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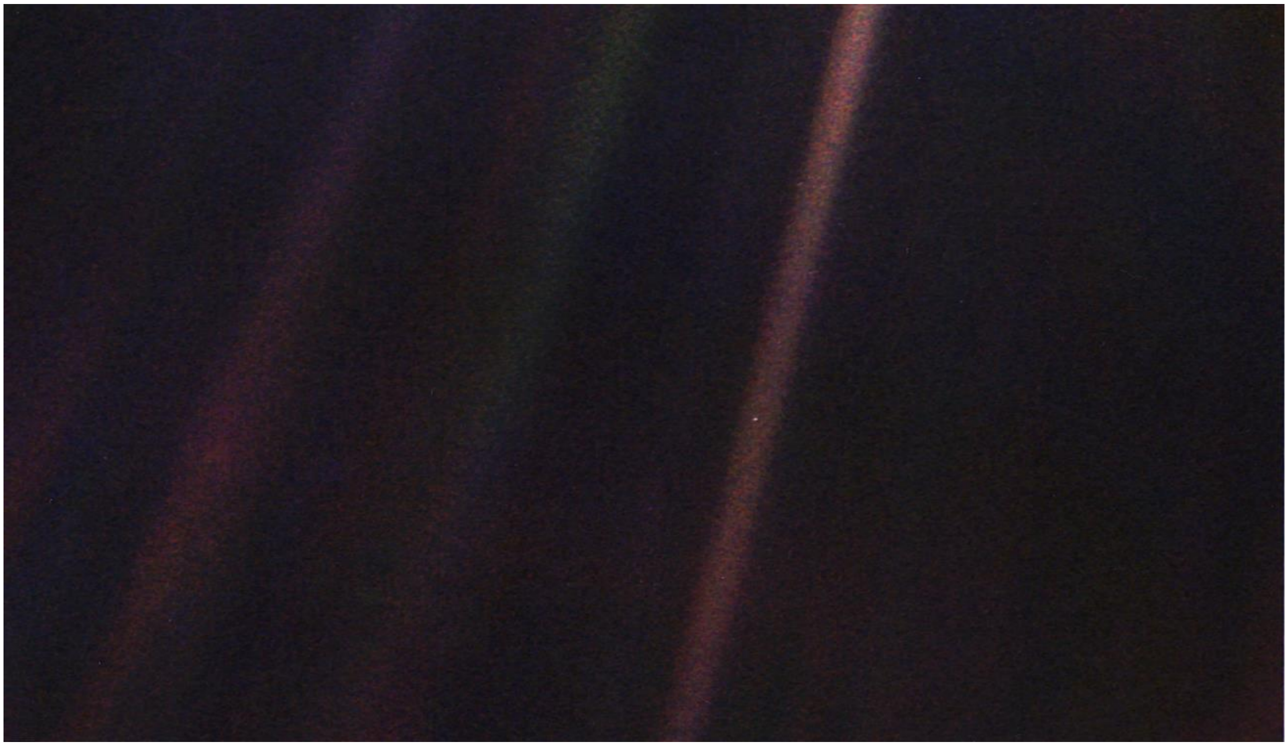

# To Measure the Unmeasurable

## Evaluation of biodiversity and ecosystem services indicators for land use impact accounting

Master's thesis in Industrial Ecology

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# Abstract

In recent centuries, the magnitude of stress humans have put on biodiversity and ecosystems has reached an unprecedented level. Several internationally coordinated environmental efforts have attempted to reduce anthropogenic impacts by setting up common targets and trajectories for achieving them. In order to assess progress towards these targets as well as the efficacy of our policies, methods are needed for quantifying the human impact on the environment.

Currently, in the context of measuring anthropogenic impact in land use, the quantification efforts are limited to inventories of greenhouse gases. Therefore, the objective of this thesis is to develop a proof-of-concept framework for quantifying biodiversity and ecosystem services in land use. The main research question involved finding and evaluating suitable indicators for this framework. The research began by identifying five essential criteria for evaluating potential biodiversity and ecosystem service indicators in the context of land use accounting: 1) land use appropriateness, 2) relevance, 3) spatial scale and scalability, 4) site-specificity, and 5) practicality and affordability. Then, by conducting a literature review, 117 unique indicators were identified from 34 studies, which were categorised into indicators of biodiversity or 24 different ecosystem services. The indicators were then ranked by scores based on these five criteria.

The results include sorted lists of indicators based on their suitability in the context of land use. This serves as a starting point for testing and further sophistication of land use indicators that account for biodiversity and ecosystem services.

Keywords: Kyoto Protocol; Land use, land-use change, and forestry (LULUCF); Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES); Sustainable Development Goal (SGD); Inventory report; Proof of concept; Mitigation and adaptation; Land management; Impact assessment

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# 1 Introduction

## 1.1 Background

### 1.1.1 Decline of biodiversity and ecosystem services

> "The variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems"
>
> - Definition of biodiversity by the Convention on Biological Diversity (United Nations, 1992, p. 4)

The Earth hosts an estimated 10 million species of living organisms such as plants, animals and microbes (Pimm et al., 1995) and the degree of variability among them and their habitats is described by the term biodiversity. A healthy and productive natural environment with a high level of biodiversity is an essential element for the functioning of ecosystems, and in turn, for human survival (Pimentel et al., 1997). Along with the irreversible nature of the loss of biodiversity (Dirzo and Raven, 2003), a general and well-established scientific consensus is that it is also accelerating due to human involvement (Díaz et al., n.d.; Hooper et al., 2005; MA, 2005). Research on how to qualitatively and quantitatively measure the anthropogenic impact on the loss of biodiversity therefore has become increasingly important (Winter et al., 2018).

The latest Living Planet Report (2018) produced by the Zoological Society of London for the World Wide Fund for Nature (WWF) reports a decline of 60% in wildlife populations between 1970 and 2014. This alarming rate of decline has been estimated by Pimm et al. (1995) to be in the range of 100-1,000 times higher than the standard background rate of extinction prior to major human impact on the environment. More recent research even suggests an even higher estimate of 10,000 times (Ceballos and Ehrlich, 2010; De Vos et al., 2015). All these estimates suggest a rapid loss of biodiversity, which some researchers have referred to as the "Sixth Mass Extinction" (Ceballos and Ehrlich, 2010).

One of the important roles that biodiversity plays is in the functioning of ecosystems, which depend greatly on the functional characteristics, variety and abundance of the organisms present (Hooper et al., 2005). The loss of biodiversity has the potential not only to greatly alter an ecosystem's properties, but also, in turn, to directly affect how it can provide goods and services to humanity through ecosystem services (ES) (Díaz et al., 2006; Hooper et al., 2005; Luck et al., 2003). Initially when loss of biodiversity occurs in an ecosystem, its impact on the ES is relatively minor. However, the magnitude of that impact is expected to accelerate with continuous losses of biodiversity, and may rival some of the major global change stressors such as global warming and ozone depletion (Cardinale et al., 2012).

In 2005, Millennium Ecosystem Assessment defined ‘ecosystem service’ as ‘the benefits that people obtain from ecosystems’ (MA, 2005) with examples being food, nutrient cycling, water purification, etc. It estimated that “approximately 60% of the ES ... are being degraded or used unsustainably…” (MA, 2005, p. 1). Since 2017, a new and similar concept, ‘Nature’s Contributions to People (NCP)’, was presented by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al., 2018; Pascual et al., 2017). It attempts to include more insights and knowledge from the humanities and other scientific disciplines that ES has so far excluded. However, it has been argued that this new approach requires more validation as well as operational guidance from further research (Ellis et al., 2019; Kadykalo et al., 2019).

Besides having an instrumental value for humans in the form of ecosystem services, biodiversity also has an intrinsic value that makes its conservation morally correct: it is an important part and product of continuous ecological evolution, and like humans, it has the right to a continued existence (Alho, 2008).

### 1.1.2 Sustainable land use

Land is an essential and invaluable natural resource for human survival, and also for the functioning of terrestrial ecosystems (FAO, 2020). Some of the most essential land use (LU) practices for humans include shelter, food production, freshwater balance, and climate regulation (Foley, 2005).

More than a decade ago, the Millennium Ecosystem Assessment (MA, 2005) concluded that LU is one of the main drivers of biodiversity loss. Recent research by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al., 2006, n.d.; Maier et al., 2019) also supports this conclusion. In one of IPBES’s latest summary reports, it argues that changes in LU have had the largest relative negative impact on terrestrial ecosystems in the past half-century (Díaz et al., 2006, n.d.). This issue has been addressed as one of the United Nation’s Sustainable Development Goals (SGDs), SDG 15 Life on Land (United Nations, 2019). This rapid and unprecedented decline of biodiversity is likely to undermine the progress of many international societal and environmental goals. The current trajectories suggest that most of them, including SDG 15, will not be achieved by their deadline (Díaz et al., 2006).

In the process of using land, humans have transformed large parts of the terrestrial surface, primarily through conversion of natural land to agricultural land (Olofsson and Hickler, 2008;

Ramankutty and Foley, 1999). Currently 40% of the global land surface is occupied by croplands and pastures (Ramankutty and Foley, 1999), with total global areas having increased by 110% and 59% respectively, from 1850 to 2015 (Houghton and Nassikas, 2017). The emissions from agricultural production, together with lost carbon storage at various LU activities, accounted for 24% of the total anthropogenic GHG emissions in 2010 (Pachauri et al., 2015). During the period of 1850 to 2015, the total global area of cropland has more than doubled, and the area of forest land shrank by 17% (Houghton and Nassikas, 2017). Searchinger et al. (2014) estimated that the demand for food is expected to have a 50% increase by 2050. With human activities playing a part in nearly 40% of global terrestrial net primary productivity (Vitousek et al., 1986) and major demographic stresses (e.g. population growth, urbanization, etc.), the pressure on our land and ecosystems is set to intensify as demand soars (Searchinger et al., 2014).

Deforestation holds the largest share of total carbon emissions caused by LU changes, accounting for 77% since 1850, and 85% between 2006 and 2015 (Houghton and Nassikas, 2017); leading drivers include swidden agriculture practices, frontier settlements and logging operations (Lambin et al., 2001). Forest land plays a critical role in climate mitigation because of its ability to sequester carbon (Houghton and Nassikas, 2017), and as such, the removal of native forests is a primary driver for the loss of biodiversity worldwide (Pandit et al., 2007; Panfil and Harvey, 2016). According to satellite imaging, currently we lose approximately 0.6% of global forest cover every year (Hansen et al., 2010). However, the rate of deforestation globally has been decreasing since its peak in the 1990s, after several hundreds of years of steady climbs (Houghton and Nassikas, 2017). The same downward trend has been found for swidden areas worldwide (van Vliet et al., 2012).

Due to this unprecedented rate of deforestation, the looming mass extinction of species has been discussed widely in many case studies. Although there is a scarcity of empirical meta-analysis for the normalized global state of biodiversity loss, many seem to agree that up to half of all species are under threat (Barlow et al., 2016; Brook et al., 2003, 2003; Pandit et al., 2007; Pitman and Jørgensen, 2002; Sayer and Whitmore, 1991; Whitmore et al., 1992).

### 1.1.3 International environmental agreements

Changes in LU may appear to have only local effects, but they have global impacts as well, and as such, require both global and local policy responses (Gupta et al., 2007). In June 1992, after months of global negotiation efforts, an international treaty (United Nations Framework Convention on Climate Change (UNFCCC)) was presented and opened for signing at the Earth Summit in Rio de Janeiro, Brazil (UNFCCC, 1992). The convention itself had no binding environmental actions and was intended to outline frameworks for future agreements that were action-oriented towards achieving the convention’s objectives. Its main long-term objective is to “...stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992, p. 4). Since then, it has received signatures from almost all global states, and entered into force in 1994.

Also presented at the Earth Summit was the Convention on Biological Diversity (CBD), another important milestone for the conservation of biodiversity (United Nations, 1992). Its three main objectives are "the conservation of biodiversity, sustainable use of biodiversity, and the fair and equitable sharing of the benefits arising from the use of genetic resources" (United Nations, 1992, p. 3). In 2010, under the CBD, 20 Aichi Biodiversity Targets were agreed upon to be achieved by 2020 (Smith, 2015).

#### 1.1.3.1 Kyoto protocol

One of the major results extended from the UNFCCC was the establishment of the Kyoto Protocol in 1997, which sets forth concrete binding commitment targets towards emission limitation and reductions during certain commitment periods (Kyoto Protocol, 1998). Additionally, it requires transparent and verifiable annual reporting of GHG emissions and removal of its sinks to the UNFCCC secretariat (Kyoto Protocol, 1998), including those resulting from, among others, Land Use, Land Use Change, and Forestry (LULUCF) activities (EU, 2014; UNFCCC, 2013). LULUCF is one of the GHG inventory sectors that addresses emissions and removal of GHG, and its main categories include LU changes between forest land, cropland, grassland, wetland, settlement, harvested wood products and others, with impact categories for carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), nitrogen oxides (NOx), carbon monoxide (CO) and non-methane volatile organic compounds (NMVOC) (Naturvårdsverket, 2020). The requirements for GHG emission inventories enable the tracking of progress for GHG reduction targets.

#### 1.1.3.2 Paris agreement

> "By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts."
>
> \- Sustainable Development Goal Target 15.9:
> Ecosystems and biodiversity (United Nations, 2019)

In 2015, almost two decades after the Kyoto protocol was established, another important milestone in terms of multilateral climate negotiations towards the UNFCCC's goals was set, which was the adaptation of the Paris Agreement (Rajamani, 2016). Apart from enhancing the UNFCCC, the main aim of the Paris Agreement is to hold the increase of global average temperature well below 2 °C above pre-industrial level, and pursue the effort to limit it to 1.5 °C (Paris Agreement, 2015). While the agreement itself contains no tangible plans towards the goal, it requires all the signed parties to communicate and maintain their domestic mitigation and adaptation ambitions in terms of Nationally Determined Contributions (NDCs) (Paris Agreement, 2015). The NDCs are required to be submitted every five years from 2015, with each successive one representing a higher level of ambition than the previous (Paris Agreement, 2015).

#### 1.1.3.3 Sustainable development goal

In the same year that the Paris Agreement was adopted, 17 Sustainable Development Goals (SDGs) were presented as part of the United Nations (UN) 2030 Agenda for Sustainable Development (Rosa, 2017), which was unanimously adopted by all UN member states (Martin, 2015). It addresses the universal, global challenges that all humans face, and aims to provide a comprehensive and people-centred set of goals and targets to work towards (United Nations, 2019). In recent years, there has been an increasing amount of literature linking climate change mitigation efforts to some societal objectives, especially those among SDGs (Campagnolo and Davide, 2019; Iyer et al., 2018; von Stechow et al., 2016, 2015). This finding is consistent with Northrop et al. (2016), who found climate actions across all the NDCs aligned with more than 90% of SDG targets. The close alignment between NDCs and SDGs represents an opportunity for both to be implemented together, in a synergic and mutually supportive manner (Iyer et al., 2018; Northrop et al., 2016).

Those key SDGs of LULUCF that impact biodiversity and ES include SDG 12 Responsible Production and Consumption and SDG 15 Life on Land. Despite slowing deforestation and more resources in conservation, the 2020 targets for SDG 15 are unlikely to be met (United Nations, 2019). Many proposed indicators (a measurement of value that can represent the state of something) for biodiversity assessment exist, although a general consensus for the most appropriate one is lacking (Petchey et al., 2009). Given the global nature of the problem it seeks to address, this would surely be one of the most irreplaceable and essential factors to incorporate quantitatively (Ahmed et al., 2019).

#### 1.1.3.4 Nagoya protocol

Similarly to how the Kyoto Protocol was an extension of the UNFCCC, the Nagoya Protocol on Access to Genetic Resources and Benefit-Sharing is an extension of the CBD. Its main aim is to create a legally binding framework that promotes transparency for CBD’s third objective, which is to share all benefits from the utilization of genetic resources equally and fairly.

### 1.1.4 Mitigation and adaptation

The relationship between mitigation and adaptation is an important aspect to address when tackling climate and biodiversity issues. Mitigation addresses the problem of how to dampen the physical emission of GHGs, while adaptation addresses how people and ecosystems anticipate changes in order to minimize potential damage (Tol, 2005; Vermeulen, 2014). While both approaches have the same ultimate goal, which is to reduce climate change, they differ in their methods and should be analysed together, even though most climate change projects focus on one or the other (Kongsager, 2018; Kongsager et al., 2016; Tol, 2005). Kongsager argued that all mitigation projects can potentially contribute to adaptation in some form (Kongsager, 2018); the most sustainable action arguably comes from a combination of these two (Laukkonen et al., 2009). However, with drastic mitigation measures to halt the climate change process, people in the poorest parts of the world may suffer (Gordijn and ten Have, 2012). By limiting the development potential of those regions that have contributed least to climate change, this triggers many questions about justice, compromise and responsibility (Gordijn and ten Have, 2012).

In the fifth report of the Intergovernmental Panel on Climate Change (IPCC, 2019), it is reported with high confidence that the Earth will rise 1.5°C in mean temperature in the middle of this century if it continues to increase at its current rate. Even if all emissions are halted to zero now, the effect of climate change will still persist for centuries as a result of the emissions that already exist in the atmosphere (Vermeulen, 2014). Furthermore, many of its effects will be irreversible, such as the loss of ecosystems and biological species (IPCC, 2019). Hence, it is important to consider the adaptation approach in our effort to accommodate the changing environment.

The annual reporting of GHG inventories mandated by Kyoto Protocol, is considered a tool for mitigation since it aims to document and track the progress of climate change goals. This thesis argues that it is just as important to track the status of biodiversity and ES, which are irreplaceable and essential for human survival (Vermeulen, 2014). Having a similar reporting scheme as for GHG, would enable early detection of changes in biodiversity and ES, and hence, related aspects of the adaptation process could be expediated.

### 1.1.5 Land use impact accounting

Given the continuous degradation of ecosystems, it is important to be able to measure and track how they are impacted by LU activities. Without this, we are incapable of assessing the impact and efficacy of any of the environmental commitments listed above, or indeed those implemented in the future.

This thesis defines ‘Land use impact accounting” as the methodology that quantitatively measures the human-induced impact of LULUCF in GHG, biodiversity and ecosystem services. As part of Swedish annual report of GHG inventories, Table 1.1 provides an example of land use impact accounting for GHG (Naturvårdsverket, 2019). The leftmost column lists types of LU and changes in those types. Their corresponding GHG emissions and removals are listed on the right. Using this table as an example, “Net $CO_2$ emissions/removals”, “$CH_4$” and “$N_2O$” can be defined as indicators of “Global warming”, with a unit of kiloton.

Table 1.1 Part of Swedish GHG source and sink categories of LULUCF sector in 2018.

| GREENHOUSE GAS SOURCE AND SINK CATEGORIES | Net $CO_2$ emissions/removals | $CH_4$ | $N_2O$ |
|---|---|---|---|
| | (kt) | | |
| **4. Total LULUCF** | -45381,99 | 17,38 | 4,09 |
| **A. Forest land** | -44490,23 | 8,77 | 3,62 |
| 1. Forest land remaining forest land | -43169,97 | 0,08 | 0,06 |
| 2. Land converted to forest land | -1320,26 | NO,IE | 0,06 |
| **B. Cropland** | 3473,55 | 8,02 | 0,02 |
| 1. Cropland remaining cropland | 3330,82 | NO,IE | NO,IE |
| 2. Land converted to cropland | 142,73 | NO,IE | 0,02 |
| **C. Grassland** | 66,72 | 0,29 | 0,06 |
| 1. Grassland remaining grassland | -183,06 | 0,01 | 0,06 |
| 2. Land converted to grassland | 249,79 | NO,IE | NO,IE |
| **D. Wetlands** | 195,48 | 0,29 | 0,00 |
| 1. Wetlands remaining wetlands | 195,48 | NO | NO |
| 2. Land converted to wetlands | NO,NA | NO | NO |

## 1.2 Aim of the study

There are a number of reviews of ES indicators (Cardinale et al., 2012; Haase et al., 2014; Hernández-Morcillo et al., 2013; Seppelt et al., 2011), but comprehensive assessments of indicators in an LU accounting context are rare, and more research is needed on this topic. The following questions have not been addressed by the literature and will serve as research questions of this study:

- With an inventory of biodiversity and ES indicators, what are the best ones in the context of LU impact accounting?
- Which criteria can be used to evaluate these indicators?
- Given the limited data and studies available, which indicators are recommended to be tested first?

This thesis aims to offer a proof-of-concept framework for biodiversity and ES in an LU accounting matrix. This involves evaluating existing indicators of biodiversity and ecosystem services and finding the most appropriate ones. Many indicators exist to assess the progress of global biodiversity efforts (Butchart et al., 2010; Tittensor et al., 2014), although few have the potential to be used in conjunction with LU. The first step in acknowledging the links between climate change and biodiversity goals within the LU sector is to, measure and document them. The intention is to focus on recommending a set of indicators that are practical for other researchers to test and develop further.

Currently, in the annual reporting scheme for LULUCF mandated by the Kyoto Protocol, only GHG fluxes have been taken into account, in forms of LU matrices and often in units of $CO_2$ equivalents (Naturvårdsverket, 2020), and yet the effects of climate change go beyond GHG and global warming. This thesis therefore suggests that this type of quantitative accounting can be augmented to include parameters for biodiversity and ES, so that the status and progress of SDGs can be measured and accounted for, similarly to how GHG accounting measures the progress of GHG reduction goals. While reducing GHGs is one of the main goals of policymakers when making LU decisions (Searchinger et al., 2018), it is equally important to consider how these decisions influence SDGs for biodiversity and ES. Having a method to quantify biodiversity and ES will support policymakers in their decision-making process and help them to evaluate potential mutual benefits and trade-offs between policies and measures, thus allowing them to prioritise actions.

## 1.3 Delimitations

- The concept of ecosystem service was dealt with as a social construct that does not exist in the absence of humans (Fu et al., 2013), hence, the complexity of ecosystem processes underpinning and producing those ecosystem services (Wallace, 2007) was not considered.
- Due to time constraints, only the top 200 most-cited papers out of nearly 18,000 found were selected for literature review.
- Indicators consolidated from multiple indicators were disregarded
- Evaluation of indicators was done primarily by the author, and hence, subject to personal bias.

# 2 Methodology

The research process consisted of four stages: 1) Selection of evaluation criteria, 2) Selection of biodiversity and ecosystem indicators, 3) Processing of indicators and 4) Evaluation of indicators and criteria. This is illustrated by Figure 2.1 below.

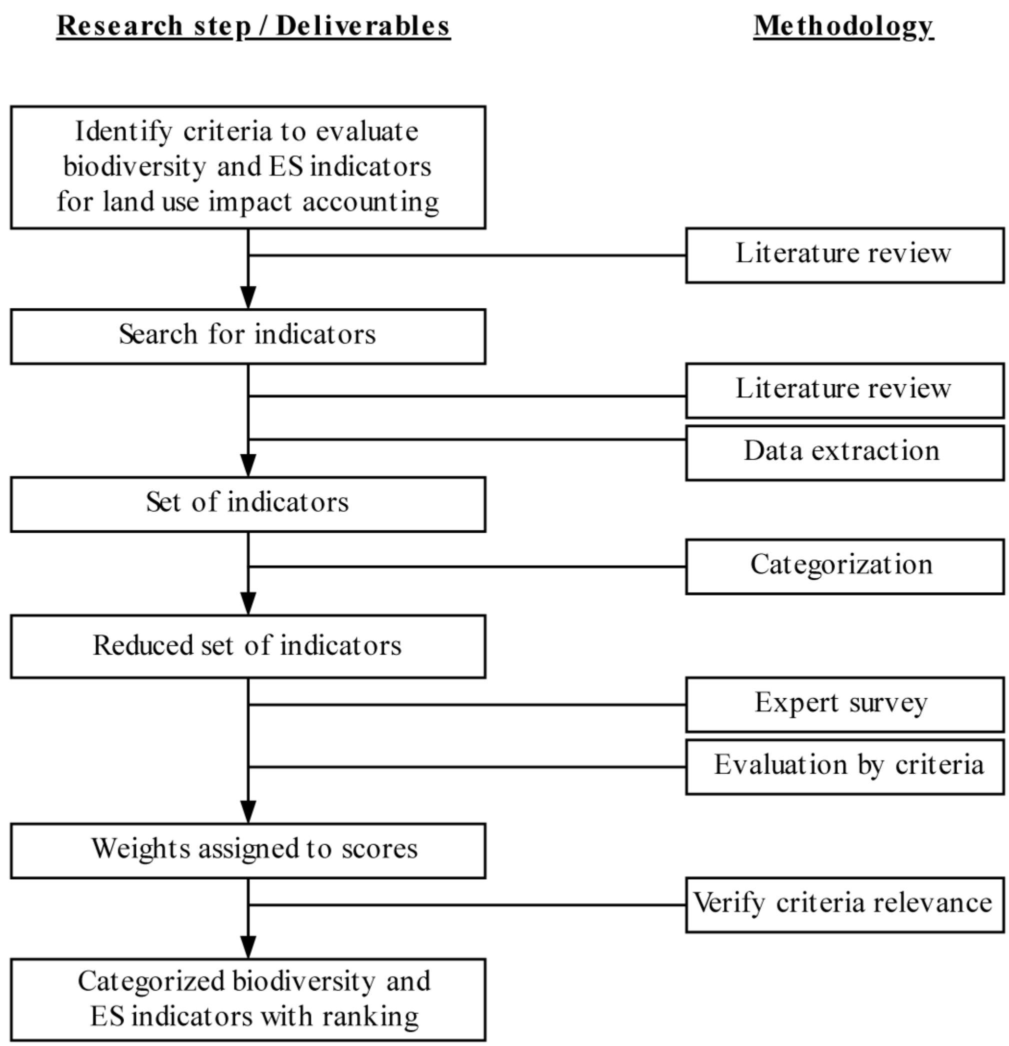


Figure 2.1. Summary of research steps and methodology.

During the first half of the research process, two independent rounds of literature research were conducted. The first round was dedicated to identifying suitable properties and thresholds for evaluating indicators' potential in an LU accounting matrix. In the second round, a broad search was done to collect as many relevant indicators as possible in preparation for the upcoming evaluation. Subsequently, the indicators were matched against the chosen criteria and a multi-criteria analysis conducted to evaluate their appropriateness as indicators in the context of LU.

## 2.1 Selection of evaluation criteria

### 2.1.1 Literature research

Before being able to evaluate indicators, a set of criteria is required to match them against. Therefore, the first step was to identify the criteria of biodiversity and ES indicators in the context of LU impact accounting. The academic search engines Web of Science (Web of Science, 2020) and Scopus (Scopus, 2020) were used to identify any comprehensive study that has analysed biodiversity and ES indicators with a set of evaluation criteria. The following advanced search strings were used.

- Web of Science
  - TS=(("criteria*" OR "propert*" OR attribute or characteristic) AND (desirable OR good OR suit* OR relevant OR applicable) AND (indicator OR dataset) and ("biodiversity" AND "ecosystem service*")
- Scopus
  - TITLE-ABS-KEY(("criteria*" OR "propert*" OR attribute OR characteristic) AND (desirable OR good OR suit* OR relevant OR applicable) AND ("indicator*" OR dataset) AND ("biodiversity" AND "ecosystem service*"))

These searches resulted in 184 and 119 studies, respectively. After removing duplicates, six comprehensive reviews that fulfilled the requirements were found by going through the result list. The criteria were extracted from the reviews, and compared on the basis of relevance to LU impact accounting. Ultimately, a set of relevant and independent criteria were selected to grade the indicators.

### 2.1.2 Identification of criteria

A number of studies have assessed the effectiveness of biodiversity and ES indicators (Brown et al., 2014; Feld et al., 2010; Haase et al., 2014; Hernández-Morcillo et al., 2013; Nordborg et al., 2017; Teixeira et al., 2018). By analysing these studies, five criteria were identified to be essential in the context of LU impact accounting, see Table 2.1. These criteria are used to evaluate indicators at the step of “Evaluation by criteria” (Figure 2.1).

With the goal to quantify impact in the context of a LU accounting matrix, it is essential for indicators to be applicable to different LU types. The LU types referred to here are from Volume 4, Chapter 3 of the 2019 IPCC guidelines (IPCC, 2019) which consist of Forest Land, Cropland, Grassland, Wetlands, Settlements, and Other Land (subject to nationally determined area thresholds):

- Forest Land - Land with woody vegetation or structure

- Cropland - Agriculture and agro-forestry land
- Grassland - Rangeland and pasture, including also woody vegetation land that falls below the threshold for Forest Land
- Wetlands - Land that is covered or saturated by water, including peatlands, reservoirs and natural rivers and lakes
- Settlements - Developed land, such as transportation infrastructure and human settlements
- Other Land - Land that does not fall into the above-mentioned categories

Table 2.1. List of indicator criteria for LU impact accounting.

| Indicator criteria | Definition | Source | Evaluation score |
|---|---|---|---|
| Land use | Applicable and quantifiable for LU types: forest, cropland, grassland, wetland, settlements, others | See text | 0 - Not for more than one<br>1 - Yes for a few types<br>2 - Yes for most types |
| Relevance | Direct/indirect linkages to biodiversity and/or ES with considerable scientific evidence | (Feld et al., 2010) | 0 - No<br>1 - Partly<br>2 - Yes |
| Spatial scale and scalability | Applicable over ranges of spatial scales and capable of scaling up/down to local, regional, global level | (Feld et al., 2010) | 0 - No<br>1 - Yes with another unit<br>2 - Yes |
| Site-specificity | Can be site-specific | (Teixeira et al., 2016) | 0 - No<br>1 - Under certain conditions<br>2 - Yes |
| Practicality and affordability | Being practical and affordable ensures continued use which improves the reliability of the data | (Brown et al., 2014) | 0 - Requires substantial resources or specialist technical knowledge<br>1 - Requires some knowledge<br>2 - Practical and can be done without any previous training |

Indicators that are applicable to different LU types enable comparison and congregation across those types, which is a fundamental feature of the existing GHG reporting scheme for LULUCF. The source field for “Land use” in Table 2.1 was left empty since it is this study’s addition.

Feld et al. (2010) suggested the following seven assessment criteria when testing general biodiversity and ES indicators: 1) purpose of indication, 2) indicator type according to the European Environment Agency’s Driver-Pressure-State-Impact-Response scheme, 3) direct/indirect linkages to biodiversity and ES, 4) spatial scale and scalability across scales, 5) applicability of benchmarks/reference values, 6) availability of data and protocols, 7) applicability of remote sensing.

The criterion no. 1) in Feld et al. (2010) was disregarded as an evaluation criterion for this thesis since it is considered a common requisite for all indicators. Those that did not fulfil the common characteristics of good indicators, namely, representativeness, reliability, and feasibility (Nordborg et al., 2017), had already been discarded at the step of “Data extraction” (Figure 2.1, section 2.2.3). This was to ensure quality standard of the indicators before being evaluated for suitableness in a LU accounting matrix. With regard to the second criterion, it used an indicator framework that enables feedbacks on environmental quality, which does not align with the purpose of this thesis. Instead, we used the ES classification framework proposed by the Millennium Ecosystem Assessment (MA, 2005) to categorise the indicators ("Categorisation" on Figure 2.1). This step came before "Evaluation by criteria", hence, the second criterion was not used for evaluation.

Regarding the third criterion by Feld et al. (2010), "Relevance", it concerns the linkage to biodiversity and ES. Although this criterion is relevant for indicator evaluation, anthropogenic relevance of the linkage was not considered in their study, this is one of the limitations of this thesis. With regard to the criteria 5-7), this study considered those to be used for optimisation rather than being essential characteristics of indicators for a proof-of-concept type of framework. For the purpose of testing such a framework, it is also important that the indicators can be site-specific (Teixeira et al., 2016) such that biodiversity and ES can be accurately accessed at a local or regional level.

Furthermore, in a guidance brochure for developing ES indicators, published by Stockholm Resilience Centre (Brown et al., 2014), one additional, non-overlapping criterion was identified: practicality and affordability. This criterion is important because, if the research and practical process are affordable and easy to conduct, it is more likely that it will be done more frequently, hence more data sets will be available. Ultimately, this improves the reliability of the data.

For cultural ecosystem services, a comprehensive study has been done to evaluate the indicators (Hernández-Morcillo et al., 2013). The evaluation framework used was called SPICED (Roche, 1999), and included the properties 'subjective', 'participatory', 'interpreted', 'communicable, cross-checked, and compared', 'empowering', and 'diverse and disaggregated'. This set of criteria was not used in this study; it is presented here for future work reference.

#### 2.1.2.1 Weighting of criteria

An attempt was made to establish how the criteria differ with regard to their overall relevance to the aim. If such difference exists, weighting can be used to make the rankings of the indicator more valid. Therefore, in this study, in order to compensate for lack of experience and knowledge, a rank-order weighting method (Wang et al., 2009) was utilised to generate a set of weights. The method essentially requires weights to be normalised and fulfilled as $w_1 \geq w_2 \geq \cdots \geq w_n \geq 0$ and $\sum_{i=1}^{n} w_i = 1$.

A questionnaire was created for this study's supervisors, asking them to give a score from 1 to 10 for each criterion (1 - not at all important, 10 - very important), depending on the importance of the criteria that they consider an indicator should have in this context. After normalising the answer, the final result showed a similar value for latter four of the five criteria: {0.13, 0.23, 0.21, 0.21, 0.22} for ‘Land use’, ‘Relevance’, ‘Spatial scale and scalability’, ‘Site-specificity’, ‘Practicality and Affordability’, respectively. The result can be loosely interpreted as the ‘Land use’ criterion being half as important, compared to each of the other criteria.

## 2.2 Selection of indicators

Establishing the set of biodiversity and ES indicators to be used in the assessment was crucial to this research process. The main aim for this step was to conduct a literature review to assemble as many indicators of biodiversity and ES as possible. The framework of the review methodology was primarily adopted from Kitchenham and Charters (2007) and Templier and Paré (2015) which suggests the following key steps:

1. Problem Formulation
2. Literature Research
3. Study Selection
4. Data Extraction
5. Data Synthesis
6. Evaluation

The first step, ‘Problem Formulation’, has already been addressed in Section 1.2 above.

In order to reduce the resulting collection of indicators to a manageable range within the time constraint, several strategies were employed: firstly, only 100 of the most cited articles on each of the two search engines were considered. This maximizes the chance of getting indicators that are scientifically sound as well as frequently used by other researchers.

Secondly, this study chose to evaluate the indicators as they were, based on the reasoning that it is valuable to understand which types of units tend to work better in this context, and that new units may lack scientific ground and/or have less data available.

### 2.2.1 Literature research

The next step was to find and identify studies relevant to the research questions stated in Section 1.2. In view of the fact that different types of assessment indicators and methods exist for biodiversity and for each type of ecosystem service, the first step was to construct a search strategy. Levac et al. (2010) suggest that one should include “where to search, which terms to use, which sources are to be searched, time span, and language”. This process was an iterative one and included other sources besides the preliminary ones below. For secondary resources, reference lists of influential papers, key journals, and conferences were included. The time span for relevant studies was set to the past ten years. Regarding the language, only resources in English were considered. Additionally, since limiting the scope was unavoidable, discussion was held to acknowledge the decisions involved, as well as the effects of the limitations.

With the aim of understanding current research and terminology pertaining to the research questions stated above in section 1.2, this study's initial information sources were as follows:

- Schemes by Intergovernmental organizations
    - Annual reporting of GHG emission and sinks (Kyoto Protocol, 1998; SLU, 2019)
- Indicator sets and reference levels embedded in various sustainability and economic schemes, such as Flexible Mechanisms (Kyoto Protocol, 1998), REDD+ (Halpern, 2016)
- Life Cycle (Impact) Assessment (Ahmed et al., 2019; Baumann and Tillman, 2004; de Souza et al., 2013; Koellner et al., 2013; Lindner et al., 2019; Maier et al., 2019; Turner et al., 2019; Winter et al., 2018)
- Various independent definition and measurements of biodiversity (Butchart et al., 2010; Duelli and Obrist, 2003; Girardello et al., 2019; Korner and Spehn, 2019; Schröter et al., 2020)

Besides these sources, ad-hoc research was also involved by searching under different keywords (land use, assessment, indicator, biodiversity conservation, ES etc.) on Google Scholar (Google, 2020) without any specific search strategy.

After getting familiar with the topic, a comprehensive search was conducted using the academic database search engines Scopus (Scopus, 2020) and Web of Science (Web of Science, 2020) with keywords relevant to the research questions, limited to literature in English in the past 10 years. The reason behind choosing 10 years was that, in 2010, 20 Archi Biodiversity Targets were agreed upon, to be achieved by 2020 (Tittensor et al., 2014). During this time frame, new indicators would have been developed, and pre-existing ones have been tested. It was also assumed that the suggested time frame was lengthy enough for any trend in biodiversity and ecosystem indicators to be noticeable.

Using the following search strings, 9,554 hits and 8,185 hits are found respectively prior to duplication check.

- Web of Science:
    - TS=((biodiversity OR "ecosystem service*") AND indicator)
        - Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI
          Timespan= 2011-2020

    - With the TS tag, WoS searches through Title, Abstract, Author Keywords and its proprietary Keywords Plus® database built with related articles based on relevance (Web of Science, 2020).
- Scopus:
    - TITLE-ABS-KEY ((biodiversity OR "ecosystem service*" ) AND indicator) AND PUBYEAR > 2010
    - TITLE-ABS-KEY indicates that it searches through Title, Abstract and Author Keywords.

Then, the reference information was extracted from the top 100 cited articles on each of the search engines and imported it into a BibTex (BibTex, 2020) file. Subsequently, the file was imported into Zotero, an open-source reference management software (Zotero, 2020).

### 2.2.2 Study selection

This step aimed to filter and identify relevant studies from the list in the previous step, so that data could be extracted and synthesized (Templier and Paré, 2015). To do this, a systematic study selection process inspired by PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) (Liberati et al., 2009) was utilised:

1. # of studies identified through
    a) Database search
    b) Other sources
2. # of studies after removing duplicates removed
    a) Initial screening of titles and abstracts
3. # of studies excluded
4. Screening of full-text articles
    a) # of studies excluded, with reason
5. # of studies included

A systematic process like the one above serves the additional purpose of reproducibility. To ensure relevance to the research questions, the following list of inclusion criteria was used initially to screen against the studies.

- studies anthropogenic impacts on biodiversity or ES
- has quantified indicators that reflect impacts for biodiversity or ES

After removing 65 duplicate results with Zotero's built-in duplicate record management function, a total of 135 unique articles remained from Scopus and Web of Science. After putting all the titles and abstracts against the aforementioned selection criteria, of the 76 articles left for full-text review, 34 articles matched the criteria and were selected for the next step of data extraction.

### 2.2.3 Data extraction

The objective of this step is to record and categorise information from the studies selected previously. To calculate the anthropogenic impact, Koellner et al. (2013) recommends calculating the differentiation of ecosystem quality with an absolute scale rather than a relative one. However, the aim was to collect as many potential indicators as possible with different units. To minimize the opportunity for bias, Kitchenham and Charters (2007) suggest that a data extraction form should be defined at an earlier stage of such a study, and then used to collect the information needed. Besides the indicator and its unit, which is essential, biodiversity and ES type will also be documented, as well as the source of literature. To assure the quality of the indicators, only those that fulfilled the basic common characteristics of a good indicator, namely, representativeness, reliability, and feasibility, were extracted (Nordborg et al., 2017).

- Biodiversity / ES type
- Indicator
- Unit
- Source

From the 34 studies chosen after the full-text review in the previous step, 192 potential indicators were identified.

## 2.3 Processing of indicators

The list of 192 indicators had many duplicates, and lacked a proper structure of categorization. Sequentially, the indicators were categorised into their appropriate assessment category of biodiversity and four categories of ES. According to the Millennium Ecosystem Assessment (MA, 2005), ES are generally classified into four categories with their corresponding subcategories (see Table 2.2):

Table 2.2. List of ecosystem service subcategories.

| | ES Subcategory |
|---|---|
| Provisioning | Food |
| | Fibre |
| | Fuel |
| | Genetic resources |
| | Biochemicals |
| | Ornamental resources |
| | Fresh water |

| | ES Subcategory |
|---|---|
| Supporting | Soil formation |
| | Photosynthesis |
| | Primary production |
| | Nutrient cycling |
| | Water cycling |

| | ES Subcategory |
|---|---|
| Regulating | Air quality regulation |
| | Climate regulation |
| | Water regulation |
| | Erosion regulation |
| | Water purification |
| | Disease regulation |
| | Pest regulation |
| | Pollination |
| | Natural hazard regulation |

| | ES Subcategory |
|---|---|
| Cultural | Cultural diversity |
| | Spiritual and religious values |
| | Knowledge systems |
| | Educational values |
| | Inspiration |
| | Aesthetic values |
| | Social relations |
| | Sense of place |
| | Cultural heritage values |
| | Recreation and ecotourism |

- Provisioning services: “Products obtained from ecosystems”
- Regulating services: “Benefits obtained from the regulation of ecosystem processes”
- Supporting services: “Services necessary for the production of all other ecosystem services”
- Cultural services: “Nonmaterial benefits obtained from ecosystems”

Once the indicators had been categorised into their corresponding subcategories, indicators with similar units were merged. It is important to note that some indicators were initially in the category of “Ecological Integrity” in the literature (Ahern et al., 2014; Burkhard et al., 2014; Roo-Zielinska et al., 2019) but due to their similarity to some indicators in the rest of the biodiversity and ES categories, they were distributed to their corresponding ES categories.

The list was then down to 117 indicators and ready for evaluation

## 2.4 Evaluation

### 2.4.1 Evaluation of indicators

Each of the indicators was scored between 0, 1 and 2 according to each criterion’s scoring definition in Table 2.1; their cells were coloured red, yellow, and green, respectively. This turned out to be a challenging process since a lot of assumptions had to be made. The process of evaluation itself is described in detail in the Results section. When computing for the indicator ranking, a weighted sum approach was chosen for its simplicity, which is one of the most commonly used methods (Wang et al., 2009). The final score of an indicator should be between 0 and 1:

$$S_i = \frac{1}{2}\sum_{j=1}^{n} w_j x_{ij}, \quad i = 1,2,\ldots,m$$

where $w_j$ denotes the weight of $j$-th criteria, with $n$ and $m$ being number of criteria and number of indicators, respectively. See Appendix C for the full list.

### 2.4.2 Evaluation of criteria

From the earlier step, it was noted that the "Site-specificity" property had less variance than its counterparts in the valuations. Hence, an analysis of the chosen criteria was conducted once most of the evaluations were filled in. The aim was to establish whether all the chosen criteria were relevant enough and also to statistically measure the contributions of each criteria to the final score. For this task, this study utilised the Least Mean Square (LMS) method (Wang et al., 2009), in which a criterion that has less contribution than others can be eliminated from the calculation, thereby allowing for bigger influences from other criteria. Let $n$ and $m$ denote the number of total criteria and indicators, respectively, and

$$s_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(x_{ij} - \overline{x}_j\right)^2} \quad (j = 1,2,\ldots,n)$$

where $x_{ij}$ is the $i$-th data point of the $j$-th criteria with $i = 1,2,\ldots,m$, and

$$\overline{x}_j = \frac{1}{m}\sum_{i=1}^{m} x_{ij}$$

If there is a $k$ such that $s_k = min_{1\le j\le n}\{s_j\}$ and $s_k \approx 0$, then the $k$-th criteria can be eliminated.

# 3 Results

The results are presented in two subsections. With the first, the intention is to show the evaluation process with regard to scoring the indicators. The latter will present the findings on the aggregated ranking of the assessed indicators and their corresponding categories.

## 3.1 Evaluation of criteria

By the use of Least Mean Square method, the value of (0.54, 0.50, 0.85, 0,43, 0,82) was derived for land use appropriateness, relevance, spatial scale, site-specificity, and affordability, respectively. The elements had a maximum possible value of 1. Since the smallest element (0.43), which represents site-specificity, is not near 0, all of the criteria are considered essential.

### 3.1.1 Land use appropriateness

The ultimate goal of this research is to contribute to a new framework for biodiversity and ES accounting in the context of LU. While it is not essential for an indicator to be suitable for all LU types (section 2.1.2 above), it is of interest to investigate if the indicator can be comparable in-between LU types. Therefore, a high score is given if it can be representative for more LU types, since it facilitates the data collection process and comparisons. Each of the LU types can be further categorized into smaller subtypes, but this criterion does not consider this scenario, as discussed in section 1.3 Delimitations.

Taking “Food” as an ES example, two of the proposed indicators are “Percentage of urban green area dedicated to agricultural activities” and “Plant biomass available”, having “%” and “kJ/ha” as units, respectively (Burkhard et al., 2012; Haase et al., 2014; Maes et al., 2012). In an LU accounting matrix, an indicator should be comparable between major LU categories. This property makes comparisons straightforward and easy to interpret. “Percentage of urban green area dedicated to agricultural activities” is only representative of one major land category (urban land uses), and is therefore given a score of 0. On the other hand, “Plant biomass available” can be representative for almost all LU categories since they are considered ubiquitous.

Another example is “Fibre”, for which there are two proposed indicators “Harvested wood (solid)” and “Yield”. The first is restricted to some of the major LU types where wood harvested is prevalent (1 in score), while the second can be used in conjunction with other fibre products, ultimately, with all LU types (2 in score).

### 3.1.2 Relevance as biodiversity and ES indicators

For the data collection stage, a filter was created to exclude any indicator that did not fit into the essential characteristics of being a good indicator of any kind, particularly for “representativeness” of biodiversity and ES (Nordborg et al., 2017), which should not be misinterpreted as “relevance”. One indicator may represent a connection to the impact category which it is measuring, but its relevance and effectiveness varies.

In this study, the emphasis is on indicators that can reliably and directly assess the state and capability of the biodiversity and ES. Although many indicators had the potential to be a proxy parameter in the assessment, they were given a lower score in the evaluation because of their indirectness. Take “temperature”, for instance, as an indicator for “climate regulation”: even though it is an essential parameter and is part of the overall assessment of the climate regulating capability, it does not offer reliable correlation as to how well the regulating functions. Hence it only received one point in the score, as opposed to two for carbon sequestration which measures how much carbon dioxide gets dampened and stored, which in turn directly correlates to the speed of carbon dioxide accumulation and the heating of the planet.

### 3.1.3 Spatial scale and scalability

For an indicator to be included in an LU accounting matrix, it was evaluated on whether it can scale up or down, and be applied in different spatial scales. The possibility of being applied across different spatial scales is considered useful, since it enables comparisons across regions or ecosystems. For the future users of the matrix, it is also practical if the listed data can be scaled up or down to be applied at a local, regional or even global level (Feld et al., 2010). It has been argued that some indicators of the biodiversity and LU categories receive less benefits from this criteria, such as species diversity (Huston, 1999) or soil related indicators (Nortcliff, 2002). However, no special treatment were introduced for those indicators. During the evaluation process, it also became obvious that most of the indicators with a relative unit did not score well in this category due to their unscalability.

For example, “Mean Species Abundance (MSA) of original species” is an indicator for biodiversity that measures naturalness or biodiversity intactness and has a unit of “% of original species if it is fully natural” (Alkemade et al., 2009). This indicator received 0 in this scoring category because it cannot be scaled spatially. On the other hand, “Species richness”, which calculates the number of different species present, received the highest score 2 because it can be scaled to represent a bigger area.

### 3.1.4 Site-specificity

One of the aims is to offer recommendations of indicators to test in LU accounting purposes. For an indicator to be site-specific, it must enable the researcher to: 1) work in a sufficiently small scale with more precision, and fewer uncertainties and assumptions, 2) collect site-specific data that is comparable across different local sites for cross-examination and verification.

While most of the collected indicators can be tested locally to be site-specific, some of the indicators lack this property completely or require more work / assumptions to fulfil. Some of the more notable ones are “Atmospheric CO2 concentration”, and “Number of floods causing damages”. The former may have variations lower to the ground, but is considered well-mixed in the atmosphere (0 as score). The latter has an ambiguous threshold of area, and assumptions have to be made in order to have site-specific data (1 as score).

### 3.1.5 Practicality and affordability

When an indicator is measured continuously over a long period of time, its scientific rigour is improved. One of the factors that can encourage this is to have indicators that are inexpensive to measure and require less technical knowledge to conduct. With the aim of creating an accounting matrix, it is expected that data will be flowing in periodically and continuously. Hence, being practical and affordable is an important trait for an indicator in this context. An indicator’s score is 0 if it required substantial resources or specialist technical knowledge to conduct the measurement, with examples being “Dissolved organic and inorganic matter” and “Human appropriation of net primary productivity (HANPP)”. Some examples of the most practical ones are “PM2.5 concentration in air”, which can be read off a measuring instrument, and “Area of natural barriers (dunes, mangroves, wetlands, coral reefs)”, which does not require specialist technical knowledge to measure.

## 3.2 Collection of indicators

After data extraction from 34 different studies, a total of 192 indicators were collected (see part of the list in Table 3.1 below; the full list can be found in Appendix A). These were organised by the impact category of biodiversity and all ecosystem service types. Duplicated items exist and the impact categories are not standardised.

Table 3.1. Part of uncategorised indicators prior to processing.

| Biodiversity / ES type | Indicator | Unit | Source |
|---|---|---|---|
| Stormwater infiltration | Soil permeability | # | Ahern et al., (2014) |
| Timber | Harvested wood (solid) | m3*a, volume*a | Kandziora et al., (2013) Burkhard et al., (2012) |
| Timber | Net primary production | t C/ha*a, kJ/ha*a | Kandziora et al., (2013) |
| Timber | Yield | €/ha*a | Kandziora et al., (2013) |
| Timber stock | Timber | m3/ha | Maes et al., (2012) |
| Urban climate | Diurmal heat flux | # | Ahern et al., (2014) |
| Urban climate | Maximum daily air temperature | # | Ahern et al., (2014) |
| Urban climate | Tree canopy cover | % | Ahern et al., (2014) |
| Water purification | Nitrogen removal rate | kgN/ha/yr | Liquete et al., (2013) |
| Water purification | Oxygen concentration | mg/l | Liquete et al., (2013) |
| Water purification | Removal of total nutrient | kg/ha | Liquete et al., (2013) |
| Water quality | Nutrient concentration | mg/L | Martin-Lopez et al., (2014) |
| Water quality | Biological Oxygen Demand | # | Ahern et al., (2014) |

Once standardised using the categories of Millennium Ecosystem Assessment, 75 indicators were removed due to duplications (see part of the standardised list for the impact category "Air quality regulation" under "Regulating ecosystem service" in Table 3.2 below; the full list can be found in Appendix B).

Table 3.2 Processed indicator list for air quality regulation.

| Category | Subcategory | Indicator | Unit | Source |
|---|---|---|---|---|
| Regulating | Air quality regulation | Leaf area index (Tree canopy cover) | % | Ahern et al., (2014) Kandziora et al.(2013) |
| | | Level of pollutants in the air | kg/ha*a | Kandziora et al., (2013) |
| | | Total particulates | # | Ahern et al., (2014) |
| | | Maximum urban daily air temperature | # | Ahern et al., (2014) |
| | | Total particulate matter less than 2.5 µm diameter (PM2.5) | µg/m3 | McBride et al, (2011) |
| | | Total particulate matter less than 10 µm diameter (PM10) | µg/m3 | McBride et al., (2011) |
| | | Atmospheric CO2 concentration | ppm, g/m3 | van Oudenhoven et al., (2012) |
| | | Tropospheric ozone | ppb | McBride et al., (2011) |
| | | Carbon monoxide | ppb | McBride et al., (2011) |

## 3.3 Ranking of indicators

All of the indicators collected in Appendix B were evaluated based on the evaluation criteria and processes listed in section 3.1 above. See Table 3.3 - Table 3.7 for the highest ranked indicators of each category (full list with scoring can be found in Appendix C).

It is difficult to quantify biodiversity in the context of LU accounting since living organisms do not live within a certain perimeter, thus double counting occurs when scaling. However, comparing the values from different regions and ecosystems is an important use of these indicators.

Most of the indicators in ES categories are suitable for LU accounting without modification, especially the ones in the provisioning category. However, a few indicators with relative units can be modified to be more scalable when adopting units with an absolute scale. One example of this is going from "percentage of area" to "area".

Table 3.3. Highest ranked indicators for biodiversity.

| Category | Indicator | Unit | LU | RE | SP | SI | AF | Total score | Source |
|---|---|---|---|---|---|---|---|---|---|
| Biodiversity | Species richness | #/ha | | | | | | 0.89 | (Gerlach et al., 2013; McBride et al., 2011; Tittensor et al., 2014) |
| | Bioindicator of some taxa, functional group | #/ha | | | | | | 0.89 | |

Table 3.4 Highest ranked indicators for provisioning ecosystem services.

| Category | Subcategory | Indicator | Unit | LU | RE | SP | SI | AF | Total score | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| Provisioning | Food | Available plants, livestocks, fish and plant biomass | kJ/ha, #/ha, kg/ha | | | | | | 1.00 | (Burkhard et al., 2012; Cloern et al., 2011; Haase et al., 2014; Kandziora et al., 2013; Maes et al., 2016, 2012) |
| | Fibre | Harvested wood (solid) | m³*a, volume*a, m³/ha | | | | | | 0.93 | |
| | Biochemicals and natural medicines | Amount or number of products used for medicine/biochemical | kg/ha*a, #/ha*a | | | | | | 0.89 | |
| | Fresh water | Precipitation | m³/ha, mm/yr | | | | | | 1.00 | |
| | Mineral resources | Excavated minerals | t/ha*a | | | | | | 1.00 | |

Table 3.5. Highest ranked indicators for regulating ecosystem services.

| Category | Subcategory | Indicator | Unit | LU | RE | SP | SI | AF | Total score | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| Regulating | Air quality regulation | Total particulate matter (PM2.5, PM10) | µg/m³ | | | | | | 0.88 | (Burkhard et al., 2012; Dobbs et al., 2011; Kandziora et al., 2013; Liquete et al., 2013; McBride et al., 2011) |
| | Climate regulation | Shaded areas | ha, % | | | | | | 0.89 | |
| | Erosion regulation | Vegetation cover area of total | % | | | | | | 0.79 | |
| | Water purification and waste treatment | Nitrogen removal rate / total amount | kgN/ha/yr, kg/ha | | | | | | 0.78 | |
| | | Decomposition rate / total amount | kg/ha*a, #/ha | | | | | | 0.78 | |
| | Pollination | Species numbers and number of pollinators | #/ha | | | | | | 0.89 | |
| | Natural hazard regulation | Natural barriers (dunes, mangroves, wetlands, coral reefs) | %, ha | | | | | | 1.00 | |
| | Noise reduction | Weighted distance to roads by leaf area in m² per m | # | | | | | | 0.68 | |
| | Pest regulation | Populations of biological disease and pest control agents | #/ha | | | | | | 0.79 | |

Table 3.6. Highest ranked indicators for supporting ecosystem services.

| Category | Subcategory | Indicator | Unit | LU | RE | SP | SI | AF | Total score | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| Supporting | Soil formation | Total / density of organic carbon (TOC), N, P | Mg/ha | | | | | | 0.78 | (Kandziora et al., 2013; Maes et al., 2016, 2012; Martin-Lopez et al., 2014; McBride et al., 2011; Serna-Chavez et al., 2014) |
| | Primary production | Net primary production | t C/ha*a, kJ/ha*a | | | | | | 0.78 | |
| | Nutrient cycling | N, P or other nutrient turnover rates | g/yr | | | | | | 0.78 | |
| | Water cycling | Groundwater recharge rate | mm/ha*a, million m³ year-1 | | | | | | 0.68 | |

Table 3.7. Highest ranked indicators for cultural ecosystem services.

| Category | Subcategory | Indicator | Unit | LU | RE | SP | SI | AF | Total score | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| Cultural | Spiritual and religious values | Number of spiritual facilities per area and number of their visitors | n/ha, n/facility*a | | | | | | 1.00 | (Ahern et al., 2014; Burkhard et al., 2012; Hernández-Morcillo et al., 2013; Kandziora et al., 2013; Martin-Lopez et al., 2014; van Oudenhoven et al., 2012) |
| | Knowledge systems | Number of environmental educational-related facilities and/or events and number of their users | n/ha*a | | | | | | 1.00 | |
| | Educational values | Number of visiting researchers | # / yr | | | | | | 1.00 | |
| | Aesthetics | Housing prices as aesthetic value proxies | $ | | | | | | 0.68 | |
| | Cultural heritage values | Number of employees in traditional land use forms | n/ha | | | | | | 0.90 | |
| | Recreation | Number of people performing outdoor activities in a park | #/park/ha | | | | | | 1.00 | |
| | | Number of visitors or facilities (e.g. hotels, restaurants, hiking paths, parking lots) | n/ha, n/facility*a | | | | | | 1.00 | |
| | | Turnover from tourism | (€/ha*a) | | | | | | 1.00 | |
| | Intrinsic value of biodiversity | Number of endangered, protected or rare species or habitats | n/ha | | | | | | 0.46 | |

## 3.4 Examples

In this section some LU accounting examples are presented (Table 3.8 - Table 3.10). The data is extracted and categorised from recent case studies that have quantified and accessed LU impact on biodiversity and ES, using indicators similar to those found in this thesis. With more specific LU subtypes (jungle, oil palm plantation, rubber plantation, etc., are categorised as part of forest land), these tables showcase how LU accounting can be done for biodiversity and ES in real world.

Table 3.8. Nitrogen, phosphorus density in soil.

| **LU type** | | **N content** | **P available** |
|---|---|---|---|
| Forest Land | Rainforest | 4.3 | 25.5 |
| | Jungle | 3.0 | 17.3 |
| | Rubber | 2.0 | 14.0 |
| | Oil palm | 1.7 | 14.5 |
| Category: Soil formation<br>Indicator: N, P density<br>Unit: mg N/g, µg P/g<br>Source: (Guillaume et al., 2016) | | | |

Table 3.9. NNP-based exergy for biomass productivity.

| **LU type** | | $NPP_{ex}$ |
|---|---|---|
| Forest Land | Old-growth native forest | 65.7 |
| | Second-growth native forest | 75.4 |
| | Exotic tree plantations | 88.5 |
| | Shrublands | 66.9 |
| Cropland | | 59.8 |
| Grassland | | 49.6 |
| Category: Biomass productivity<br>Indicator: net primary production (NPP) - based exergy<br>Unit: MJex m−2yr−1<br>Source: (Martinez et al., 2019) | | |

Table 3.10. Proportion of species per LU type.

| **LU type** | | **Flora** | **Vertebrates** | **Invertebrates** | **All Species** |
|---|---|---|---|---|---|
| Forest Land | Native forest | 1 | 1 | 1 | 1 |
| | Rubber plantation | 0.65 | 0.56 | 0.49 | 0.57 |
| | Bushland | 0.16 | - | - | - |
| Cropland | Paddy rice | 0.18 | - | 0.29 | 0.16 |
| | Annual crop | 0.32 | - | 0.37 | 0.23 |
| Category: Biodiversity<br>Indicator: Proportion of species found in a specific LU class related to the LU class with the highest absolute number of species found (100%)<br>Unit: Relative, %<br>Source: (Cotter et al., 2017) | | | | | |

# 4 Discussion

This chapter discusses the findings drawn from the literature review and evaluation of the indicators. Due to limited number of studies included, this thesis was not intended to serve as a comprehensive review of LU impact indicators. A more refined literature review with targeted ES and LU types is recommended to identify suitable indicators for specific categories.

In this thesis, a broad range of recommendations for indicators are provided to test and further develop in future research, with an emphasis on proven and already-used indicators rather than the latest ones. The proof-of-concept framework suggested in this thesis, once supplied with data, can be used for many different purposes: measuring progress of environmental targets, facilitating land use management decision, and comparing states of biodiversity and ES in different geographical areas.

## 4.1 Evaluation criteria

The start of this study began by finding out which criteria are essential for evaluating potential biodiversity and ES indicators in the context of LU accounting. Since no previous research has covered this area, with an aim to find a potential set of criteria, a literature review was done to find relevant studies that analysed biodiversity and ES indicators. This resulted in a non-comprehensive set of evaluation criteria being pieced together from six different studies. Although a statistical analysis was done to evaluate the relevance of evaluation criteria on the total scoring result, the validity and complementary nature of the set was not investigated. Furthermore, by omitting some evaluation criteria that served for the purpose of optimisation, this study opted for a smaller but essential set of criteria, while ensuring that they were independent and contributed meaningfully to the final evaluation score. However, for future studies, adding such criteria for optimisation may improve the quality of the evaluation.

Once the set of evaluation criteria was established, based on survey result from the thesis' supervisors in terms of weighing the criteria, each criterion received its corresponding weight. It was observed that all criteria had a similar weight except "LU appropriateness", which only received half of the score of its counterparts. This was due to the ambivalent definition of the criterion given in the questionnaire. The original definition scored the criterion by how broad a range of LU types that the indicator can be used in, but the description for the LU types was absent. The criterion could therefore be interpreted as referring to either the broad categories of LU types suggested by the IPCC (e.g., forest, cropland, and settlement), or their subtypes (e.g., native forest, rubber plantation, and shrubland as subtypes of forest). Furthermore, since only two academics were involved in weighting of the criteria, involving different groups of stakeholders may have presented more objective weighting priorities. For instance, when selecting indicators for the first prototype of impact accounting matrix, it may be more important for some stakeholders that the indicators are practical and easy to measure, such that feasibility of the prototype can be established quickly.

## 4.2 Indicators

The indicators were collected from a limited set of literature based on numbers of citations. While this made the workload feasible for building a prototype, in order to achieve a higher precision for identifying good indicators, it is required to work with smaller and specialised scales with biodiversity and ES subcategories. By using literature based on citation frequency, this thesis has put a heavier emphasis on proven and previously-existing indicators. Many potentially appropriate and newly developed indicators have been overlooked, such as NNP-based exergy, which was proposed recently (Martinez et al., 2019) and has not yet had the time to prove its worth.

At the data collection stage, several indicators / assessment methods were excluded due to being consolidated from multiple indicators in accord with the scope of this thesis. Some examples are Toolkit for Ecosystem Service Site-Based Assessment (TESSA) (TESSA, 2020), WET-health (Beuel et al., 2016), and Landscape Integrity Index / Site Impact Score (Walston and Hartmann, 2018). While this thesis did not include consolidated indicators, it was recognized that no single indicator can accurately represent the complex nature of biodiversity and ES, thus, further research is needed to understand how consolidated indicators perform in LU accounting.

During the study, it was noted that indicators with spatial units fitted the purpose of LU accounting more than others, due to its ability to scale with area or numbers:

- Water purification - “Nitrogen removal rate” (kgN/ha/yr)
- Pollination - “Species numbers of pollinators” (#/ha)
- Nutrient cycling - “Nutrients stored in the Ocean sediments” (mmol N/m$^3$/yr)
- Spiritual and religious values - “Number of spiritual facilities visitors for performance of rituals” (n/facility)

For other indicators without similar units, it was possible to change the unit to be more appropriate in the context of LU accounting, especially for units on a relative scale. For instance, indicators like “Percentage of land covered by the Natura 2000 network” for assessing biodiversity, or “Percentage of impervious cover” for water cycling capability function poorly in an accounting context, where data is expected to be consolidable. By changing the unit from percentage to, e.g., a unit of area like hectare, would make the indicator more suitable. However, no modification was done to any of the indicators in this thesis in order to preserve the state in which they were extracted in.

All of the collected indicators (Appendix B) were evaluated by the author, with the aid of the evaluation scoring rules defined in section 2.1.2. This approach was subject to personal assumption and bias. An example being when evaluating the criteria “Practicality and affordability” for “Nitrogen removal rate” and “Natural barriers (dunes, mangrove, coral reef)”, the author assumed that the former required advanced and specialised knowledge and tools (0 in score), while the latter only required counting and measuring with some knowledge (1 in score). With this limitation, therefore, the best-scoring indicators for various categories listed in Table 3.3 - Table 3.7 cannot be considered as the best suitable in general, but the better ones subject to the author’s assumptions made on the chosen criteria. Given this consideration, many indicators with slightly lower scores may be worth investigating and developing further.

Even the best sole indicators cannot accurately depict the complexities of biodiversity or any ES. As a limitation of this study, consolidated indicators or other assessment methodologies had been disregarded, but they may be suited to access the states of biodiversity and ES more accurately, albeit research is needed to access their suitableness in the context of LU accounting. On the other hand, some sole indicators may be able to represent more than one category of ES. Having such indicators can facilitate the collection of data since the same methodology can be adjusted to accommodate for different ES types. For example, it is viable to represent a broad range of provisioning ES using the indicator “Yield” with a monetary unit (Appendix C), since many of the services reflect in amount of retrieved goods, which can be measured and accounted for economically. However, the subtypes in regulating and supporting ES are less homogeneous than the ones in provisioning ES, thus harder to quantify using common indicators and units.

# 5 Conclusion

In summary, this thesis offers a proof-of-concept framework for quantifying biodiversity and ES in an LU accounting matrix. Ultimately, 117 unique indicators categorised into biodiversity and 24 ES types were evaluated, and scored based on five criteria: 1) land use appropriateness, 2) relevance, 3) spatial scale and scalability, 4) site-specificity, and 5) practicality and affordability. Combined with a weighted sum approach with expert input, a list of recommended starter indicators was presented. Although the main findings of the studies are provided in the form of tables and references, some general observations can be concluded:

- The weights for evaluation criteria may vary among stakeholders.
- Indicators that are easy to measure are important in improving rigorousness of research.
- Indicators with a density/spatial type usually perform best (#/$m^3$, #/$m^2$, per facility/site).
- Indicators in relative scales usually performed worst and can be improved by adopting a different unit.
- One indicator cannot fully measure all aspects of any category. A consolidated indicator or a suite of indicators may be better suited to assess the state of biodiversity and ES more accurately.

While this thesis presented a potentially viable solution for quantifying biodiversity and ES in LU impact accounting, the framework needs to be developed with further sophistication in order to prepare for real world usage. The following extensions are recommended for this study:

- The indicators can be tested with different LU types in the real world to obtain data for prototypes of accounting matrices.
- Adding additional non-overlapping criteria may prove beneficial in more accurate evaluation of the indicators.
- Involvement with other stakeholders for the weighting and evaluation of the criteria can bring more objectivity to the ranking of the indicators.
- A refined literature review with specific ES and LU types is recommended to identify more suitable indicators.
- Research is needed to identify indicators that may represent more than one ES category.

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# Appendix A. List of indicators after data collection.

| Biodiversity / ES type | Indicator | Unit | Source |
|---|---|---|---|
| Abiotic energy sources | Converted energy | kWh/ha | Kandziora et al., (2013) |
| Abiotic energy sources | Produced electricity | kWh/ha | Kandziora et al., (2013) |
| Aesthetics | Metrics-based assessment by visual estimation | # | Frank et al., (2013) |
| Aesthetics | Housing prices as aesthetic value proxies | $ | Hernández-Morcillo et al., (2013) |
| Aesthetics | Preferences from questionnaires<br>Scenic beauty estimation via landscape metrics | # | Kandziora et al., (2013) |
| Aesthetics | Number of paintings/illustrations, songs, products portraying the resp. landscape/ecosystem | n/landscape type | Kandziora et al., (2013) |
| Aesthetics | Travel cost estimation<br>Willingness to pay | $ | Kandziora et al., (2013) |
| Air quality | Total particulates | # | Ahern et al., (2014) |
| Air quality | Tropospheric ozone | ppb | McBride et al., (2011) |
| Air quality | Carbon monoxide | ppb | McBride et al., (2011) |
| Air quality | Total particulate matter less than 2.5 µm diameter (PM².5) | µg/m³ | McBride et al., (2011) |
| Air quality | Total particulate matter less than 10 µm diameter (PM10) | µg/m³ | McBride et al., (2011) |
| Air quality regulation | Leaf area index | Index value | Kandziora et al., (2013) |
| Air quality regulation | Level of pollutants in the air<br>Critical loads | kg/ha*a | Kandziora et al., (2013) |
| All | Potential to provide ES | # | Burkhard et al., (2014) |
| All | Participatory | # | Fagerholm et al., (2012) |
| All | Currency | $ | Song and Deng, (2017) |
| Biochemicals and medicine | Amount or number of products used for medicine/biochemical | kg/ha*a, n/ha*a | Kandziora et al., (2013) |
| Biochemicals and medicine | Yield | €/ha*a | Kandziora et al., (2013) |
| Biochemicals and medicine | Net primary production | t C/ha*a, kJ/ha*a | Kandziora et al., (2013) |

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|---|---|---|---|
| Biodiversity | Shannon diversity | Index value | Ahumada et al., (2011) |
| Biodiversity | Evenness | # | Ahumada et al., (2011) |
| Biodiversity | Dominance | # | Ahumada et al., (2011) |
| Biodiversity | Functional diversity | # | Ahumada et al., (2011) |
| Biodiversity | Species richness | # | Ahumada et al., (2011) Carvalheiro et al., (2013) |
| Biodiversity | Dirt DNA | # | Andersen et al., (2012) Lodge et al., (2012) |
| Biodiversity | Biotic homogenisation, comparing assemblages in 10-km grid cells. beta-diversity, e.g. Sorensen similarity or Jaccard similarity | # | Carvalheiro et al., (2013) |
| Biodiversity | Ecosystem invasion: Relative alien species richness (Alien richness as a proportion of community richness) / Presence/absence of alien species | % | Catford et al., (2012) |
| Biodiversity | Functional homogenization: Community specialization index | Index value | Clavel et al., (2011) |
| Biodiversity | Shannon diversity and evenness index | Index value | Dobbs et al., (2011) |
| Biodiversity | Ratio of native trees | % | Dobbs et al., (2011) |
| Biodiversity | Bioindicator of some taxa, functional group | # | Gerlach et al., (2013) |
| Biodiversity | Habitat potential for bird species | Index value | Haase et al., (2012) |
| Biodiversity | HANPP | C/yr | Haberl et al., (2004) |
| Biodiversity | Mean Species Abundance | % remaining biodiversity | Maes et al., (2012) |
| Biodiversity | Shannon index of tree diversity | # | Maes et al., (2012) |
| Biodiversity | Percent of land covered by the Natura 2000 network | % | Maes et al., (2012) |
| Biodiversity | Number of species | # | Martin-Lopez et al., (2014) |
| Biodiversity | Presence of taxa of special concern | Presence | McBride et al., (2011) |
| Biodiversity | Habitat area of taxa of special concern | ha | McBride et al., (2011) |
| Biodiversity | Ecological Footprint | Number of earths needed to support human society | Tittensor et al., (2014) |
| Biodiversity | Red List Index | Index value | Tittensor et al., (2014) |

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|---|---|---|---|
| Biodiversity | Human Appropriation of Net Primary Production (HANPP) | Pg C / Year | Tittensor et al., (2014) |
| Biodiversity | Wetland Extent Index | Index value | Tittensor et al., (2014) |
| Biodiversity | Wild Bird Index for habitat specialists | Index value | Tittensor et al., (2014) |
| Biodiversity | Living Planet Index | Index value | Tittensor et al., (2014) |
| Biodiversity | Mammal and bird extinctions | # | Tittensor et al., (2014) |
| Biodiversity | Natural habitat extent | Percent global area | Tittensor et al., (2014) |
| Biodiversity | Funds towards species protection | Constant million USD | Tittensor et al., (2014) |
| Biomass | Aboveground net primary productivity (ANPP)/yield | g $C/m^2$/year | McBride et al., (2011) |
| Biotic diversity | Shannon-Wiener index | Index value | Kandziora et al., (2013) |
| Biotic diversity | Simpson index | Index value | Kandziora et al., (2013) |
| Biotic diversity | Indicator species representing a certain phenomenon or being sensitive to distinct changes | n/ha | Kandziora et al., (2013) |
| Biotic diversity | Number and identity of selected species | # | Kandziora et al., (2013) |
| Biotic water flows | Transpiration/total evapotranspiration | % | Kandziora et al., (2013) |
| Carbon storage and sequenstration | Net carbon stored by trees | Mg CO2 | Ahern et al., (2014) Bastian et al., (2012) |
| Carbon storage and sequenstration | Above ground carbon storage | MgCO2 | Haase et al., (2012) |
| Carbon storage and sequenstration | Change in atmospheric CO2 concentration | ppm, $g/m^3$ | van Oudenhoven et al., (2012) |
| Climate regulation | Carbon flow | TgC/yr | Liquete et al., (2013) |
| Climate regulation | Dissolved organic and inorganic matter | $gC/m^2$/yr | Liquete et al., (2013) |
| Climate regulation | Above- and below-ground carbon density | Mg carbon ha-1 | Serna-Chavez et al., (2014) |
| Climate regulation | Top-soil carbon content | Mg carbon ha-1 | Serna-Chavez et al., (2014) |
| Climate regulation | Net ecosystem productivity | Mg carbon ha-1 year-1 | Serna-Chavez et al., (2014) |
| Cultural heritage and cultural diversity | Results from questionnaires on local people's personal preferences | # | Kandziora et al., (2013) |
| Cultural heritage and cultural diversity | Number of employees in traditional land use forms | n/ha | Kandziora et al., (2013) |
| Cycling & nutrient loss reduction | Leaching of nutrients, e.g. N, P | kg/ha/a, mg/l | Kandziora et al., (2013) |
| Entropy production | Respiration entropy balance | C/year | Kandziora et al., (2013) |

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|---|---|---|---|
| Erosion prevention | Percentage of vegetated land weighted by erosion risk | % | Maes et al., (2012) |
| Erosion regulation | Loss of soil particles by wind or water; vegetation cover | # | Burkhard et al., (2012) |
| Erosion regulation | Vegetation cover | % | Kandziora et al., (2013) |
| Erosion regulation | Loss of soil particles by water and wind | kg/ha*a | Kandziora et al., (2013) |
| Erosion regulation | USLE factors for assessment of landslide frequency | n/ha*a | Kandziora et al., (2013) |
| Exergy capture | Net primary production | t C/ha*a, kJ/ha*a | Kandziora et al., (2013) |
| Flood protection | Number of floods causing damages | # | Burkhard et al., (2012) |
| Flood protection | Water level | cm | Cloern et al., (2011) |
| Food security | % urban green area dedicated to agricultural activities | % | Ahern et al., (2014) |
| Food security | Plants/ha, kJ/ha, Animals/ha, Fishes available for catch/ha, Plant biomass/ha. | # | Burkhard et al., (2012) |
| Food security | Food supply | GJ/ha | Haase et al., (2012) |
| Food security | crops/animal/biomass/fodder/livestock/fibre | t/ha*a, kJ/ha*a | Kandziora et al., (2013) Martin-Lopez et al., (2014) |
| Food security | Net primary production | t C/ha*a, kJ/ha*a | Kandziora et al., (2013) Martin-Lopez et al., (2014) |
| Food security | Yield | €/ha*a | Kandziora et al., (2013) Martin-Lopez et al., (2014) |
| Food security | Percentage of land under crop production | % | Maes et al., (2012) |
| Food security | Livestock density | Number/ha | Maes et al., (2012) |
| Freshwater | Withdrawal of freshwater | l/ha*a, $m^3$/ha*a | Kandziora et al., (2013) |
| Global climate regulation | Source-sink of water vapour, methane, CO | # | Burkhard et al., (2012) |
| Global climate regulation | Source-sink of methane, carbon dioxide and water vapour | t C/ha*a | Kandziora et al., (2013) |
| Global climate regulation | Amount of stored trace gases in marine systems, vegetation and soils | t C/ha | Kandziora et al., (2013) |
| Global climate regulation | Carbon storage | ton/ha | Maes et al., (2012) Maes et al., (2016) |
| Global climate regulation | Carbon stock | ton C | Maes et al., (2012) Maes et al., (2016) |

| | | | |
|---|---|---|---|
| Global climate regulation | Carbon sequestration | ton C/year | Maes et al., (2012)<br>Maes et al., (2016) |
| Global climate regulation | pH | # | Maes et al., (2012)<br>Maes et al., (2016) |
| Global climate regulation | Primary Production | ton C/year | Maes et al., (2012)<br>Maes et al., (2016) |
| Global climate regulation | C storage in forest | # | Maes et al., (2016) |
| Global climate regulation | C sequestration by forest | # | Maes et al., (2016) |
| Global climate regulation | Net Primary Production | # | Maes et al., (2016) |
| Global climate regulation | Net Ecosystem Production | # | Maes et al., (2016) |
| Habitat provisioning | Index of Biotic Integrity | Index value | Ahern et al., (2014) |
| Habitat provisioning | Fish Index of Biotic Integrity | Index value | Ahern et al., (2014) |
| Habitat provisioning | City Biodiversity Index | Index value | Ahern et al., (2014) |
| Heterogeneity | Abiotic habitat components' heterogeneity indices (e.g. humus content in the soil) | % | Kandziora et al., (2013) |
| Heterogeneity | Number/area of habitants | n/ha | Kandziora et al., (2013) |
| Intrinsic value of biodiversity | Number of endangered, protected or rare species or habitats | # | Burkhard et al., (2012) |
| Knowledge systems | Number of environmental educational-related facilities and/or events and number of their users | n/ha*a | Kandziora et al., (2013) |
| Local climate regulation | Surface emissivity | Index value | Haase et al., (2012)<br>Larondelle et al., (2013) |
| Local climate regulation | Temperature | °C | Kandziora et al., (2013) |
| Local climate regulation | Albedo | % | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| Local climate regulation | Precipitation | mm | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| Local climate regulation | Wind | Bft | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| Local climate regulation | Temperature amplitudes | °C | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| Local climate regulation | Shaded areas | ha, % | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| Local climate regulation | Evapotranspiration | mm | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| Metabolic efficiency | Respiration/biomass (metabolic quotient) | # | Kandziora et al., (2013) |

| | | | |
|---|---|---|---|
| Mineral resources | Excavated minerals | t/ha*a | Kandziora et al., (2013) |
| Natural hazard protection | Natural barriers (dunes, mangroves, wetlands, coral reefs) | %, ha | Kandziora et al., (2013) |
| Natural heritage and natural diversity | number of endangered, protected and/or rare species or habitats | n/ha | Kandziora et al., (2013) |
| Noise reduction | Calculated by weighting distance to roads by leaf area in m² per m | % | Dobbs et al., (2011) |
| Noise reduction | Percent evergreen species in the sampling unit | % | Dobbs et al., (2011) |
| Nutrient regulation | N, P or other nutrient turnover rates | g/yr | Burkhard et al., (2012) |
| Nutrient regulation | Water quality indicators, e.g. N, P | mg/l | Kandziora et al., (2013) |
| Nutrient regulation | Leakage of nutrients | kg/ha*a | Kandziora et al., (2013) |
| Nutrient regulation | Electrical conductivity | µS/cm | Kandziora et al., (2013) |
| Nutrient regulation | Total dissolved solids | mg/l | Kandziora et al., (2013) |
| Nutrient regulation | Turnover rates of nutrients, e.g. N, P | g/yr | Kandziora et al., (2013) |
| Ocean nourishment | Nutrients stored in the sediments | mmol N/m³/yr | Liquete et al., (2013) |
| Pest and disease control | Populations of biological disease and pest control agents | n/ha | Kandziora et al., (2013) |
| Pollination | Availability of pollinators | # | Burkhard et al., (2012) |
| Pollination | Species numbers and amount of pollinators | n/ha | Kandziora et al., (2013) |
| Pollination | MODIS – continuous vegetation cover. Herbaceous and tree cover. | % | Serna-Chavez et al., (2014) |
| Recreation | Park visitation activity mapping | # | Ahern et al., (2014) |
| Recreation | Favorite places identified | # | Ahern et al., (2014) |
| Recreation | Number of visitors or facilities | # | Burkhard et al., (2012) |
| Recreation | Percent tree and maintained grass cover in forest | % | Dobbs et al., (2011) |
| Recreation | Green space per capita | m² / person | Haase et al., (2012) Larondelle et al., (2013) |
| Recreation | Number of people performing outdoor activities in a park | # | Hernández-Morcillo et al., (2013) |
| Recreation | Number of visitors or facilities (e.g. hotels, restaurants, hiking paths, parking lots) | n/ha, n/facility*a | Kandziora et al., (2013) |

| | | | |
|---|---|---|---|
| Recreation | Results from questionnaire on nature preferences and leisure preferences (wildlife-viewing, hiking, fishing, sports) | # | Kandziora et al., (2013) |
| Recreation | Turnover from tourism | (€/ha*a) | Kandziora et al., (2013) |
| Recreation | Number of visitors | # | Martin-Lopez et al., (2014) |
| Recreation | Recreation Opportunity Spectrum | Mapping, index | Paracchini et al., (2014) |
| Recreation | Recreational hiking | Density of hiking paths km km-2 | Schröter et al., (2020) |
| Regulation of waste | Amount and number of decomposers | n/ha | Kandziora et al., (2013) |
| Regulation of waste | Decomposition rate | kg/ha*a | Kandziora et al., (2013) |
| Regulation of water flows | Water infiltration capacity of soils | mm | Maes et al., (2012) |
| Religious and spiritual experience | Number of spiritual facilities | n/ha | Kandziora et al., (2013) |
| Religious and spiritual experience | number of their visitors for performance of rituals | n/facility*a | Kandziora et al., (2013) |
| Research and education | Number of excursions | # / yr | van Oudenhoven et al., (2012) |
| Research and education | Number of visiting researchers | # / yr | van Oudenhoven et al., (2012) |
| Soil erosion control | Soil loss | t hm-2 yr-1 | Fu et al., (2011) |
| Soil fertility | Percent soil organic matter | % | Dobbs et al., (2011) |
| Soil fertility | pH | # | Dobbs et al., (2011) |
| soil fertility | Soil organic matter content | % | Maes et al., (2012) |
| Soil formation | Sedimentation rates | mm/year | Martin-Lopez et al., (2014) |
| Soil formation | sedimentation cones | ha | Martin-Lopez et al., (2014) |
| Soil formation | Conductivity | mS/cm | Martin-Lopez et al., (2014) |
| Soil quality | Total organic carbon (TOC) | Mg/ha | McBride et al., (2011) |
| Soil quality | Total nitrogen (N) | Mg/ha | McBride et al., (2011) |
| Soil quality | Extractable phosphorus (P) | Mg/ha | McBride et al., (2011) |
| Soil quality | Bulk density | g/cm³ | McBride et al., (2011) |
| Storage capacity | N in the soil | kg/ha/a | Kandziora et al., (2013) |
| Storage capacity | C_(org) in the soil | kg/ha/a | Kandziora et al., (2013) |
| Storage capacity | N, C in biomass | kg/t/a | Kandziora et al., (2013) |
| Stormwater infiltration | Impervious cover | % | Ahern et al., (2014) |
| Stormwater infiltration | Soil permeability | # | Ahern et al., (2014) |
| Stormwater infiltration | Slope of surface | # | Ahern et al., (2014) |
| Timber | Net primary production | t C/ha*a, kJ/ha*a | Kandziora et al., (2013) |

| | | | |
|---|---|---|---|
| Timber | Yield | €/ha*a | Kandziora et al., (2013) |
| Timber | Harvested wood (solid) | m³*a, volume*a | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| Timber stock | Timber | m³/ha | Maes et al., (2012)<br>Maes et al., (2016) |
| Urban climate | Tree canopy cover | % | Ahern et al., (2014) |
| Urban climate | Maximum daily air temperature | # | Ahern et al., (2014) |
| Water flow regulation | Groundwater recharge rate | mm/ha*a | Kandziora et al., (2013) |
| Water purification | Water quality indicators:<br>Sediment load | g/l | Kandziora et al., (2013) |
| Water purification | Total dissolved solids | mg/l | Kandziora et al., (2013) |
| Water purification | Nitrogen removal rate | kgN/ha/yr | Liquete et al., (2013) |
| Water purification | Oxygen concentration | mg/l | Liquete et al., (2013) |
| Water purification | Removal of total nutrient content | kg/ha | Liquete et al., (2013) |
| Water quality | Total N | # | Ahern et al., (2014) |
| Water quality | Total P | # | Ahern et al., (2014) |
| Water quality | Biological Oxygen Demand | # | Ahern et al., (2014) |
| Water quality | pH | # | Ahern et al., (2014) |
| Water quality | Nutrient concentration | mg/L | Martin-Lopez et al., (2014) |
| Water quality | Nitrate concentration in streams | mg/L | McBride et al., (2011) |
| Water quality | Total phosphorus (P) | mg/L | McBride et al., (2011) |
| Water quality | Suspended sediment concentration in streams | mg/L | McBride et al., (2011) |
| Water quality | Herbicide concentration in streams | mg/L | McBride et al., (2011) |
| Water quality | Insecticide use | Tonnes | Tittensor et al., (2014) |
| Water quality | Nitrogen surplus | Tg N / Year | Tittensor et al., (2014) |
| Water retention | Change in ground water level | m | van Oudenhoven et al., (2012) |
| Water supply | Precipitation | m³/ha | Burkhard et al., (2012) |
| Water supply | Precipitation | mm/yr | Cloern et al., (2011) |
| Water supply | Percent of wetlands and lakes | % | Maes et al., (2012) |
| Water supply | Long-term average groundwater recharge rate | million m³ year-1 | Serna-Chavez et al., (2014) |

# Appendix B. List of indicators after data synthesis.

| Category | Subcategory | Indicator | Unit | Source |
|---|---|---|---|---|
| Provisioning | Food | Percentage of urban green area dedicated to agricultural activities | % | Ahern et al., (2014) |
| | | Percentage of land under crop production | % | Maes et al., (2012) |
| | | Plants, Livestocks, Fishes available for catch, Plant biomass | #, kJ/ha, #/ha, kg/ha | Burkhard et al., (2012) Haase et al., (2012) |
| | | Yield | €/ha*a | Kandziora et al., (2013) Martin-Lopez et al., (2014) |
| | Fibre | Timber net primary production | t C/ha*a, kJ/ha*a | Kandziora et al., (2013) |
| | | Yield | €/ha*a | Kandziora et al., (2013) |
| | | Harvested wood (solid) | $m^3$*a, volume*a, $m^3$/ha | Kandziora et al., (2013) Burkhard et al., (2012) Maes et al., (2012) Maes et al., (2016) |
| | Biochemicals, natural medicines, and pharmaceuticals | Amount or number of products used for medicine/biochemical | kg/ha*a, n/ha*a | Kandziora et al., (2013) |
| | | Yield | €/ha*a | Kandziora et al., (2013) |
| | Fresh water | Withdrawal of freshwater | l/ha*a, $m^3$/ha*a | Kandziora et al., (2013) |
| | | Change in ground water level | m | van Oudenhoven et al., (2012) |
| | | Percent of wetlands and lakes in area | % | Maes et al., (2012) |
| | | Precipitation | $m^3$/ha, mm/yr | Burkhard et al., (2012) Cloern et al., (2011) |
| | Mineral resources | Excavated minerals | t/ha*a | Kandziora et al., (2013) |
| Category | Subcategory | Indicator | Unit | Source |
| Regulating | Air quality regulation | Leaf area index (Tree canopy cover) | % | Kandziora et al., (2013) Ahern et al., (2014) |
| | | Level of pollutants in the air | kg/ha*a | Kandziora et al., (2013) |
| | | Total particulates | # | Ahern et al., (2014) |
| | | Maximum urban daily air temperature | # | Ahern et al., (2014) |

| | | | | |
|---|---|---|---|---|
| | | Total particulate matter less than 2.5 µm diameter (PM$^2$.5) | µg/m$^3$ | McBride et al., (2011) |
| | | Total particulate matter less than 10 µm diameter (PM10) | µg/m$^3$ | McBride et al., (2011) |
| | | Atmospheric $CO_2$ concentration | ppm, g/m$^3$ | van Oudenhoven et al., (2012) |
| | | Tropospheric ozone | ppb | McBride et al., (2011) |
| | | Carbon monoxide | ppb | McBride et al., (2011) |
| | Climate regulation | Net carbon stored by trees | Mg$CO_2$ | Ahern et al., (2014)<br>Bastian et al,. (2012)<br>Maes et al., (2016) |
| | | Above ground carbon storage | Mg$CO_2$ | Haase et al., (2012)<br>Serna-Chavez et al., (2014) |
| | | Carbon storage | ton/ha | Maes et al., (2012)<br>Maes et al., (2016) |
| | | Carbon flow | TgC/yr | Liquete et al., (2013) |
| | | Carbon sequestration | ton C/year | Maes et al., (2012)<br>Maes et al., (2016) |
| | | Top-soil carbon content | Mg carbon ha-1 | Serna-Chavez et al., (2014) |
| | | Dissolved organic and inorganic matter | gC/m$^2$/yr | Liquete et al., (2013) |
| | | Source-sink of methane, carbon dioxide and water, vapour methane, CO | t C/ha*a | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| | | Amount of stored trace gases in marine systems, vegetation and soils | t C/ha | Kandziora et al., (2013) |
| | | Surface emissivity | # | Haase et al., (2012)<br>Larondelle et al., (2013) |
| | | Temperature | °C | Kandziora et al., (2013) |
| | | Albedo | % | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| | | Precipitation | mm | Kandziora et al., (2013)<br>Burkhard et al., (2012) |

| | | | | |
|---|---|---|---|---|
| | | Wind | Bft | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| | | Shaded areas | ha, % | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| | | Evapotranspiration | mm / h | Kandziora et al., (2013)<br>Burkhard et al., (2012) |
| | Erosion regulation | Vegetation cover area of total | % | Kandziora et al., (2013) |
| | | Loss of soil particles by water and wind | kg/ha*a, t hm-2 yr-1 | Kandziora et al., (2013)<br>Fu et al., (2011)<br>Burkhard et al., (2012) |
| | | USLE factors for assessment of landslide frequency | n/ha*a | Kandziora et al., (2013) |
| | Water purification and waste treatment | Water quality indicators: Sediment load | g/l | Kandziora et al., (2013) |
| | | Total dissolved solids | mg/l | Kandziora et al., (2013) |
| | | Nitrogen removal rate | kgN/ha/yr | Liquete et al., (2013) |
| | | Oxygen concentration | mg/l | Liquete et al., (2013) |
| | | Removal of total nutrient content | kg/ha | Liquete et al., (2013) |
| | | Amount and number of decomposers | n/ha | Kandziora et al., (2013) |
| | | Decomposition rate | kg/ha*a | Kandziora et al., (2013) |
| | Pollination | Availability of pollinators | # | Burkhard et al., (2012) |
| | | Species numbers and amount of pollinators | n/ha | Kandziora et al., (2013) |

| | | | | |
|---|---|---|---|---|
| | | MODIS – continuous vegetation cover. Herbaceous and tree cover. | % | Serna-Chavez et al., (2014) |
| | Natural hazard regulation | Number of floods causing damages | # | Burkhard et al., (2012) |
| | | Flood prevention water level | cm | Cloern et al., (2011) |
| | | Natural barriers (dunes, mangroves, wetlands, coral reefs) | %, ha | Kandziora et al., (2013) |
| | Noise reduction | Calculated by weighting distance to roads by leaf area in m² per m | % | Dobbs et al., (2011) |
| | | Percent of evergreen species in the sampling unit | % | Dobbs et al., (2011) |
| | Pest regulation | Populations of biological disease and pest control agents | n/ha | Kandziora et al., (2013) |
| Category | Subcategory | Indicator | Unit | Source |
| **Supporting** | Soil formation | Soil formation: Sedimentation rates | mm/year | Martin-Lopez et al., (2014) |
| | | Soil formation: Conductivity | mS/cm | Martin-Lopez et al., (2014) Kandziora et al., (2013) |
| | | Soil fertility: Percent soil organic matter | % | Dobbs et al., (2011) Maes et al., (2012) |
| | | Soil fertility: pH | # | Dobbs et al., (2011) |
| | | Soil quality: Total organic carbon (TOC), nitrogen (N), extractable phosphorus (P) | Mg/ha | McBride et al., (2011) |
| | | Soil quality: Bulk density | g/cm³ | McBride et al., (2011) |
| | | Storage capacity: N, C_(organic) in the soil | kg/ha/a | Kandziora et al., (2013) |
| | | Storage capacity: N, C in biomass | kg/t/a | Kandziora et al., (2013) |
| | Primary production | Net primary production | t C/ha*a, kJ/ha*a, ton C/year, Mg carbon ha-1 year-1 | Kandziora et al., (2013) Martin-Lopez et al., (2014) Kandziora et al., (2013) Serna-Chavez et al., (2014) Maes et al., (2012) Maes et al., (2016) McBride et al., (2011) |

| | | | | |
|---|---|---|---|---|
| | Nutrient cycling | N, P or other nutrient turnover rates | g/yr | Burkhard et al., (2012) Kandziora et al., (2013) |
| | | Water quality indicators, e.g. N, P | mg/l | Kandziora et al., (2013) |
| | | Leakage of nutrients, e.g. N, P | kg/ha*a, kg/ha/a, mg/l | Kandziora et al., (2013) |
| | | Nutrients stored in the Ocean sediments | mmol N/m³/yr | Liquete et al., (2013) |
| | Water cycling | Groundwater recharge rate | mm/ha*a, million m³ year-1 | Kandziora et al., (2013) Serna-Chavez et al., (2014) |
| | | Biotic water flows: Transpiration/total evapotranspiration | % | Kandziora et al., (2013) |
| | | Stormwater infiltration: Impervious cover | % | Ahern et al., (2014) |
| | | Stormwater infiltration: Soil permeability | # | Ahern et al., (2014) Maes et al., (2012) |
| | | Stormwater infiltration: Slope of surface | # | Ahern et al., (2014) |
| Category | Subcategory | Indicator | Unit | Source |
| **Cultural** | Spiritual and religious values | Number of spiritual facilities | n/ha | Kandziora et al., (2013) |
| | | Number of spiritual facilities visitors for performance of rituals | n/facility*a | Kandziora et al., (2013) |
| | Knowledge systems | Number of environmental educational-related facilities and/or events and number of their users | n/ha*a | Kandziora et al., (2013) |
| | Educational values | Number of excursions | # / yr | van Oudenhoven et al., (2012) |
| | | Number of visiting researchers | # / yr | van Oudenhoven et al., (2012) |
| | Aesthetics | Metrics-based assessment by visual estimation | # | Frank et al., (2013) Kandziora et al., (2013) |
| | | Housing prices as aesthetic value proxies | $ | Hernández-Morcillo et al., (2013) |
| | | Number of paintings/illustrations, songs, products portraying the resp. landscape/ecosystem | n/landscape type | Kandziora et al., (2013) |

| Category | Subcategory | Indicator | Unit | Source |
|---|---|---|---|---|
| | | Travel cost estimation<br>Willingness to pay | $ | Kandziora et al., (2013) |
| | Cultural heritage values | Results from questionnaires on local people's personal preferences | # | Kandziora et al., (2013) |
| | | Number of employees in traditional land use forms | n/ha | Kandziora et al., (2013) |
| | Recreation | Favorite places identified | # | Ahern et al., (2014) |
| | | Percent tree and maintained grass cover in forest | % | Dobbs et al., (2011) |
| | | Green space per capita | m² / person | Haase et al., (2012)<br>Larondelle et al., (2013) |
| | | Number of people performing outdoor activities in a park | # | Hernández-Morcillo et al., (2013)<br>Ahern et al., (2014) |
| | | Number of visitors or facilities (e.g. hotels, restaurants, hiking paths, parking lots) | n/ha, n/facility*a | Kandziora et al., (2013)<br>Burkhard et al., (2012)<br>Martin-Lopez et al., (2014) |
| | | Results from questionnaire on nature preferences and leisure preferences (wildlife-viewing, hiking, fishing, sports) | # | Kandziora et al., (2013) |
| | | Turnover from tourism | (€/ha*a) | Kandziora et al., (2013) |
| | | Recreational hiking | Density of hiking paths km km-2 | Schröter et al., (2014) |
| | Intrinsic value of biodiversity | Number of endangered, protected or rare species or habitats | # | Burkhard et al., (2012)<br>Kandziora et al., (2013) |
| Category | Subcategory | Indicator | Unit | Source |
| Biodiversity | | Shannon diversity | Index value | Ahumada et al., (2011)<br>Dobbs et al., (2011)<br>Maes et al., (2012) |
| | | Species evenness | # | Ahumada et al., (2011)<br>Dobbs et al., (2011) |
| | | Functional diversity | # | Ahumada et al., (2011) |

| | | | |
|---|---|---|---|
| | Species richness | # | Ahumada et al., (2011)<br>Carvalheiro et al., (2013)<br>Martin-Lopez et al., (2014) |
| | Dirt DNA | # | Andersen et al,. (2012)<br>Lodge et al., (2012) |
| | Biotic homogenisation, comparing assemblages in 10-km grid cells. beta-diversity, e.g. Sorensen similarity or Jaccard similarity | # | Carvalheiro et al., (2013) |
| | Ecosystem invasion: Relative alien species richness (Alien richness as a proportion of community richness) / Presence/absence of alien species | % | Catford et al., (2012) |
| | Ratio of native trees | % | Dobbs et al., (2011) |
| | Bioindicator of some taxa, functional group | # | Gerlach et al., (2013)<br>McBride et al., (2011) |
| | Habitat potential for bird species | Index value | Haase et al., (2012) |
| | Human appropriation of net primary productivity (HANPP) | C/yr | Haberl et al., (2007)<br>Tittensor et al., (2014) |
| | Mean Species Abundance | % remaining biodiversity | Maes et al., (2012) |
| | Percent of land covered by the Natura 2000 network | % | Maes et al., (2012) |
| | Habitat area of taxa of special concern | ha | McBride et al., (2011) |
| | Red List Index | Index value | Tittensor et al., (2014) |
| | Wetland Extent Index | Index value | Tittensor et al., (2014) |
| | Wild Bird Index for habitat specialists | Index value | Tittensor et al., (2014) |
| | Living Planet Index | Index value | Tittensor et al., (2014) |
| | Mammal and bird extinctions | # | Tittensor et al., (2014) |
| | Natural habitat extent | Percent global area | Tittensor et al., (2014) |
| | Funds towards species protection | $ | Tittensor et al., (2014) |

# Appendix C. List of indicators after evaluation.

| Category | Subcategory | Indicator | Unit | LU | RE | SP | SI | AF | Total score | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| Provisioning | Food | Percentage of green area dedicated to agricultural activities | % | | | | | | 0,54 | Ahern et al., (2014) |
| | | Percentage of land under crop production | % | | | | | | 0,65 | Maes et al., (2012) |
| | | Yield | €/ha*a | | | | | | 0,88 | Kandziora et al., (2013) Martin-Lopez et al., (2014) |
| | | Plants, Livestocks, Fishes available for catch, Plant biomass | #, kJ/ha, #/ha, kg/ha | | | | | | 1,00 | Burkhard et al., (2012) Haase et al., (2012) |
| | Fibre | Timber net primary production | t C/ha*a, kJ/ha*a | | | | | | 0,71 | Kandziora et al., (2013) |
| | | Yield | €/ha*a | | | | | | 0,88 | Kandziora et al., (2013) |
| | | Harvested wood in (solid) | m3*a, volume*a, m3/ha | | | | | | 0,93 | Kandziora et al., (2013) Burkhard et al., (2012) Maes et al., (2012) Maes et al., (2016) |
| | Biochemicals, natural medicines, and pharmaceuticals | Yield | €/ha*a | | | | | | 0,88 | Kandziora et al., (2013) |
| | | Amount or number of products used for medicine/biochemical | kg/ha*a, n/ha*a | | | | | | 0,89 | Kandziora et al., (2013) |
| | Fresh water | Change in ground water level | m | | | | | | 0,58 | van Oudenhoven et al., (2012) |
| | | Percent of wetlands and lakes in area | % | | | | | | 0,65 | Maes et al., (2012) |
| | | Withdrawal of freshwater | l/ha*a, m3/ha*a | | | | | | 0,90 | Kandziora et al., (2013) |
| | | Precipitation | m3/ha, mm/yr | | | | | | 1,00 | Burkhard et al., (2012) Cloern et al., (2011) |
| | Mineral resources | Excavated minerals | t/ha*a | | | | | | 1,00 | Kandziora et al., (2013) |

| Category | Subcategory | Indicator | Unit | LU | RE | SP | SI | AF | Total score | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| Regulating | Air quality regulation | Tropospheric ozone | ppb | | | | | | 0,57 | Kandziora et al., (2013) Ahern et al., (2014) |
| | | Atmospheric CO2 concentration | ppm, g/m3 | | | | | | 0,57 | Kandziora et al., (2013) |
| | | Level of pollutants in the air | kg/ha*a | | | | | | 0,66 | McBride et al., (2011) |
| | | Total particulates | n/m3 | | | | | | 0,66 | Ahern et al., (2014) |
| | | Maximum daily air temperature | °C | | | | | | 0,68 | Ahern et al., (2014) |
| | | Carbon monoxide | ppb | | | | | | 0,68 | McBride et al., (2011) |
| | | Leaf area index (Tree canopy cover) | # | | | | | | 0,72 | van Oudenhoven et al., (2012) |
| | | Total particulate matter less than 2.5 µm diameter (PM2.5) | µg/m3 | | | | | | 0,88 | McBride et al., (2011) |
| | | Total particulate matter less than 10 µm diameter (PM10) | µg/m3 | | | | | | 0,88 | McBride et al., (2011) |
| | Climate regulation | Wind | Bft | | | | | | 0,57 | Kandziora et al., (2013) Burkhard et al., (2012) |
| | | Dissolved organic and inorganic matter | gC/m2/yr | | | | | | 0,65 | Liquete et al., (2013) |
| | | Evapotranspiration | mm / h | | | | | | 0,68 | Kandziora et al., (2013) Burkhard et al., (2012) |
| | | Temperature | °C | | | | | | 0,68 | Kandziora et al., (2013) |
| | | Net carbon stored by trees | MgCO2 | | | | | | 0,68 | Ahern et al., (2014) Bastian et al,. (2012) Maes et al., (2016) |
| | | Above ground carbon storage | MgCO2 | | | | | | 0,68 | Haase et al., (2012) Serna-Chavez et al., (2014) |
| | | Carbon flow | TgC/yr | | | | | | 0,68 | Liquete et al., (2013) |
| | | Carbon sequestration | ton C/year | | | | | | 0,68 | Maes et al., (2012) Maes et al., (2016) |
| | | Surface emissivity | # | | | | | | 0,68 | Haase et al., (2012) Larondelle et al., (2013) |

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|---|---|---|---|---|---|---|---|---|---|---|
| | | Albedo | # | | | | | | 0,68 | Kandziora et al., (2013) Burkhard et al., (2012) |
| | | Top-soil carbon content | Mg carbon ha-1 | | | | | | 0,78 | Serna-Chavez et al., (2014) |
| | | Carbon storage | ton/ha | | | | | | 0,78 | Maes et al., (2012) Maes et al., (2016) |
| | | Source-sink of methane, carbon dioxide and water, vapour methane, CO | t C/ha*a | | | | | | 0,78 | Kandziora et al., (2013) Burkhard et al., (2012) |
| | | Amount of stored trace gases in marine systems, vegetation and soils | t C/ha | | | | | | 0,78 | Kandziora et al., (2013) |
| | | Precipitation | mm | | | | | | 0,88 | Kandziora et al., (2013) Burkhard et al., (2012) |
| | | Shaded areas | ha, % | | | | | | 0,89 | Kandziora et al., (2013) Burkhard et al., (2012) |
| | Erosion regulation | Loss of soil particles | kg/ha*a, t hm-2 yr-1 | | | | | | 0,66 | Kandziora et al., (2013) Fu et al., (2011) Burkhard et al., (2012) |
| | | USLE factors for assessment of landslide frequency | n/ha*a | | | | | | 0,68 | Kandziora et al., (2013) |
| | | Vegetation cover area of total | % | | | | | | 0,79 | Kandziora et al., (2013) |
| | Water purification and waste treatment | Oxygen concentration | mg/l | | | | | | 0,39 | Liquete et al., (2013) |
| | | Water quality indicators: Sediment load | g/l | | | | | | 0,49 | Kandziora et al., (2013) |
| | | Total dissolved solids | mg/l | | | | | | 0,49 | Kandziora et al., (2013) |
| | | Nitrogen removal rate | kgN/ha/yr | | | | | | 0,78 | Liquete et al., (2013) |
| | | Removal of total nutrient content | kg/ha | | | | | | 0,78 | Liquete et al., (2013) |
| | | Amount and number of decomposers | n/ha | | | | | | 0,78 | Kandziora et al., (2013) |
| | | Decomposition rate | kg/ha*a | | | | | | 0,78 | Kandziora et al., (2013) |
| | Pollination | MODIS – continuous vegetation cover. Herbaceous and tree cover. | % | | | | | | 0,67 | Serna-Chavez et al., (2014) |

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|---|---|---|---|---|---|---|---|---|---|---|
| | | Availability of pollinators | # | | | | | | 0,89 | Burkhard et al., (2012) |
| | | Species numbers and amount of pollinators | n/ha | | | | | | 0,89 | Kandziora et al., (2013) |
| | Natural hazard regulation | Number of floods causing damages | # | | | | | | 0,32 | Burkhard et al., (2012) |
| | | Flood prevention water level | cm | | | | | | 0,51 | Cloern et al., (2011) |
| | | Natural barriers (dunes, mangroves, wetlands, coral reefs) | %, ha | | | | | | 1,00 | Kandziora et al., (2013) |
| | Noise reduction | Percent of evergreen species in the sampling unit | % | | | | | | 0,49 | Dobbs et al., (2011) |
| | | Calculated by weighting distance to roads by leaf area in m2 per m | # | | | | | | 0,68 | Dobbs et al., (2011) |
| | Pest regulation | Populations of biological disease and pest control agents | n/ha | | | | | | 0,79 | Kandziora et al., (2013) |

| Category | Subcategory | Indicator | Unit | LU | RE | SP | SI | AF | Total score | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| **Supporting** | Soil formation | Soil formation: Sedimentation rates | mm/year | | | | | | 0,57 | Martin-Lopez et al., (2014) |
| | | Soil formation: Conductivity | mS/cm | | | | | | 0,57 | Martin-Lopez et al., (2014) Kandziora et al., (2013) |
| | | Soil fertility: Percent soil organic matter | % | | | | | | 0,68 | Dobbs et al., (2011) Maes et al., (2012) |
| | | Soil quality: Bulk density | g/cm3 | | | | | | 0,68 | McBride et al., (2011) |
| | | Soil fertility: pH | # | | | | | | 0,68 | Dobbs et al., (2011) |
| | | Soil quality: Total organic carbon (TOC), nitrogen (N), Extractable phosphorus (P) | Mg/ha | | | | | | 0,78 | McBride et al., (2011) |
| | | Storage capacity: N, C_(organic) in the soil | kg/ha/a | | | | | | 0,78 | Kandziora et al., (2013) |
| | | Storage capacity: N, C in biomass | kg/t/a | | | | | | 0,78 | Kandziora et al., (2013) |
| | Primary production | Net primary production | t C/ha*a, kJ/ha*a, ton C/year, Mg carbon ha-1 year-1, g C/m2/year | | | | | | 0,78 | Kandziora et al., (2013) Martin-Lopez et al., (2014) Kandziora et al., (2013) Serna-Chavez et al., (2014) Maes et al., (2012) |

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|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Maes et al., (2016) McBride et al., (2011) |
| | Nutrient cycling | Water quality indicators, e.g. N, P | mg/l | | | | | | 0,49 | Kandziora et al., (2013) |
| | | Nutrients stored in the Ocean sediments | mmol N/m3/yr | | | | | | 0,49 | Liquete et al., (2013) |
| | | Leakage of nutrients, e.g. N, P | kg/ha*a, kg/ha/a, mg/l | | | | | | 0,66 | Burkhard et al., (2012) Kandziora et al., (2013) |
| | | N, P or other nutrient turnover rates | g/yr | | | | | | 0,78 | Kandziora et al., (2013) |
| | Water cycling | Biotic water flows: Transpiration/total evapotranspiration | % | | | | | | 0,46 | Kandziora et al., (2013) |
| | | Stormwater infiltration: Impervious cover | % | | | | | | 0,57 | Ahern et al., (2014) |
| | | Stormwater infiltration: Soil permeability | # | | | | | | 0,57 | Ahern et al., (2014) Maes et al., (2012) |
| | | Stormwater infiltration: Slope of surface | # | | | | | | 0,57 | Ahern et al., (2014) |
| | | Groundwater recharge rate | mm/ha*a, million m3 year-1 | | | | | | 0,68 | Kandziora et al., (2013) Serna-Chavez et al., (2014) |

| Category | Subcategory | Indicator | Unit | LU | RE | SP | SI | AF | Total score | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| **Cultural** | Spiritual and religious values | Number of spiritual facilities per area | n/ha | | | | | | 1,00 | Kandziora et al., (2013) |
| | | Number of spiritual facilities visitors for performance of rituals | n/facility*a | | | | | | 1,00 | Kandziora et al., (2013) |
| | Knowledge systems | Number of environmental educational-related facilities and/or events and number of their users | n/ha*a | | | | | | 1,00 | Kandziora et al., (2013) |
| | Educational values | Number of excursions | # / yr | | | | | | 0,88 | van Oudenhoven et al., (2012) |
| | | Number of visiting researchers | # / yr | | | | | | 1,00 | van Oudenhoven et al., (2012) |
| | Aesthetics | Metrics-based assessment by visual estimation | # | | | | | | 0,58 | Frank et al., (2013) Kandziora et al., (2013) |
| | | Travel cost estimation Willingness to pay | $ | | | | | | 0,58 | Hernández-Morcillo et al., (2013) |
| | | Number of paintings/illustrations, songs, products | n/landscape type | | | | | | 0,58 | Kandziora et al., (2013) |

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|---|---|---|---|---|---|---|---|---|---|---|
| | | portraying the resp. landscape/ecosystem | | | | | | | | |
| | | Housing prices as aesthetic value proxies | $ | | | | | | 0,68 | Kandziora et al., (2013) |
| | Cultural heritage values | Results from questionnaires on local people's personal preferences | # | | | | | | 0,68 | Kandziora et al., (2013) |
| | | Number of employees in traditional land use forms | n/ha | | | | | | 0,90 | Kandziora et al., (2013) |
| | Recreation | Green space per capita | m2 / person | | | | | | 0,57 | Haase et al., (2012) Larondelle et al., (2013) |
| | | Percent tree and maintained grass cover | % | | | | | | 0,68 | Ahern et al., (2014) |
| | | Favorite places identified | # | | | | | | 0,79 | Kandziora et al., (2013) |
| | | Results from questionnaire on nature preferences and leisure preferences (wildlife-viewing, hiking, fishing, sports) | # | | | | | | 0,79 | Dobbs et al., (2011) |
| | | Recreational hiking | Density of hiking paths km km-2 | | | | | | 0,89 | Schröter et al., (2014) |
| | | Number of people performing outdoor activities in a park | # | | | | | | 1,00 | Hernández-Morcillo et al., (2013) Ahern et al., (2014) |
| | | Number of visitors or facilities (e.g. hotels, restaurants, hiking paths, parking lots) | n/ha, n/facility*a | | | | | | 1,00 | Kandziora et al., (2013) Burkhard et al., (2012) Martin-Lopez et al., (2014) |
| | | Turnover from tourism | (€/ha*a) | | | | | | 1,00 | Kandziora et al., (2013) |
| | Intrinsic value of biodiversity | Number of endangered, protected or rare species or habitats | n/ha | | | | | | 0,46 | Burkhard et al., (2012) Kandziora et al., (2013) |
| **Category** | **Subcategory** | **Indicator** | **Unit** | **LU** | **RE** | **SP** | **SI** | **AF** | **Total score** | **Source** |
| **Biodiversity** | | Wetland Extent Index | Index value | | | | | | 0,32 | Tittensor et al., (2014) |
| | | Funds towards species protection | $ | | | | | | 0,33 | Maes et al., (2012) |
| | | Mammal and bird extinctions | # | | | | | | 0,41 | Tittensor et al., (2014) |
| | | Habitat potential for bird species | Index value | | | | | | 0,46 | Tittensor et al., (2014) |

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|---|---|---|---|---|---|---|---|---|---|
| | Percent of land covered by the Natura 2000 network | % | | | | | | 0,56 | Tittensor et al., (2014) |
| | Ecosystem invasion: Relative alien species richness | % | | | | | | 0,57 | Haase et al., (2012) |
| | Functional diversity | # | | | | | | 0,57 | Dobbs et al., (2011) |
| | Dirt DNA | # | | | | | | 0,57 | Catford et al., (2012) |
| | Habitat area of taxa of special concern | ha | | | | | | 0,66 | Ahumada et al., (2011) |
| | Human appropriation of net primary productivity (HANPP) | C/yr | | | | | | 0,66 | Andersen et al,. (2012) Lodge et al., (2012) |
| | Natural habitat extent | Percent global area | | | | | | 0,67 | McBride et al., (2011) |
| | Shannon diversity | # | | | | | | 0,68 | Haberl et al., (2007) |
| | Species evenness | # | | | | | | 0,68 | Ahumada et al., (2011) Dobbs et al., (2011) Maes et al., (2012) |
| | Biotic homogenisation, beta-diversity, e.g. Sorensen similarity or Jaccard similarity | # | | | | | | 0,68 | Ahumada et al., (2011) Dobbs et al., (2011) |
| | Mean Species Abundance | % remaining biodiversity | | | | | | 0,68 | Ahumada et al., (2011) Carvalheiro et al., (2013) Martin-Lopez et al., (2014) |
| | Red List Index | Index value | | | | | | 0,68 | Carvalheiro et al., (2013) |
| | Wild Bird Index | Index value | | | | | | 0,68 | Maes et al., (2012) |
| | Living Planet Index | Index value | | | | | | 0,68 | Tittensor et al., (2014) |
| | Ratio of native trees | % | | | | | | 0,72 | Tittensor et al., (2014) |
| | Species richness | # | | | | | | 0,89 | Tittensor et al., (2014) |
| | Bioindicator of some taxa, functional group | # | | | | | | 0,89 | Gerlach et al., (2013) McBride et al., (2011) |

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