	47,689
	0,70	12,12	1,5	forest with grassland or cropland finger-shaped through context area low density housing along roads	80,266	7,412
	0,66	32,12	1,5	quarry along road with forest mixed with scrub or grassland and encroaching cropland. HFI: high population density, road, cropland, nightlights	-70,862	47,070
d2	1,00	12,02	2,0	surrounded by forest and schrubland. HFI: indirect road, population density	96,355	22,885
	0,99	17,87	1,0	surrounded by orderly tree rows of palm-like trees, mapped as mostly cropland by ELU	-69,639	19,249
	0,98	15,54	3,0	surrounded by forest. HFI: urban area at East of context areas	20,581	48,112
	0,98	17,33	1,0	surrounded by orderly tree rows, valuated as not perforating due to the high density of tracks	11,166	50,456
	0,97	31,25	1,5	cropland, forest cover, urban area incorrectly captured as forest by GlobeLand30	-73,940	4,901
	0,95	15,86	1,5	surrounded by forest with large patches of cultivated land, scattered houses	15,528	57,618
	0,92	13,79	2,5	surrounded by forest, road, modified landscape and quarry along road. HFI: direct road, population density	12,307	47,732
	0,91	12,93	1,5	forest and grassland or schrubland and cropland	-43,420	-20,337
	0,90	16,47	1,5	surrounded by forest, vegetation cut by well defined roads and low density houses. HFI: indirect road, medium population density	-75,772	41,096
	0,90	12,77	2,0	surrounded by forest with tracks, cropland encroaching. HFI: indirect road, population density	13,087	48,168

Appendix C

This appendix serves the purpose of verifying the plausibility of the decision of using the HFI's input layer of cropland, pastureland, and build environment as an indicator for the absence of natural vegetation cover. This assumption can be tested, for example, if comparing HFI modifying pressures with the original cover on the context areas. For simplicity, this comparison will be carried out for forest biomes, calculating the amount of forest cover and the absence of land cover modifying pressures in quarries and mines context areas.

The area of land cover modifying pressures in the context areas was calculated using the zonal statistics function in ArcGIS and a cell size of 50 m. In other words, any raster cell of pressure types cropland, pastureland, or build environment in the context areas is accounted for by the zonal statistics, and its area is calculated based on the cell size. The percentage of cropland, pastureland, or build environment is then calculated for each context area. Areas that are not cropland, pastureland, or build environment can be coarsely assumed to be the original land cover type, and its percentage was calculated for each context area.

The percentage of forest cover in context areas of quarries and mines was calculated in the valuation step. The correlation of the two variables was r = 0,567, with p = 0; and n = 37.819. Correlation coefficient values range from -1 to 1 indicate the strength of the relationship between the parameters. However, naming the strength of the relationship is subjected to the interpretation of the authors (Akoglu 2018). Several approaches to translate the correlation coefficient into descriptors, such as weak, moderate, and strong, have been proposed (Schober et al. 2018; Mukaka 2012; Akoglu 2018). Akoglu (2018) compared the interpretation of correlation coefficients of three authors and in which, for example, r = 0,5 has been interpreted as strong, moderate, and fair by authors of different research fields (Akoglu 2018). Large samples often have lower p-values since p-values quickly approach zero as sample sizes increase (Lin et al. 2013). The sample size n = 37.819 explains the p = 0.

When interpreting the correlation result, it must be taken into account that each dataset has its own intrinsic error, data is obtained by different satellites with different accuracies and in different years, and the comparison is subjected to the coarse assumption of forest as ideal cover in all forest biomes. With these limitations in mind, a correlation of 0,567 can be considered sufficient to justify the use of the HFI modifying pressures as absence of natural cover.

A plot of the percentage of forest cover in quarries and mines context areas against the area that is not cropland, pastureland, or built environment is presented in Figure C1.

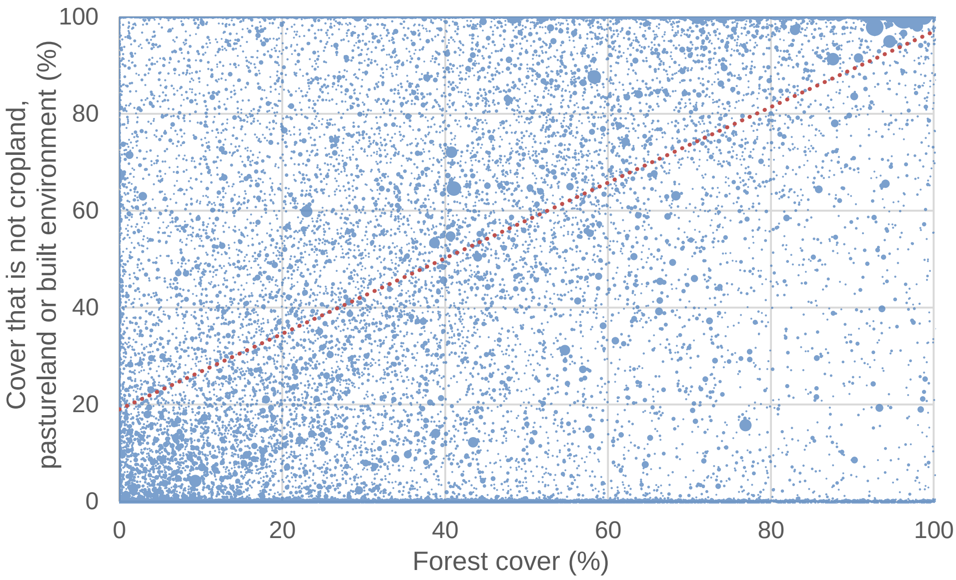


Figure C 1 Scatter plot of forest cover (x-axis) and land cover different from cropland, pastureland, or built environment (y-axis) (in %) in context areas of quarries and mines of minimum size 3 km^2. Larger sizes represent larger context areas.

The influence of the context area size in the correlation between the two data sets is evident when filtering out the context areas by minimum size. A higher correlation was found with the increase in the minimum size of the context area. Scatter plots for context area of minimum size from 5 km^2 up to 30 km^2 are presented in Figures C 2 to C 5. The correlation results are summarized in Table C 1.

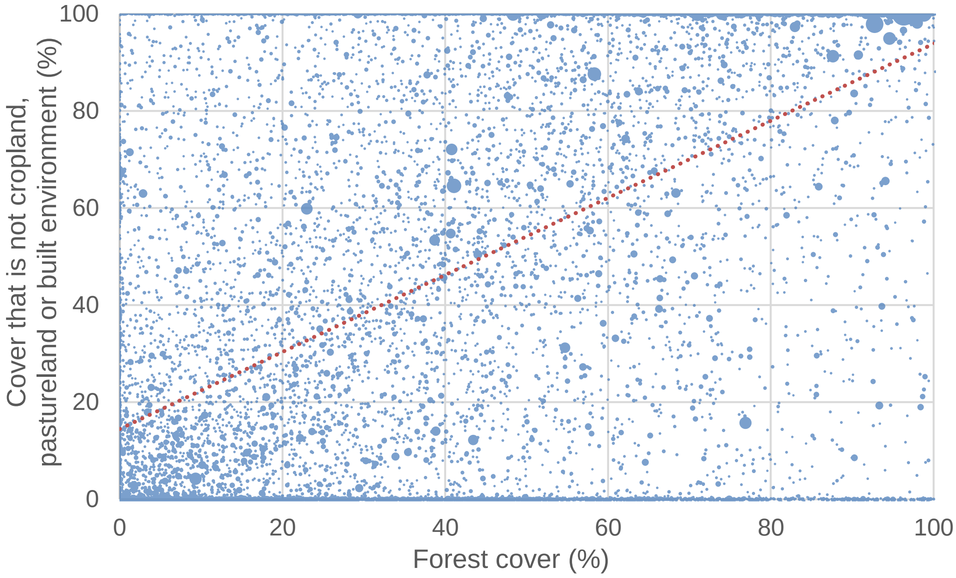


Figure C 2 Scatter plot of forest cover (x-axis) and land cover different from cropland, pastureland, or built environment (y-axis) (in %) in context areas of quarries and mines of minimum size 5 km^2. Larger sizes represent larger context areas.

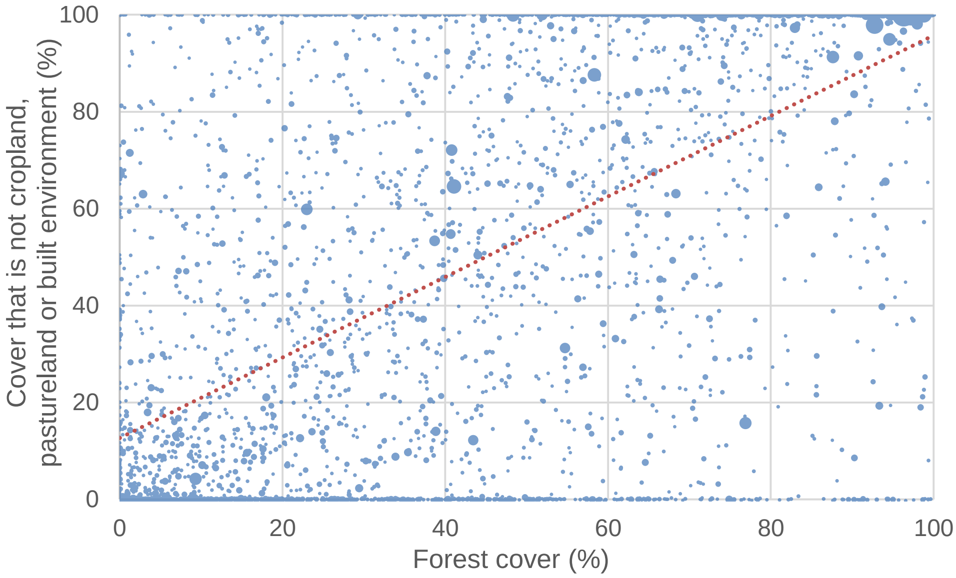


Figure C 3 Scatter plot of forest cover (x-axis) and land cover different from cropland, pastureland, or built environment (y-axis) (in %) in context areas of quarries and mines of minimum size 10 km^2. Larger sizes represent larger context areas.

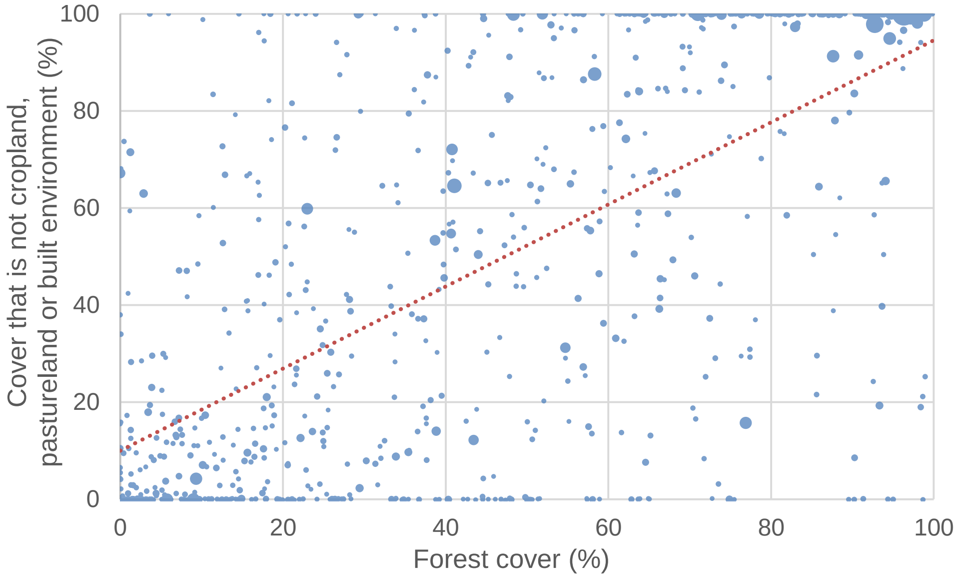


Figure C 4 Scatter plot of forest cover (x-axis) and land cover different from cropland, pastureland, or built environment (y-axis) (in %) in context areas of quarries and mines of minimum size 20 km^2. Larger sizes represent larger context areas.

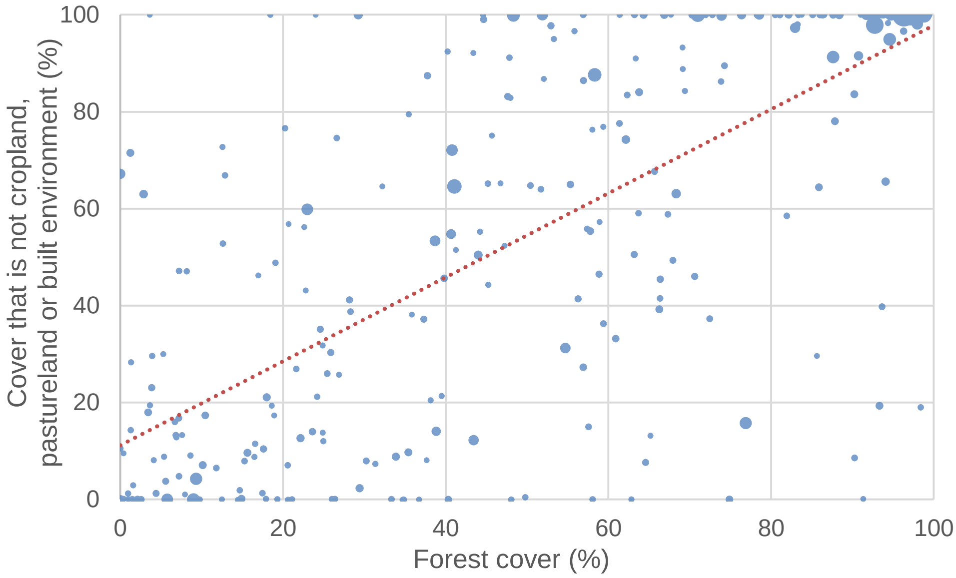


Figure C 5 Scatter plot of forest cover (x-axis) and land cover different from cropland, pastureland, or built environment (y-axis) (in %) in context areas of quarries and mines of minimum size 30 km^2. Larger sizes represent larger context areas.

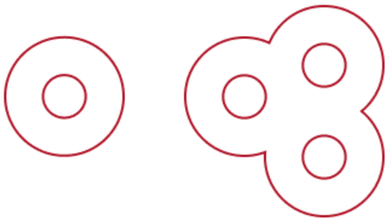
Table C 1 Correlation values (*r*), observations (*n*), and significance (*p*) results for forest cover and cover that is not cropland, pasture, or built environments in the context area.

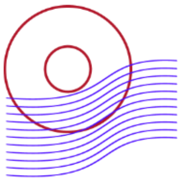
Minimum context area size (km^2)	*r*	*n*	*p*
3	0,566607	37819	0
5	0,578497	14425	< 0,001
10	0,619132	3562	< 0,001
20	0,668073	769	< 0,005
30	0,722425	278	< 0,005

When interpreting these results, it is important to keep in mind that context areas do not necessarily represent individual mining sites. Large context areas can also be the result of more than one mine or quarry within less than 2 km from each other. In other words, a large context area is not necessarily a result of a single large mining site, but it can also be a result of several mining sites close to each other. Also, in terms of geometry, elongated quarries or mines will have a larger context area than a quarry or mine of the same area of a smaller perimeter.

The comparison of two datasets, namely the GlobeLand30 and the pressure maps of the HFI has limitations derived from: the context area size, presence of other natural covers, assumptions of ideal land cover type, land cover change, and data resolution. These are further explained and illustrated in Table C 2 with examples that are not limited to the case of quarries and mines.

Table C 2 Sources of inconsistencies between HFI input data, and original land cover type in context areas.

Characteristics	Description
Context area size 	Taking the case of two context areas with 100% natural land cover type: one raster cell of 1 km^2 of incorrectly captured HFI pressures, e.g., urban area, will represent 33% of a context area of 3 km^2, but only 3 % of a context area of 30 km^2. Therefore, incorrectly captured pressures will be more pronounced in smaller context areas.

Characteristics	Description
Other natural land covers 	The assumption that the absence of pressures cropland, pastureland, or built environment represents natural cover, has to be observed with caution if compared with land cover maps. When comparing the percentages of the absence of HFI modifying pressures with the percentage of original land cover types, the existence of other natural land cover types may also be present, for example, water.
Ideal cover assumption  Image credits Haavard Lindholm.	The assumption of a homogenous ideal land cover, based on biomes or ecoregions boundaries, can be problematic even for forests cover on forest biomes. This is because not all forest biomes are composed uniquely by dense forest cover. One example is the ecoregion Bolivian montane dry forests in the biome Tropical & Subtropical Dry Broadleaf Forests, in the Torotoro National Park shown in the picture on the left. A land cover map of this area would present no forest cover despite being a forest biome. Ideal cover assumption and ecoregion borders issues were also identified in the valuation step for group b.
Land cover change  Images credits Google Earth.	As in any geospatial dataset, data is captured at one point in time. Consequently, the reference year can be a source of inconsistencies when comparing two maps, e.g., when comparing land cover maps with the pressures maps such as HFI. On the left-hand side, the top image shows forest clearings in the Brazilian Amazonia, captured in 2009. The bottom image shows the expansion of the forest clearing in 2016.
Resolution  Image credits ESRI base map.	The 1 km resolution of the HFI is a limiting factor in the assumption that the absence of cropland, pastureland, and urban area is natural cover. An area of low-intensity pasture captured by HFI can also present natural cover, for example, forest cover, as trees can also be present. The picture on the left shows the cropland raster map from HFI tinted with orange, overlaid on an aerial map. In the image, unmapped cropland areas can be seen.

Summary

The aim of this appendix was to verify the plausibility of the use of the absence of HFI land modifying pressures (cropland, pastureland, and built environment) as a surrogate for the original land cover type in context areas.

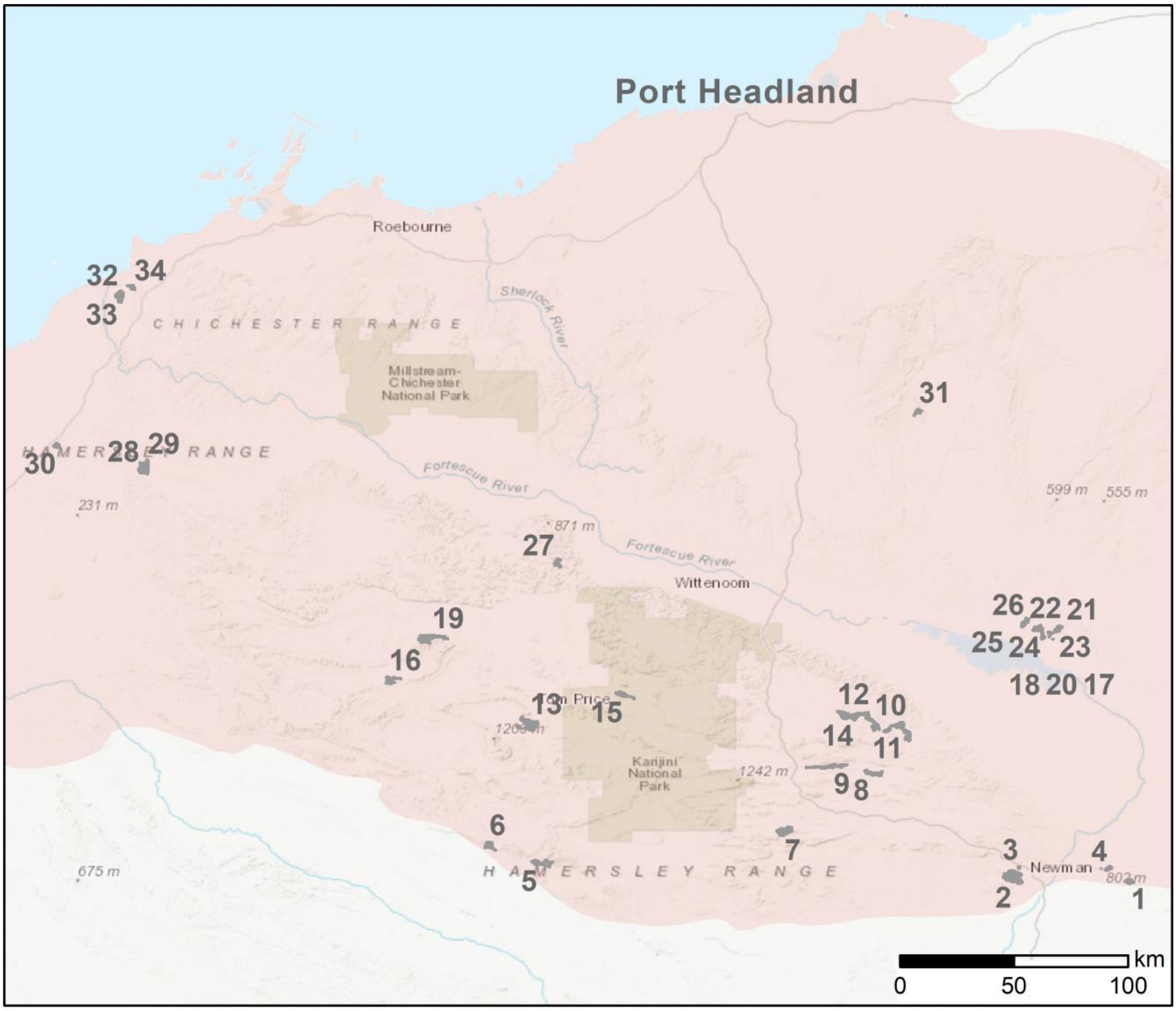
The correlation between the land cover forest from land cover map GlobeLand30 and the land cover that is not cropland, pastureland, or built environment was calculated for quarries and mines in forest biomes. The correlation increased with the increase in the minimum area size of the context area. The increase in the correlation for larger context areas was observed because discrepancies in the resolution of the HFI input data and the GlobeLand30 will be less pronounced in larger context areas. The calculated correlation of at least r = 0,567 is therefore judged sufficient to justify the use of data sets of land cover modifying pressures as an indicator of the absence of original land type.

The results presented in this appendix through correlation values, graphs, images, and text, supports the use of the absence of HFI modifying pressures, i.e., areas that are not cropland, pastureland, or built environment, to be considered as original land cover type. Thus, HFI modifying pressures can be justifiably used as the input to the general curve of landscape contribution proposed by Forman (1995) in section 5.2.3 Conversion to Perforation Potential, under heading Land cover modifying parameters contributions, starting on page 82.

Appendix D

This appendix contains maps showing the location of the mining sites that are part of the case study. The mines are identified by a unique label, respecting the ecoregions' boundaries because these boundaries are used for the calculation of the impact assessment using the biodiversity footprint method proposed by Chaudhary and Brooks (2018). The maps are presented in Figure D 1 to D 7.

Two tables are presented. Table D 1 contains the HFI_{mod} and $HFI_{non\text{-}mod}$ values, the calculated PP_i values, the size of the context area, the geographical coordinates of the individual mines of each context area, and the labels that refer to Figure D 1 to D 7. Table D 2 shows the CF provided by Chaudhary and Brooks (2018) for each mining site location.



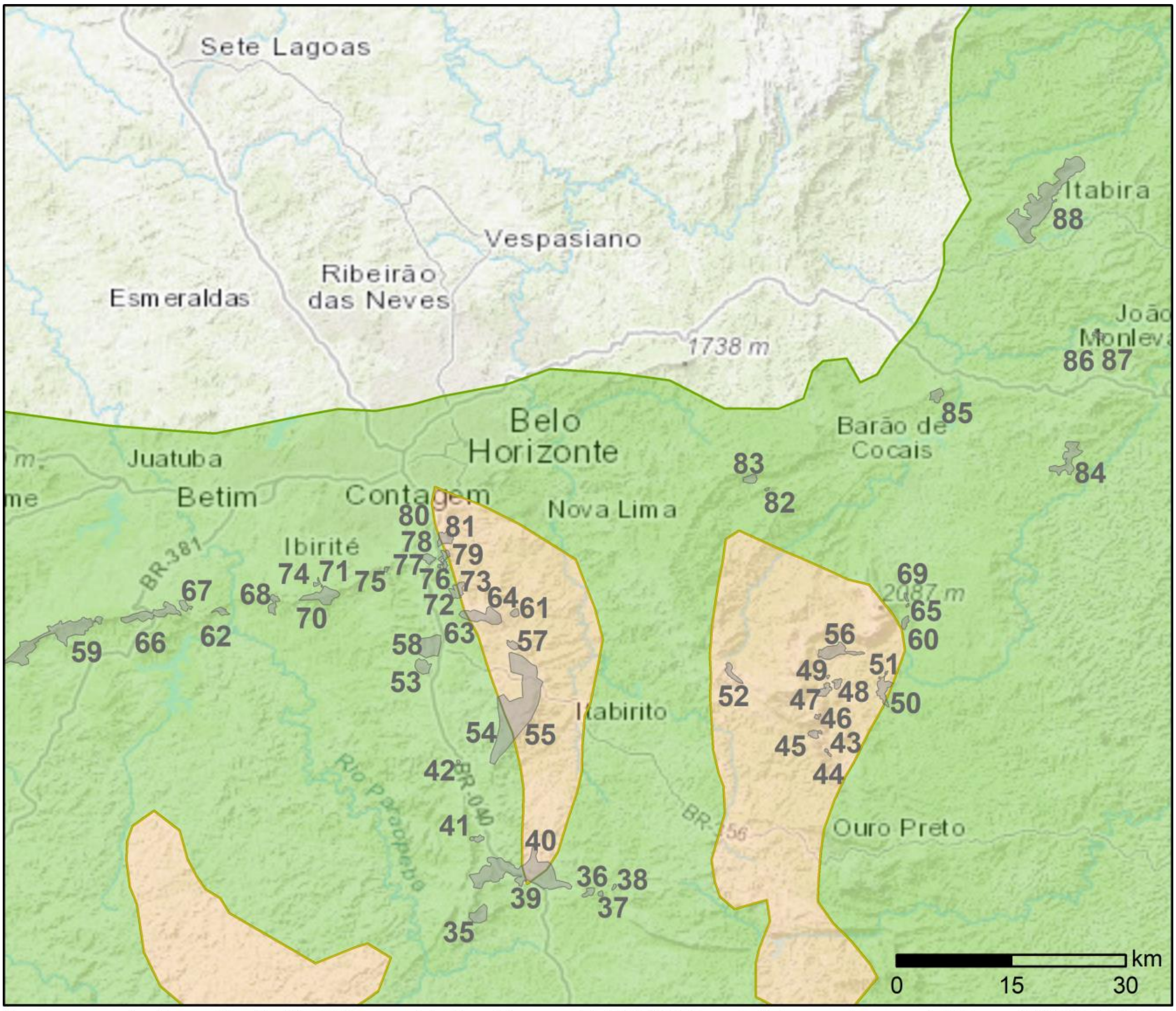
Base map service Layer Credits World Topographic Map: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community. Insert: GDAM.

Iron ore mining sites

Ecoregion

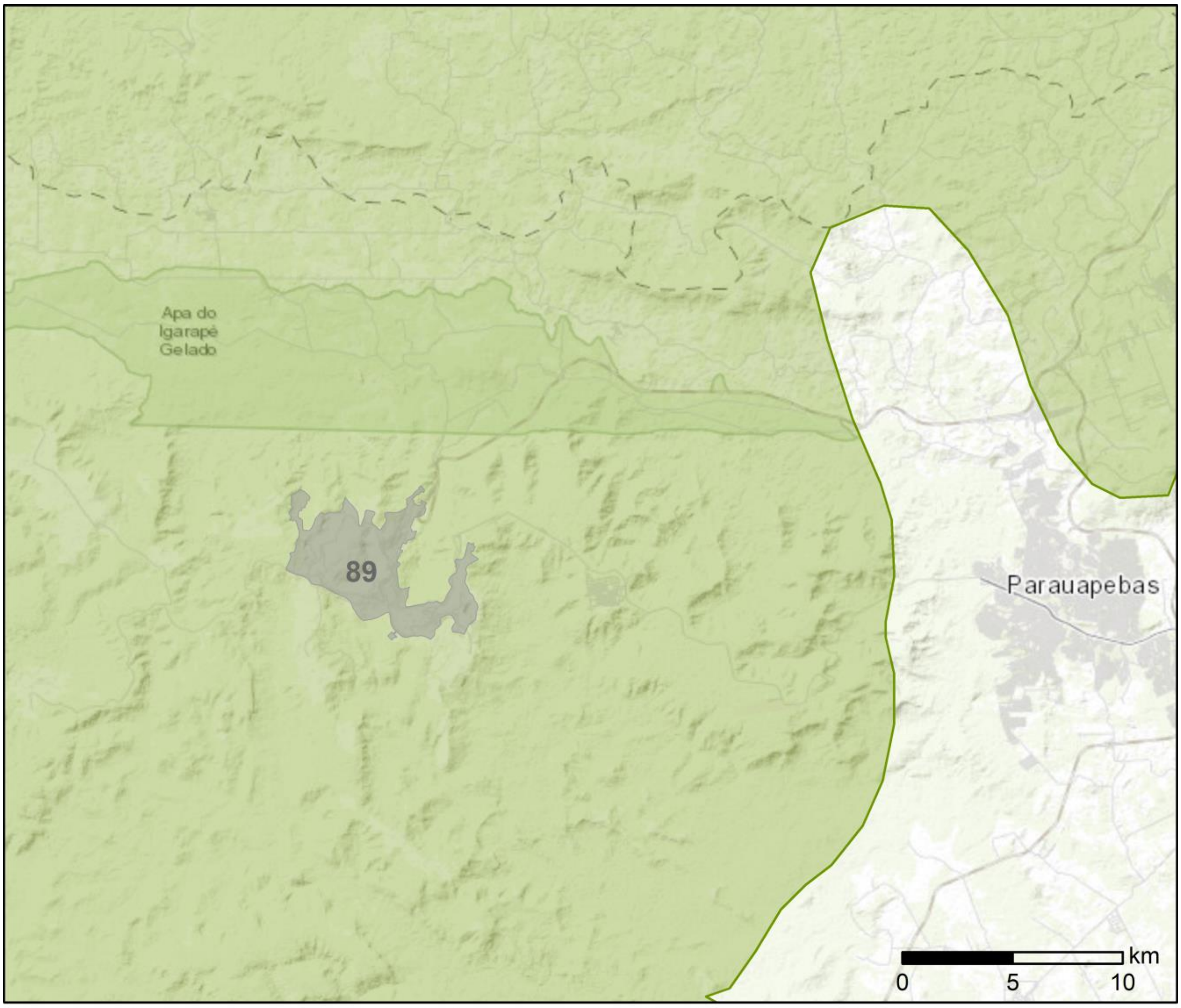
Pilbara shrublands (AA13079)

Figure D 1 Location of iron ore mining sites in Pilbara, Australia.



Base map service Layer Credits World Topographic Map: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community. Insert: GDAM.

Figure D 2 Location of iron ore mining sites in Minas Gerais, Brazil.



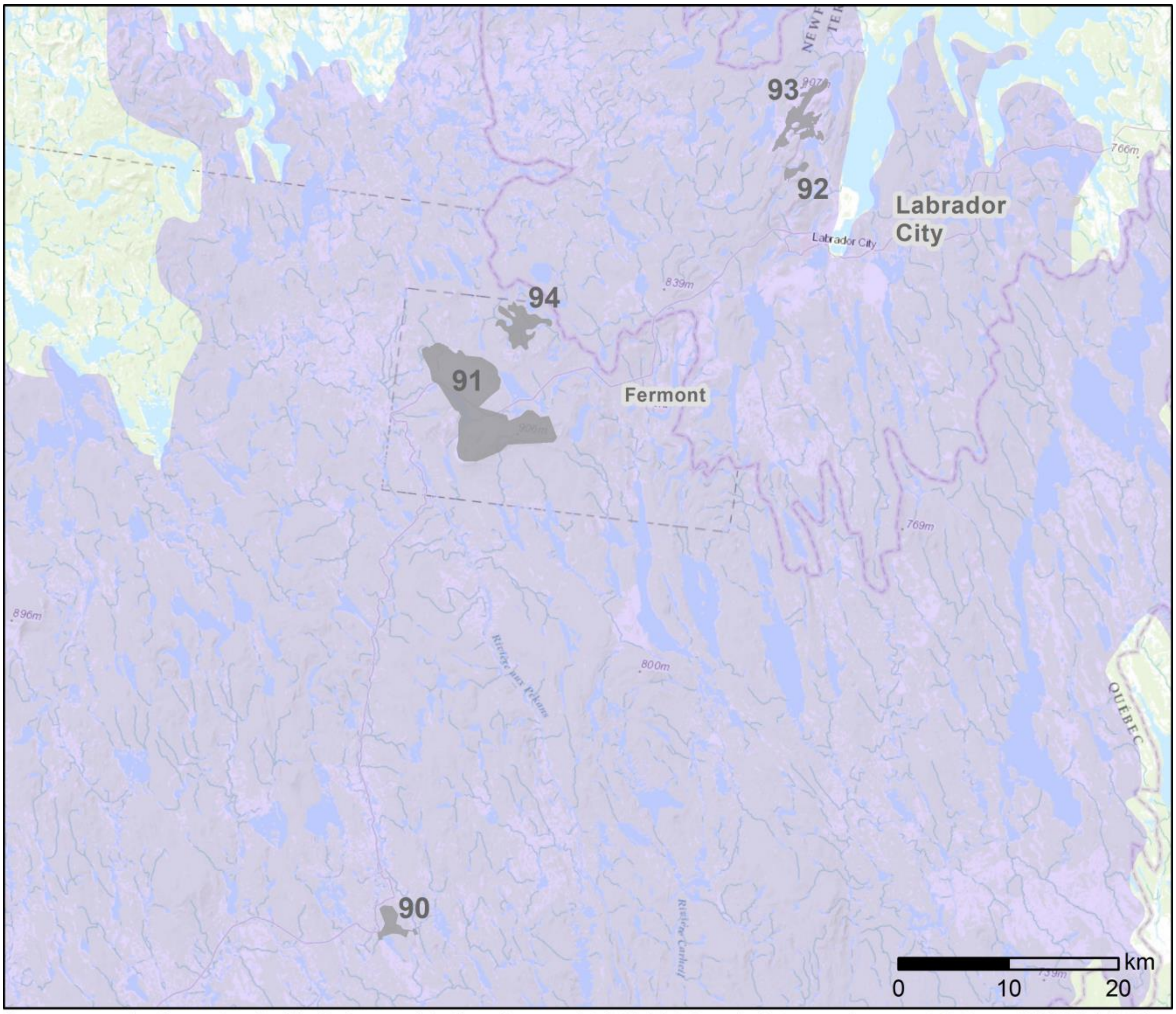
Base map service Layer Credits World Topographic Map: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community, World Terrain Reference: Sources: Esri, Garmin, USGS, NPS. Insert: GDAM.

Iron ore mining sites

Ecoregion

Xingu-Tocantins-Araguaia moist forests (NT0180)

Figure D 3 Location of the iron ore mining site in Pará, Brazil.



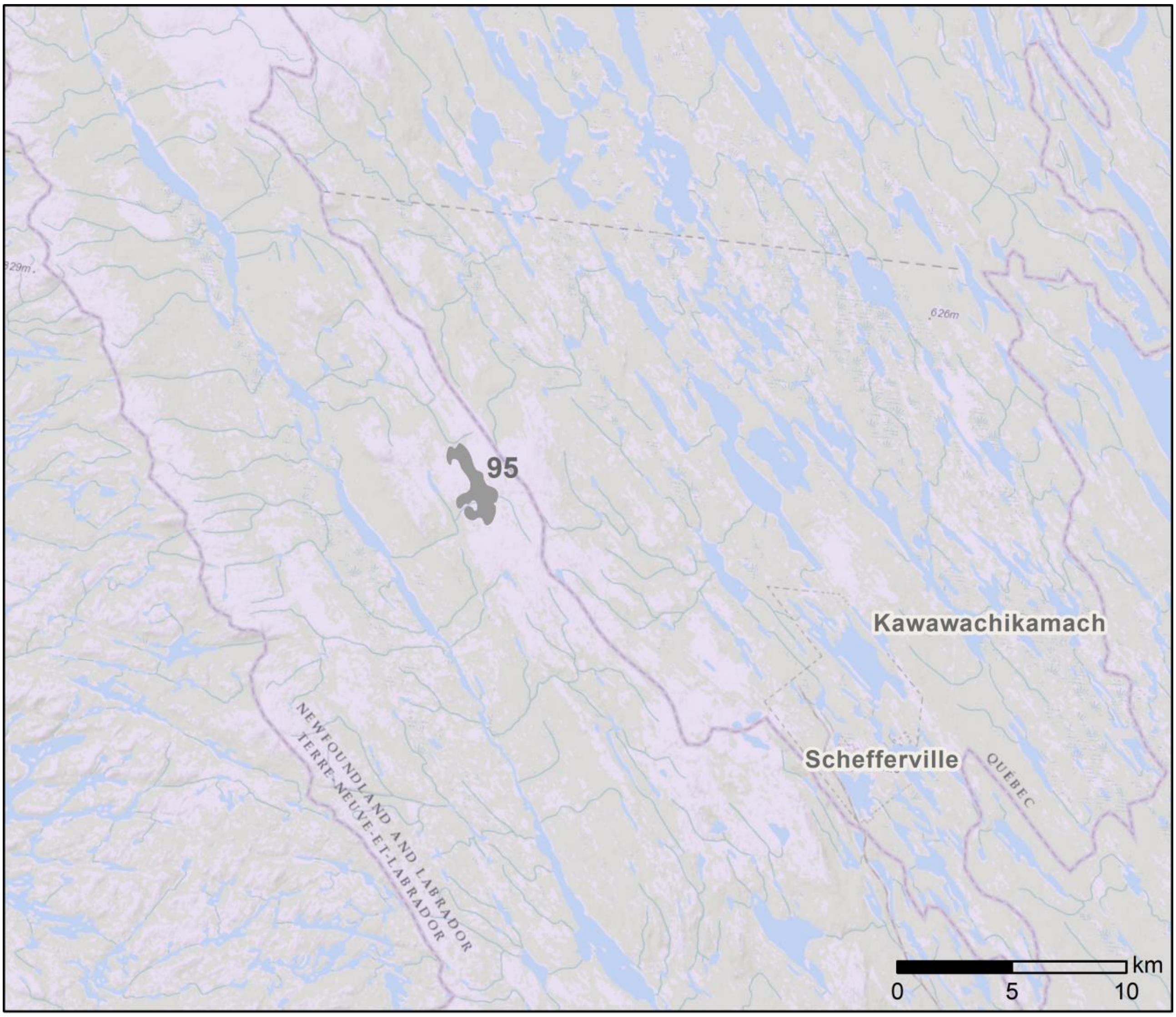
Base map service Layer Credits World Topographic Map: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community. Insert: GDAM. Projected Coordinate System NAD 1927 MTM 3.

Iron ore mining sites

Ecoregion

Eastern Canadian forests (NA0605)

Figure D 4 Location of iron ore mining sites near Labrador City, Canada.



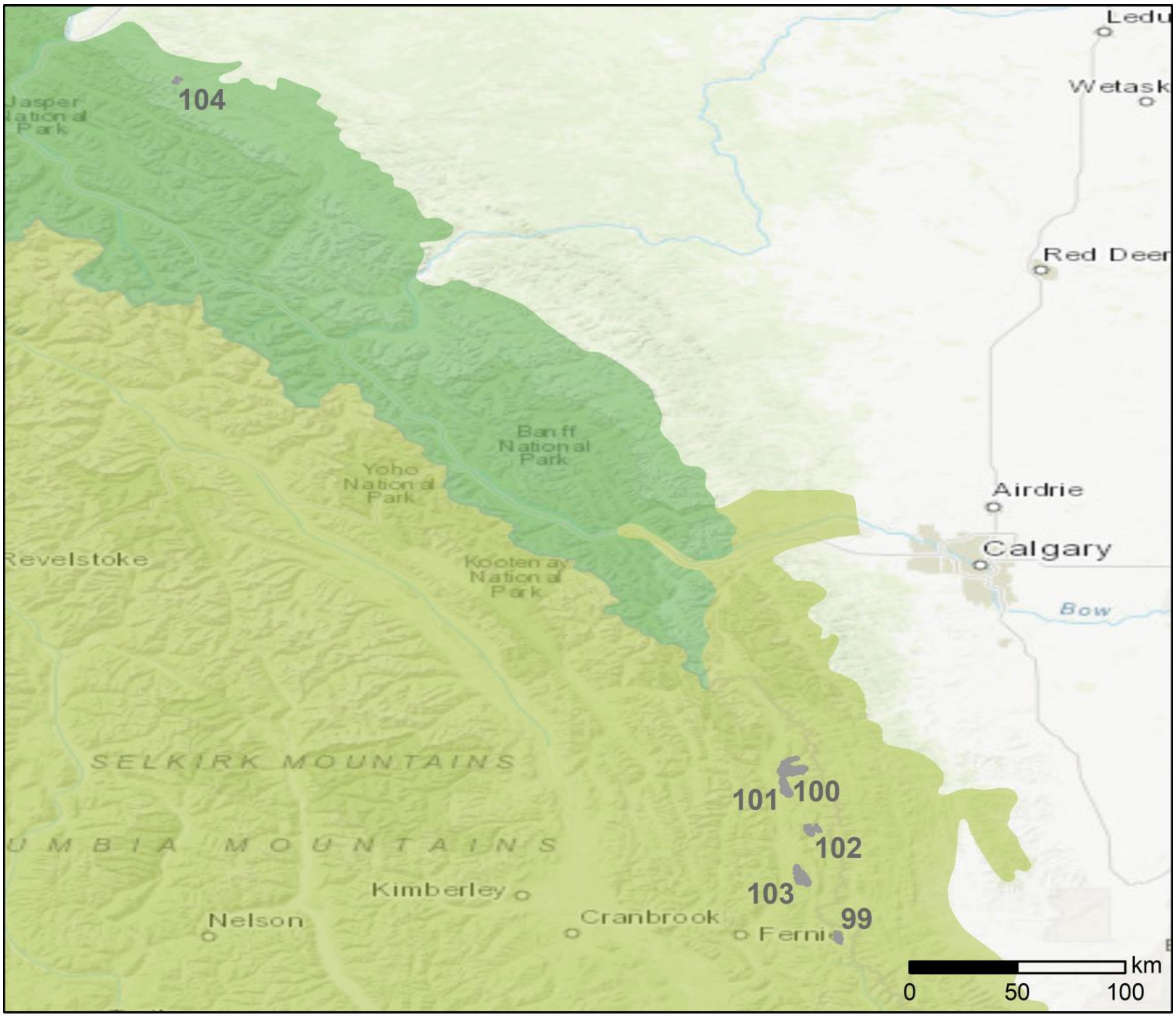
Base map service Layer Credits World Topographic Map: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community. Insert: GDAM. Projected Coordinate System NAD 1927 MTM 3.

Iron ore mining site

Ecoregion

Eastern Canadian Shield taiga (NA0606)

Figure D 5 Location of iron ore mining sites near Schefferville, Canada.



Base map service Layer Credits World Topographic Map: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community. Insert: GDAM.

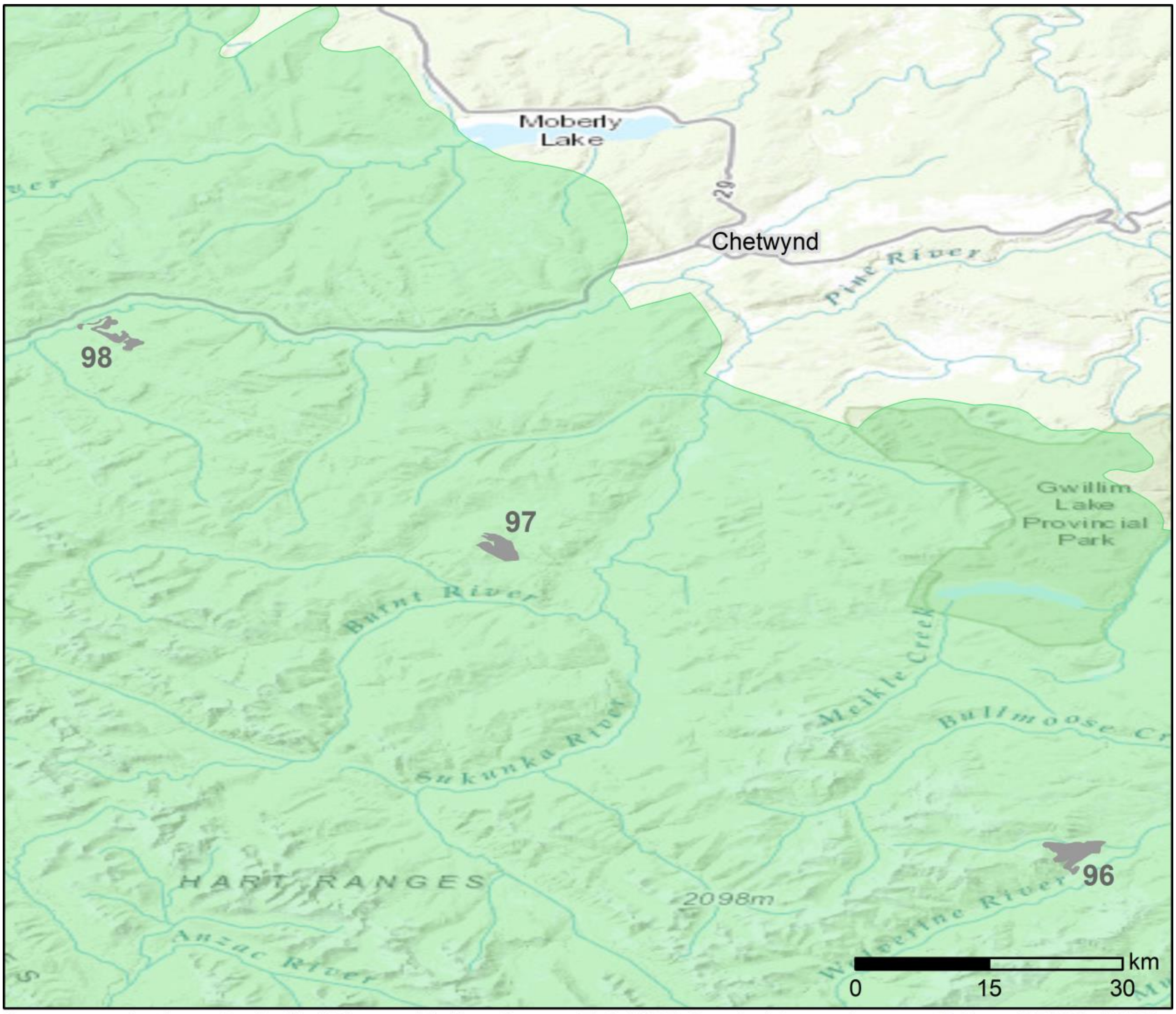
Coal mining sites

Ecoregion

Alberta Mountain forests (NA0501)

North Central Rockies forests (NA0518)

Figure D 6 Location of coal mining sites near Calgary, Canada.



Base map service Layer Credits World Topographic Map: Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community. Insert: GDAM.

Coal mining sites

Ecoregion

Central British Columbia Montain forests (NA0509)

Figure D 7 Location of coal mining sites near Chetwynd, Canada.

The HFI_{mod} and $HFI_{non\text{-}mod}$, and PP_i of the context areas created for the case study are shown in Table D 1. The column Label represents the mines in Figure D 1 to Figure D 7. Multiple labels on the same row represent more than one quarry or mine in the context area or that a mine is split by an ecoregion border, which will be used for the calculation using the method proposed by Chaudhary and Brooks (2018), in Table D 2.

Table D 1 Context area location, HFI, and PP_i. Longitude (Lon) and Latitude (Lat) of the centroid of the context area, in decimal degrees.

Commodity, location	HFI_{mod}	$HFI_{non\text{-}mod}$	PP_i	Context area [km^2]	Lon	Lat	Label
coal, Canada	0,10	5,61	0,86	19,41	-114,658	49,499	99
	2,17	10,36	0,48	31,44	-114,813	49,757	103
	1,01	5,15	0,79	27,48	-114,766	49,948	102
	1,04	4,49	0,80	73,52	-114,855	50,173	100
	0,00	9,93	0,75	16,13	-117,416	53,062	104
	0,00	1,25	0,97	20,29	-121,248	55,082	96
	0,00	1,54	0,96	13,19	-121,831	55,394	97
	0,00	6,05	0,85	18,00	-122,222	55,610	98
iron, Australia	3,00	3,88	0,40	11,58	120,134	-23,379	1
	4,60	8,00	0,13	34,36	119,675	-23,354	2
	3,00	6,00	0,38	11,54	120,049	-23,328	4
	2,00	0,74	0,68	30,34	117,817	-23,307	5
	4,33	11,88	0,14	17,65	117,610	-23,240	6
	2,80	8,44	0,39	22,17	118,772	-23,181	7
	0,81	4,66	0,83	21,43	119,123	-22,952	8
	3,86	10,19	0,20	38,23	118,937	-22,926	9
	1,34	6,33	0,71	36,19	117,756	-22,760	13
	2,60	3,87	0,49	98,97	119,131	-22,764	10, 11, 12, 14
	0,00	7,77	0,81	19,22	118,142	-22,647	15
	3,00	0,42	0,44	24,54	117,227	-22,587	16
	3,00	4,40	0,40	37,20	117,381	-22,425	19
	2,78	1,34	0,48	54,47	119,808	-22,398	17, 18, 20, 21, 22, 23, 24
	3,00	3,97	0,40	17,83	119,720	-22,361	25, 26
	1,34	0,25	0,84	17,00	117,877	-22,126	27
	3,46	7,34	0,28	26,15	116,244	-21,748	28, 29
	2,70	3,39	0,47	10,61	115,899	-21,664	30
	2,36	1,52	0,58	14,64	119,296	-21,535	31
	2,01	8,08	0,55	19,23	116,149	-21,079	32, 33
	2,47	4,71	0,51	12,62	116,195	-21,043	34

Commodity, location	HFI_{mod}	$HFI_{non\text{-}mod}$	PP_i	Context area [km²]	Lon	Lat	Label
iron, Brazil	0,95	12,31	0,63	10,63	-43,919	-20,468	35
	0,80	10,81	0,68	53,38	-43,845	-20,422	36, 37, 38, 39, 40
	0,00	7,69	0,81	7,33	-43,921	-20,380	41
	0,00	13,12	0,67	4,91	-43,943	-20,290	42
	0,00	14,51	0,64	18,92	-43,517	-20,258	43, 44, 45, 46
	6,12	15,84	0,03	13,48	-43,506	-20,200	47, 48, 49
	0,00	9,06	0,77	16,07	-43,441	-20,204	50, 51
	0,00	1,86	0,95	11,13	-43,619	-20,186	52
	2,39	10,66	0,44	16,12	-43,493	-20,160	56
	1,79	12,77	0,51	46,98	-43,876	-20,218	54, 55, 57
	7,87	18,33	0,00	18,48	-43,979	-20,163	53, 58
	0,93	7,66	0,74	36,17	-44,421	-20,147	59
	3,47	17,41	0,19	8,42	-44,223	-20,113	62
	3,17	15,34	0,25	23,93	-44,297	-20,114	66, 67
	1,67	14,57	0,49	10,62	-44,161	-20,105	68
	0,00	14,97	0,63	14,56	-43,416	-20,113	60, 65, 69
	4,56	13,31	0,11	30,73	-43,915	-20,106	61, 63, 64, 72, 73
	0,45	14,48	0,62	17,97	-44,106	-20,091	70, 71, 74
	4,92	23,78	0,05	5,45	-44,027	-20,064	75
	10,00	23,08	0,00	21,74	-43,967	-20,042	76, 77, 78, 79, 80, 81
	0,00	11,40	0,72	12,10	-43,592	-19,962	82, 83
	0,04	9,90	0,75	19,13	-43,226	-19,934	84
	0,00	11,64	0,71	8,97	-43,379	-19,860	85
	4,91	14,98	0,08	8,03	-43,189	-19,788	86, 87
	4,03	16,54	0,14	39,10	-43,251	-19,630	88
	2,45	8,73	0,45	42,68	-50,157	-6,057	89
iron, Canada	0,00	4,98	0,88	16,22	-67,356	52,351	90
	1,28	7,34	0,70	45,02	-67,320	52,778	91
	3,13	6,84	0,34	21,19	-67,286	52,847	94
	3,47	6,39	0,29	41,74	-66,946	53,033	92, 93
	0,00	2,62	0,93	12,69	-67,094	54,893	95

Table D 2 shows the ecoregion name, CF proposed by Chaudhary and Brooks (2018), and the measured area of the mine for each mining location.

Table D 2 Ecoregions and Characterization Factor (CF), for Urban intensive, aggregated taxa from Chaudhary and Brooks (2018). Longitude (Lon) and latitude (Lat) are in decimal degrees.

Commodity, location	Ecoregion name (ecoregion code)	CF [PDF/m²]	Mine area [km²]	Lon	Lat	Label
coal, Canada, AB	Alberta Mountain forests (NA0501)	$3,52 \cdot 10^{-14}$	2,80	-117,40	53,06	104
coal, Canada, BC	Central British Columbia Mountain forests (NA0509)	$2,73 \cdot 10^{-14}$	7,31	-121,20	55,08	96
			4,97	-121,80	55,39	97
			4,22	-122,20	55,61	98
coal, Canada, BC	North Central Rockies forests (NA0518)	$4,35 \cdot 10^{-14}$	10,17	-114,70	49,50	99
			27,40	-114,80	49,75	103
			13,08	-114,80	49,95	102
			18,72	-114,90	50,12	101
			41,00	-114,90	50,21	100
iron, Australia, WA	Pilbara shrublands (AA1307)	$4,98 \cdot 10^{-14}$	4,07	120,10	-23,38	1
			29,33	119,70	-23,36	2
			3,32	120,00	-23,33	4
			0,92	119,70	-23,32	3
			8,36	117,80	-23,31	5
			8,91	117,60	-23,24	6
			15,33	118,80	-23,18	7
			9,19	119,10	-22,95	8
			14,04	118,90	-22,93	9
			19,68	119,20	-22,79	11
			3,31	119,10	-22,77	10
			21,89	117,80	-22,76	13
			0,63	119,10	-22,74	12
			27,95	119,10	-22,74	14
			7,53	118,10	-22,65	15
			7,03	117,20	-22,59	16
			0,14	119,80	-22,43	17
			0,40	119,80	-22,42	18
			16,45	117,40	-22,42	19
			0,59	119,80	-22,41	20
			1,03	119,80	-22,40	21

Commodity, location	Ecoregion name (ecoregion code)	CF [PDF/m²]	Mine area [km²]	Lon	Lat	Label
iron, Australia, WA	Pilbara shrublands (AA1307)	$4{,}98 \cdot 10^{-14}$	6,16	119,80	-22,40	24
			3,35	119,80	-22,39	22
			5,11	119,80	-22,39	23
			2,77	119,70	-22,37	25
			2,91	119,70	-22,35	26
			4,97	117,90	-22,13	27
			16,04	116,20	-21,75	28
			0,91	116,30	-21,73	29
			3,58	115,90	-21,66	30
			4,28	119,30	-21,53	31
			11,11	116,10	-21,08	33
			0,14	116,10	-21,06	32
			3,75	116,20	-21,04	34
iron, Brazil, MG	Bahia interior forests (NT0104)	$7{,}27 \cdot 10^{-13}$	3,45	-43,92	-20,47	35
			0,35	-43,78	-20,44	36
			1,12	-43,79	-20,44	37
			0,27	-43,76	-20,44	38
			20,82	-43,87	-20,42	39
			0,99	-43,92	-20,38	41
			0,19	-43,94	-20,29	42
			10,17	-43,89	-20,26	54
			0,30	-43,44	-20,22	50
			2,77	-43,98	-20,18	53
			6,54	-43,98	-20,15	58
			17,46	-44,42	-20,15	59
			1,04	-43,42	-20,13	60
			0,77	-43,94	-20,12	63
			6,94	-44,30	-20,12	66
			1,09	-44,22	-20,11	62
			0,12	-43,41	-20,11	65
			1,26	-44,26	-20,11	67
			1,88	-44,16	-20,10	68
			0,31	-43,42	-20,10	69
			5,54	-44,10	-20,09	70
			1,50	-43,95	-20,09	72
			0,05	-44,10	-20,08	71
			0,44	-44,11	-20,08	74
			0,29	-44,03	-20,06	75
			0,63	-43,96	-20,06	76
			1,45	-43,98	-20,05	77
			0,79	-43,96	-20,05	78

Commodity, location	Ecoregion name (ecoregion code)	CF [PDF/m²]	Mine area [km²]	Lon	Lat	Label
iron, Brazil, MG	Bahia interior forests (NT0104)	$7{,}27 \cdot 10^{-13}$	0,38	-43,96	-20,03	80
			0,14	-43,58	-19,97	82
			1,51	-43,60	-19,96	83
			6,64	-43,23	-19,93	84
			2,10	-43,38	-19,86	85
			0,93	-43,19	-19,79	86
			0,05	-43,19	-19,78	87
			28,04	-43,25	-19,63	88
iron, Brazil, MG	Campos Rupestres montane savanna (NT0703)	$1{,}25 \cdot 10^{-12}$	7,14	-43,85	-20,41	40
			0,14	-43,51	-20,28	43
			0,17	-43,51	-20,28	44
			1,15	-43,52	-20,26	45
			0,36	-43,52	-20,24	46
			1,77	-43,51	-20,21	47
			28,68	-43,87	-20,21	55
			1,06	-43,50	-20,20	48
			3,55	-43,44	-20,20	51
			0,12	-43,51	-20,19	49
			1,86	-43,62	-20,19	52
			5,40	-43,50	-20,16	56
			1,20	-43,88	-20,15	57
			0,84	-43,88	-20,12	61
			6,12	-43,91	-20,12	64
			1,08	-43,94	-20,09	73
			0,28	-43,96	-20,05	79
			1,93	-43,96	-20,03	81
iron, Brazil, PA	Xingu-Tocantins-Araguaia moist forests (NT0180)	$1{,}94 \cdot 10^{-13}$	27,10	-50,16	-6,06	89
iron, Canada, NL	Eastern Canadian forests (NA0605)	$1{,}56 \cdot 10^{-14}$	1,64	-66,95	53,00	92
			10,00	-66,95	53,04	93
iron, Canada, NL	Eastern Canadian Shield taiga (NA0606)	$7{,}99 \cdot 10^{-15}$	3,40	-67,09	54,89	95
iron, Canada, QC	Eastern Canadian forests (NA0605)	$1{,}56 \cdot 10^{-14}$	4,66	-67,36	52,35	90
			56,45	-67,32	52,78	91
			9,55	-67,29	52,85	94

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Anthropogenic land cover modifications and human presence in natural environments are not without consequences to ecological processes. From a conservation perspective, these consequences are worrisome, especially when considering the human domination of terrestrial ecosystems worldwide. The recent loss of wilderness areas has been described as catastrophic despite pro-active conservation schemes' efforts to preserve these areas.

This thesis proposes a method to characterize a land use of interest in terms of the human pressures in its surroundings, transferring the landscape ecology concept of perforation and dissection to the product perspective of a life cycle assessment. Relying on spatial data, the Perforation Potential was designed to bring the location perspective to the heart of the analysis independently of predefined land use classes or biomes borders. The outcome is that one more level of detail regarding the potential impacts of a product's land use can be communicated to decision makers. This way, the method allows for more informed decisions to be made, ultimately avoiding harmful consequences for the environment.

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