Ecosystem Services guiding Built Environment Design

Understanding the impacts of building practice on ecosystems and their fundamental contribution to human wellbeing

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Kurzfassung

Abstrakt

Die gebaute Umwelt (in engl. ‚Built environment', abgekürzt BE) ist bestrebt, für den Menschen und sein Wohlergehen zu bauen, scheitert jedoch daran, die Grundlagen des menschlichen Fortschritts und des Wohlergehens zu verstehen und zu berücksichtigen. Die Menschheit ist auf funktionsfähige Ökosysteme und die von der Natur erbrachten Dienstleistungen (in engl. sogenannte ‚Ecosystem services', abgekürzt ES) angewiesen. Eine Analyse und Bewertung von Ökosystemdienstleistungen (ES) kann dieses Defizit überbrücken und sowohl die Verluste als auch die Beiträge zum menschlichen Wohlergehen aufzeigen. In dieser Forschungsarbeit werden zwei neuartige Ansätze zur quantitativen und qualitativen Bewertung der aktuellen Baupraxis in Bezug auf die Bereitstellung von Ökosystemdienstleistungen vorgestellt. Der erste Ansatz bietet eine breite Verwendbarkeit für eine leicht zugängliche Interpretation von Ökosystemdienstleistungsdaten und die Ermittlung von Richtwerten mit globaler Abdeckung. Die vorgestellte Anwendung identifiziert einen signifikanten Gesamtrückgang in der Bereitstellung von Ökosystemdienstleistungen bei der Umwandlung von natürlichen in städtische Umgebungen, mit einem auch monetär messbaren gesellschaftlichen Defizit. Die zweite Methodik ermöglicht ein detailliertes Verständnis der Auswirkungen von Baumaßnahmen auf das Ökosystem, die während des gesamten Lebenszyklus eines Gebäudes Verluste verursachen. Basierend auf dem entwickelten ökologischen Verständnis, ist das Ergebnis eine Anforderungs-Checkliste zur Bereitstellung von drei grundlegenden Ökosystemdienstleistungen, die auch für die biologische Vielfalt relevant sind. Ihre Anwendung zur Überprüfung naturbasierter Lösungen zeigt deren ungenutztes Potenzial und verdeutlicht die Mängel der Baubranche eine widerstandsfähige Biosphäre zu regenerieren und die Lebensbedingungen für die Weltbevölkerung zu sichern. Das vorgestellte Rahmenwerk ermöglicht es diese zu beheben und seiner Schlüsselrolle für eine regenerative und wohlhabende Zukunft gerecht zu werden.

Mehr denn je zeigt sich, dass fast alle bisher quantifizierten planetarischen Grenzen mit zunehmendem Risiko irreversibler Veränderungen von Stabilität und Resilienz des Erdsystems überschritten werden und dass dies durch anthropogene Aktivitäten verursacht wird (Potsdam Institute for Climate Impact Research 2022). Menschlicher Fortschritt und wirtschaftlicher Wohlstand haben ihren Ursprung in der Ausbeutung fossiler Ressourcen und der Zerstörung der Natur (Steffen et al. 2015a). Nichtsdestotrotz ist die Biosphäre das Lebenserhaltungssystem der Menschheit, denn die Natur liefert wesentliche Leistungen, sogenannte Ökosystemdienstleistungen (Ecosystem services, abgekürzt ES) für die menschliche Lebensgrundlage und Lebensqualität (IPBES 2019). Ihre Integrität ist neben der Eindämmung des Klimawandels von zentraler Bedeutung, da alle anderen planetarischen Grenzen am stärksten von ihnen abhängen (Häyhä et al. 2018). Daher hängt der Fortbestand des menschlichen Wohlergehens im Großen und Ganzen - jetzt und für die kommenden Generationen - von einem gesellschaftlichen Wandel ab. Dieser Wandel besteht in der Wiederherstellung einer widerstandsfähigen Biosphäre, indem der menschliche Fortschritt mit der Entwicklung gesunder Ökosysteme verknüpft wird, sodass aktiv Verantwortung für die Natur übernommen wird (Folke et al. 2021). Aktuell ist das Gegenteil der Fall, denn die gebaute Umwelt (Built environment, abgekürzt BE), die den Großteil der Weltbevölkerung beherbergt, treibt die Landumwandlung, den Klimawandel, die Zerstörung der Biosphäre und letztlich den Verlust der biologischen Vielfalt weiter voran (Ellen MacArthur Foundation 2021; Bushnell 2021). Dieser entscheidende Widerspruch wird im ersten Kapitel, der ***Einleitung*** (Introduction), näher erläutert, zusammen mit den nachfolgenden Absichten, die sich mit den beiden folgenden Hypothesen befasst:

1) "*Die Entwicklung der gebauten Umwelt verändert die Bereitstellung von Ökosystemdienstleistungen*" und

2) "*Die Baubranche könnte das menschliche Wohlbefinden regenerieren und stärken, unter gleichzeitiger Wahrung und Entwicklung mit der Natur*."

Das zweite Kapitel, ***Stand der Forschung*** (State of the art), liefert das Hintergrundwissen zu diesem relativ jungen, aber wirkungsvollen Konzept. Es werden die vier Kategorien beschrieben, in die alle Ökosystemdienstleistungen eingeteilt werden können, und wie diese Leistungen aus der biophysikalischen Struktur und den Prozessen der Natur hervorgehen. Dieses elementare Kaskadenmodell, welches auf Haines-Young und Potschin‘s (2010) Arbeit basiert, veranschaulicht, dass Ökosystemdienstleistungen als Brücke zum sozialen und wirtschaftlichen System des Menschen fungieren, innerhalb dessen einer Dienstleistung ein Nutzen und Wert zugeschrieben wird. Sie stellen eine direkte Verbindung zwischen einer intakten Umwelt und dem menschlichen Wohlergehen dar, was sie für die Baubranche und die Suche nach Lösungen für die vielfältigen planetarischen Herausforderungen von grundlegender Bedeutung macht. Im Kapitel werden Indikatoren zur Bemessung und Bewertung von Ökosystemdienstleistungen vorgestellt. Die Einführung der monetären Bewertung liefert ein quantitatives Maßsystem und gleichzeitig einen Schlüssel, um mit dem vorherrschenden ökonomischen System zu kommunizieren und sie ermöglicht somit die wirtschaftliche und politische Entscheidungsfindung, bei der Beiträge der Natur bisher nicht einbezogen wurden (O'Higgins et al. 2020; Costanza et al. 2014; Považan et al. 2021). Trotz der positiven Tendenz, dass der gesamtgesellschaftliche Mehrwert private Nutzen überwiegt, sobald eine breite Palette von Dienstleistungen berücksichtigt wird (Bradbury et al. 2021), wird ihr wahrer, vielfältiger und eigentlich unendlicher Wert in der globalen Wirtschaft nicht berücksichtigt (Sangha et al. 2022; IPBES 2022). Abschließend wird die Pionierarbeit und die Methodik zur Ökosystemdienstleistungsanalyse für die Baubranche von Pedersen Zari (2018) erörtert und es wird dargelegt, wie sich die in dieser Thesis entwickelten Ansätze von denen der Autorin unterscheiden und einen Beitrag zur aktuellen Forschung leisten.

Es folgt die Darstellung und beispielhafte Anwendung der beiden Ansätze in Kapitel drei ***Methodik*** (Methodology) und Kapitel vier ***Durchführung*** (Conduction). Der quantitative Ansatz bemisst die Bereitstellung von sechs Ökosystemdienstleistungen auf der Grundlage frei zugänglicher Daten, ohne dass weiteres Hintergrundwissen für die Nutzung erforderlich ist, sobald Dienstleistungen und Daten angemessen verknüpft sind (Kapitel 3.2). Der Ansatz untersucht und vermittelt einen Einblick in die erste Forschungsfrage „Wie unterscheidet sich die Bereitstellung von Ökosystemdienstleistungen in städtischer und natürlicher Umwelt?“. Zusätzlich kann dies mit der aktuellen ökonomischen Bewertung der untersuchten Ökosystemdienstleistungen gekoppelt werden, was zu internationalen$/Hektar/Jahr-Differenzen führt. Der Zweck dieses Ansatzes ist es, Trends in der Baubranche aufzuzeigen und Einbußen für das menschliche Wohlbefinden in Bezug auf die unterschiedliche Bereitstellung von Ökosystemdienstleistungen durch eine bauliche Entwicklung zu verdeutlichen. Bei der Anwendung dieses ersten Ansatzes werden zwei Fälle untersucht: a) der Campus Garching auf einem historisch umgewandelten gemäßigten Wald in Deutschland und b) die geplante Verlagerung der indonesischen Hauptstadt Jakarta auf einen weltweit bedeutenden Biodiversitäts-Hotspot, die Insel Borneo (Kapitel 4.2).

Der zweite Ansatz beantwortet die zweite Forschungsfrage "*Wie wirkt sich die Baubranche auf die Bereitstellung von Ökosystemdienstleistungen aus*?", indem die Konsequenzen eines architektonischen Entwurfs für das Ökosystem und die Bereitstellung von drei beispielhaft unterstützenden Ökosystemdienstleistungen, die eine wichtige Grundlage für die Entstehung anderer Ökosystemdienstleistungen sind, qualitativ untersucht werden (Kapitel 3.3) (Bereitstellung von Lebensraum, Nährstoff- und Wasserkreislauf). Dieser bietet einen systematischen Einblick auf der Entwurfsebene über den gesamten Lebenszyklus eines Gebäudes. Es sind jedoch umfassende Kenntnisse über die mit dem Vorschlag verbundenen Bautätigkeiten und ökologischen Kenntnisse zur Spezifizierung der Ökosystemdienstleistungskaskade für das untersuchte Ökosystem erforderlich. Dies Bedarf der Definition von Bautätigkeits- und Ökosystemdienstleistungsprofilen, die dann überlagert werden. Der Sinn dieses Ansatzes ist es, die spezifischen Auswirkungen einer Baumaßnahme zu identifizieren, die zu Veränderungen in der Ökosystemdienstleistungsversorgung mit Konsequenzen für das menschliche Wohlergehen führen. Dies wird anhand eines exemplarischen Entwurfsvorschlags für eine Erstbesiedlung des indonesischen tropischen Regenwalds veranschaulicht (Kapitel 4.3). Auf der Grundlage des qualitativen Bewertungsansatzes werden Entwurfsmängel und Anforderungen an die Bereitstellung der drei untersuchten Ökosystemdienstleistungen - Bereitstellung von Lebensraum, Nährstoff- und Wasserkreislauf - ermittelt. Dieser Leitfaden beantwortet die dritte Forschungsfrage, "*Wie könnte die Baubranche Ökosystemdienstleistungen durch ihre baulichen Maßnahmen bereitstellen*?", mit dem Ziel, konkrete Bereitstellungsoptionen zu identifizieren, die zum menschlichen Wohlbefinden beitragen. Die sich daraus ergebenden Anforderungen werden dann verwendet, um zwei gängige naturbasierte Lösungen (Nature-based solutions, abgekürzt NbS) zu begutachten: begrünte Dächer und Fassaden.

Die Ergebnisse der Analysen werden in Kapitel fünf ***Ergebnisse*** (Results) beschrieben. Die quantitative Studie (Kapitel 5.2) zeigt, dass die Umwandlung von tropischen und gemäßigten Wäldern in urbane Umgebungen in beiden untersuchten Fällen zu einer erheblichen Verringerung der Bereitstellung von Lebensräumen, des Nährstoffkreislaufs, der Primärproduktion und der Klimaregulierung führt. Daraus ergeben sich 14.134 internationale$/Hektar/Jahr gesellschaftliche Defizite für die vier monetär bewertbaren Ökosystemdienstleistungen (Bereitstellung von Lebensraum, Primärproduktion, Klimaregulation und Bereitstellung von Nahrung) aus den ursprünglich sechs bemessenen für a) die deutsche Fallstudie über den historischen Abholzungs- und Umwandlungsprozess, der zum heutigen Campus Garching führte und b) 645 internationale$/Hektar/Jahr gesellschaftliche Defizite für den Bau der geplanten neuen indonesischen Hauptstadt auf Borneo basierend auf Jakarta's urbaner Situation. Neben den absoluten Unterschieden bei den festgestellten Ökosystemdienstleistungsverlusten ist die Differenz des Gesamtdefizits zwischen Fall a) und b) auch auf die unterschiedlichen sozioökonomischen Kontexte und den von ihnen zugeschriebenen Wert für die gleiche Dienstleistung, wie z.B. der Klimaregulierung, zurückzuführen. Dies unterstreicht die bereits erwähnten Mängel der monetären Bewertung, zeigt aber auch, dass es bereits durchaus praktikabel ist, Nachweise für die Berücksichtigung von Ökosystemdienstleistungen auch zum Vorteil aktueller Baubranchen Diskurse wie der Dekarbonisierung zu liefern. Die Bewertung von Ökosystemen und der Vergleich mit (zuvor) bestehenden natürlichen Ökosystemen eröffnet somit eine neue Perspektive auf den gesellschaftlichen Wert, der durch bauliche Entwicklungen geschaffen wird, und kann bei der Definition von Richtwerten für die Veränderung städtischer Agenden helfen.

Die Evaluation auf Entwurfsebene (Kapitel 5.3) für den indonesischen tropischen Regenwald veranschaulicht die Auswirkungen für jede Lebenszyklusphase und zeigt, dass verschiedenste substanzielle Mängel durch die Unkenntnis oder Missachtung der Funktionsweise des Ökosystems verursacht werden. In der Folge wird die jeweilige biophysikalische Struktur gestört, geschädigt oder geht gänzlich verloren, was zu Veränderungen im Auftreten wesentlicher und zugrunde liegender Ökosystemprozesse für die Bereitstellung von Ökosystemdienstleistungen führt. Diese Defizite werden in einer Anforderungsliste für die Bereitstellung von Ökosystemdienstleistungen für jede Lebenszyklusphase und die untersuchten Dienstleistungen gebündelt. Dieser Leitfaden wird exemplarisch für die Transport- und Bauphase des Lebenszyklus zusammen mit Reduktionsmaßnahmen als Anstoß für einen Verbesserungsprozess beschrieben und zu einer verallgemeinerten, maßstabsunspezifischen Checkliste weiterentwickelt. Diese ist ein wichtiges Ergebnis, das eine zusätzliche vereinfachte Kontrolle ermöglicht. Ihre beispielhafte Anwendung verdeutlicht darüber hinaus das ungenutzte Potenzial von naturbasierten Lösungen in der gängigen Praxis und die derzeitigen Grenzen bei der Bereitstellung von Ökosystemdienstleistungen, auch in Hinblick auf die biologische Vielfalt. Darüber hinaus wird die Übertragbarkeit des ursprünglich tropischen Kontextes auf den europäischen Kontext hervorgehoben, da die Strukturen der gemäßigten und tropischen Wälder und damit die grundlegenden Ökosystemprozesse für die Bereitstellung von Ökosystemdienstleistungen ähnlich sind. Schließlich wird der Ökosystemdienstleistungsbegutachtungsansatz von Ökobilanzen (Lifecycle assessments, abgekürzt LCA) unterschieden und es wird gleichermaßen erörtert, wie beide Methoden sich gegenseitig ergänzen können.

Daran schließt sich Kapitel sechs ***Diskussion*** (Discussion) an, in dem die Limitierungen der beiden vorgestellten Ansätze erläutert werden. Dies gilt vor allem für die begrenzt verfügbaren Datensätze, die für die Messung von meist nur einem der vielen vorgeschlagenen Indikatoren für die Bemessung einer Ökosystemdienstleistung zur Verfügung stehen, und die Kopplung repräsentativer monetärer Daten. Dennoch wurde ein Rahmenwerk geschaffen, das viele Möglichkeiten für neue Forschung und interdisziplinäre Erweiterungen bietet, wie im Ausblick dieses Kapitels erläutert wird.

Im letzten Kapitel, ***Fazit*** (Conclusion), wird schließlich festgestellt, dass diese Forschungsarbeit die Hypothese 1) "*Die Entwicklung der gebauten Umwelt verändert die Bereitstellung von Ökosystemdienstleistungen*" eindeutig stützt und dass die Berücksichtigung von Ökosystemleistungen die Verluste und Beiträge zum menschlichen Wohlergehen durch bauliche Maßnahmen vermitteln kann. Diese Arbeit trägt zum Verständnis und zum neuartigen Umgang mit ökologischem Wissen bei, wodurch die Mängel, aber auch die Fülle an Möglichkeiten zur Verbesserung der Bautätigkeit und des Designs unterstrichen werden. Auch wenn naturbasierte Lösungen in der Praxis ihr volles Potenzial als ökologisch regenerative Schlüsselelemente noch nicht ausschöpfen, wird eine Leitlinie für den Transformationsprozess vorgestellt. Die Hypothese 2) "*Die Baubranche könnte das menschliche Wohlbefinden regenerieren und stärken, unter gleichzeitiger Wahrung und Entwicklung mit der Natur* ", wird damit ebenfalls bekräftigt. Durch die Berücksichtigung der Vielfalt von Ökosystemdienstleistungen innerhalb der Baubranche können Klimawandel-, Renaturierungs- und Biodiversitätsziele gleichzeitig und konkret angegangen werden, während gleichermaßen Fortschritte bei den Zielen der nachhaltigen Entwicklung (Sustainable development goals, abgekürzt SDGs) auf lokaler und globaler Ebene erzielt werden können. "Positives Bauen" in dem Sinne, dass die Grundlagen des menschlichen Wohlbefindens gesichert werden, indem auch für die Gesundheit der Natur gebaut und Naturkapital regeneriert wird, muss somit nicht nur ein geeignetes, sondern ein lebenswichtiges Vermächtnis und die Verantwortung des Bauens sein.

Summary

Abstract

The built environment (BE) strives to build for people and their wellbeing, however it fails to understand and address the foundation of human development and welfare. Society is dependent on healthy and functioning ecosystems and the services that nature provides. Ecosystem services assessment (ESA) can bridge this deficit and communicate both the losses and contributions to human wellbeing. This research presents two novel approaches to quantitatively and qualitatively assess construction practice on ecosystem service (ES) provision. The first offers wide usability for easily accessible ES data interpretation and benchmark setting with global coverage. Its showcased application identifies a significant overall decrease in the conversion of natural to urban environments with a monetary measurable societal deficit. The second enables a detailed understanding of construction impacts on the ecosystem causing losses throughout a building's entire lifecycle. A requirement checklist to provide three fundamental ES, also for biodiversity, is one outcome based on the developed ecological understanding. Its usage to review nature-based solutions indicates their unfulfilled potential and highlights the immaturity of the BE to rebuild a resilient biosphere and safeguard the living conditions for mankind. Yet the introduced blueprint offers a tangible pathway ahead to beneficially exploit the sector's key role to arrive at a regenerative and prosperous future.

It is known better than ever that almost all yet quantified planetary boundaries are exceeded with an increased risk of irreversible changes to the stability and resilience of the earth system and that this is caused by anthropogenic activity (Potsdam Institute for Climate Impact Research 2022). Human development and economic prosperity originate from the exploitation of fossil resources and the degradation of natural environments (Steffen et al. 2015a). Nevertheless, the biosphere is humanity's life support system because nature supplies essential services, so called ecosystem services, for human existence and good quality of life (IPBES 2019). Its integrity is the second core boundary besides climate change upon which all other planetary boundaries depend most (Häyhä et al. 2018). Therefore, the continuation of human wellbeing at large, now and for the generations to come, depends on a societal transformation to rebuild a resilient biosphere by reconnecting and resting human development on the development of healthy ecosystems, thus taking active stewardship of nature (Folke et al. 2021). Yet, the built environment, which houses the majority of the global human population, drives land conversion, climate change, biosphere degradation and ultimately biodiversity loss (Ellen MacArthur Foundation 2021; Bushnell 2021). This crucial context is further elaborated in the first chapter, the ***Introduction*** of this thesis, along with the subsequent intentions of the conducted research which deals with the two hypotheses that "*Developing the built environment changes the provision of ecosystem services*." and "*Built environment practice could regenerate and strengthen human wellbeing while co-evolving with nature*."

The second chapter, ***State of the art***, provides the background knowledge of this relatively young but powerful concept. The four ES categories in which all ecosystem services can be categorized are described and how these services emerge from nature's biophysical structure and processes. It is this essential cascade model based on Haines-Young and Potschin (2010) which illustrates that ecosystem services serve as bridge to human's social and economic system from which benefit and value is attributed to an ES. It represents a direct linkage between the health of the environment and human wellbeing which makes it fundamentally relevant for BE practice and finding solutions to the manifold planetary challenges. The chapter continues with indicators to measure value nature's contribution or benefits to people (NCP), as ES are also called (Díaz et al. 2018). Monetary valuation is a useful tool to communicate with the prevailing gross domestic product system and thus supports economic and political decision making where these contributions have previously been unaccounted for (O'Higgins et al. 2020; Costanza et al. 2014; Považan et al. 2021). Despite the positive tendency to outweigh private benefits if a wide set of services is taken into consideration (Bradbury et al. 2021), the global economy fails to address their true, diverse and infinite value (Sangha et al. 2022; IPBES 2022). Lastly, the pioneering work and "*Ecosystem service analysis*" methodology for the BE of Pedersen Zari (2018) is discussed and how the developed approaches of this paper differentiate and contribute to the research field.

This is followed by the presentation and exemplary execution of the two approaches for ESA in chapter three ***Methodology*** and chapter four ***Conduction***. The quantitative approach assesses the provision of six ecosystem services based on freely accessible data without requiring any further background knowledge in its use once adequately matched (Chapter 3.2). It offers a high-level insight into research question one "*How does ES provision differ in urban and natural environment?*". Additionally this can be coupled with current economic valuation of the investigated ES, resulting in international$/ha/year divergences. The purpose of the approach is to display trends of BE practice and illustrate human wellbeing tradeoffs in regard to differing ES provision by construction development. In the application of this first approach, two cases are investigated: a) the Campus Garching on historically converted temperate forest in Germany and b) the planned relocation of the Indonesian capital Jakarta to a globally important biodiversity hotspot, the island of Borneo (Chapter 4.2).

The second approach answers research question two, "*How does the BE impact ES provision?"*, by qualitatively investigating the impact of a development proposal on the natural environment and its provision of three supporting ES which are important foundations for other ES to occur (Chapter 3.3). It offers a design-level insight throughout the entire building lifecycle. However, extensive knowledge on BE activities related to the proposal and ecological knowledge for specifying the ES cascade in the investigated ecosystem are required. This entails the definition of construction activity and ES profiles which are then overlayed on each other. The purpose of the approach is to identify the specific impacts of a BE action resulting in ES provision changes which affect human wellbeing. This is illustrated with an application to a design proposal for a first development in the Indonesian tropical rainforest (Chapter 4.3). Derived from the qualitative assessment approach, design shortcomings and requirements for the provision of the three investigated supporting ES - habitat provision, nutrient- and water cycling - are identified. This guidance responds to research question three," *How can the BE provide ES by its building actions?*", with the purpose of designating tangible ES provision options for the BE to contribute to human wellbeing. The resulting requirements are then used to shortly review two common nature based solutions (NbS): green roofs and facades.

The outcomes of the analyses are described in Chapter five ***Results.*** The high level quantitative study (Chapter 5.2) identifies significant decreases in habitat provision, nutrient cycling, primary production, and climate regulation for both of the investigated cases by conversion from tropical and temperate forest to urban environments. This results in 14,134 international$/hectare/year societal deficits for the four monetary valued ecosystem services (habitat provision, primary production, climate regulation and food provision) out of the initial six measured for a) the German case study on the historical deforestation and conversion process leading to the current Campus Garching and b) 645 international$/hectare/year societal deficits for building the planned new Indonesian capital on Borneo in the same way as Jakarta. Besides absolute deviations in incurred losses, the overall deficit variation also originates from the different socio-economic contexts and their attributed value to the same service, such as climate regulation. This underlines the beforementioned shortcomings of monetary valuation but nevertheless displays its readiness to offer indications to address ecosystem services also for the benefit of current BE discourses such as decarbonization. ES assessment and the comparison to (previously) existing natural environments thus sets a new perspective on the societal value created by construction developments and can aid in the definition of benchmarks to change urban agendas.

The design-level assessment (Chapter 5.3) for the Indonesian tropical rainforest context illustrates the effects for each lifecycle phase and shows that various shortcomings are generated by the unawareness or disregard for the functioning of the ecosystem. Subsequently, the respective biophysical structure is disrupted, damaged or entirely lost which is responsible for the changes in occurrence of essential and underlying ecosystem processes for ES provision. These deficiencies are reformulated into a list of ES provision requirements for each lifecycle phase and ES investigated. This guidance is exemplary discussed for the transport and construction phase of the lifecycle along reduction measures as an initiation of an improvement process and further developed to a generalized, scale unspecific checklist. It is an important outcome which enables an additional simplified review opportunity. Its use further highlights the unutilized potential of NbS in usual practice and current limitations in providing ES, also for biodiversity. Furthermore, the transferability to the European despite the initial tropical context is emphasized because of the similarities of temperate and tropical forest structures and thus ecosystem processes for ES provision. Lastly, the ES assessment approach is differentiated from lifecycle assessments (LCA) but it is also discussed how both can complement each other and why ESA is a crucial novelty to sustainable building.

This is followed by chapter six ***Discussion*** which elaborates the limitations of the two presented approaches. This mainly applies to the limited datasets available for measuring mostly only one of the many suggested indicators for an ES and the coupling of representative monetary data. Nonetheless, a framework has been provided with many possibilities for new research and interdisciplinary extensions as detailed in the outlook of this chapter.

After all, the last chapter seven ***Conclusion***, finds that this research clearly supports the hypothesis that "*Developing the built environment changes the provision of ecosystem services*" and that ES assessment can bridge and communicate the losses and contributions to human wellbeing by BE actions. This thesis aids in the understanding and novel working with ecological knowledge through which shortcomings but also the abundance of opportunities to improve construction activities and design underlined. Moreover, even though NbS do not utilize their full potential in becoming key ecologically regenerative elements of practice yet, the blueprint for the transformation process is presented and affirms that the "*Built environment practice could regenerate and strengthen human wellbeing while co-evolving with nature*." By accounting for the diversity of ES within the BE, climate change mitigation, restoration and biodiversity strategies can be simultaneously addressed while progressing on sustainable development goals on a local and global scale. "Positive building", in the sense of safeguarding the foundations of human wellbeing by also building for the health of the natural environment and regenerating nature's supplies, must not only be a suitable but vital construction legacy.

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List of abbreviations

BE	Built Environment
CBD	Convention on Biological Diversity
CBI	Singapore City Biodiversity Index
DALY	Disability-Adjusted Life Year
EA	Ecosystem Agents
EbA	Ecosystem-based Adaptation
EP	Ecosystem Processes
EPD	Environmental Product Declaration
ES	Ecosystem Service / Ecosystem Services
ESA	Ecosystem Service Assessment
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GI	Green Infrastructure
GIS	Geographic Information System
GVA	Gross Value Added
GWP	Global Warming Potential

IPCC	Intergovernmental Panel on Climate Change
IPBES	Intergovernmental Panel on Biodiversity and Ecosystem Services
IUCN	International Union for Conservation of Nature
MEA	Millennium Ecosystem Assessment
NbS	Nature-based Solution
NCP	Nature’s Contributions to People
RQ	Research Question
UNI	Urban Nature Index

Glossary

Assessment

> "The analysis and review of information derived from research for the purpose of helping someone in a position of responsibility to evaluate possible actions or think about a problem. Assessment means assembling, summarising, organising, interpreting, and possibly reconciling pieces of existing knowledge and communicating them so that they are relevant and helpful to an intelligent but inexpert decision-maker." (Potschin-Young et al. 2018)

Biodiversity

> Biodiversity is the diversity of life which describes the biological diversity of species, genetic diversity or of entire ecosystems as habitats (Weisser 2020)

Biome

> Is the ecological land classification unit defining the overarching habitat types of the world which can consist of many ecosystems and is characterized by climate and its adapted organisms. Examples are: Tundra, grassland, desert, tropical rainforest. (National Geographic Society 2022a) This means that a biome features a similar structure and function worldwide even though that the composition in species will differ for example between South American and Southeast Asian tropical rainforests (Osborne 2000).

Biophysical structure

> "The architecture of an ecosystem as a result of the interaction between the abiotic, physical environment and the biotic communities, in particular vegetation." (Potschin-Young et al. 2018)

Biosphere

> "Relatively thin life-supporting stratum of the earth's surface, extending from a few miles into the atmosphere to the deep sea vents of the oceans. The biosphere is a global ecosystem that can be broken down into regional or local ecosystems, or biomes." (Gates et al. 2022)

Biotic

> "Living or recently living, used here to refer to the biological components of ecosystems, that is, plants, animals, soil microorganisms, leaf litter and dead wood." (Potschin-Young et al. 2018)

Built environment

> "General concept that can be related with all the structures built by man to support human activity." (Portella 2014)

Carbon sequestration

> "The process of increasing the carbon content of a reservoir other than the atmosphere." (MEA 2005)

Climax community (ecological)

> "A community of plants and animals that, following ecological succession, has reached a steady state composed of species best adapted to average conditions in that area." (Ghazoul and Sheil 2010)

Coevolution

> "is the reciprocal evolutionary change in a set of interacting populations over time resulting from the interactions between those populations." (Eaton 2008)

Community (ecological)

> "An assemblage of species occurring in the same space or time, often linked by biotic interactions such as competition or predation." (Potschin-Young et al. 2018)

Conservation

> "The protection, improvement and sustainable use of natural resources for present and future generations." (Potschin-Young et al. 2018)

Cultural ecosystem service

“All the non-material, and normally non-consumptive, outputs of ecosystems that affect physical and mental states of people.” (Potschin-Young et al. 2018)

Ecology

“Ecology is the science of how organisms interact with each other and with their environment, and how such interactions create self-organizing communities and ecosystems.” (Ghazoul 2020)

Ecological niche

Is defined by a specific set of conditions which are made up of environmental/ abiotic factors such as climate and relational/ biotic factors such as competition with other species. “Each of the various species that constitute a community occupies its own ecological niche.” (Britannica 2019)

Economic valuation

“The process of expressing a value for a particular good or service in a certain context (e.g., of decision-making) in monetary terms.” (Potschin-Young et al. 2018)

Ecosystem

“A dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit.” (CBD 2010)

Ecosystem agents

Are the individual organisms in the ecosystem which together form its biophysical structure. (Based on Mackey & Su’s definition for agents and objects in Bermingham et al. 2005)

Ecosystem approach

“A strategy for the integrated management of land, water, and living resources that promotes conservation and sustainable use. An ecosystem approach is based on the application of appropriate scientific methods focused on levels of biological organisation, which encompass the essential structure, processes, functions, and interactions among organisms and their environment. It recognises that humans, with their cultural diversity, are an integral component of many ecosystems." (Potschin-Young et al. 2018)

Ecosystem functions

"Are the effects of biota on the biological, physical, and chemical properties of the environment, including the fluxes of energy, nutrients, and materials through environments" (Ghazoul 2020). It is a "Subset of the interactions between biophysical structures, biodiversity and ecosystem processes that underpin the capacity of an 'Ecosystem' to provide 'Ecosystem services'" (Potschin-Young et al. 2018).

Ecosystem process

Here defined as intermediary between the biophysical structure and ecosystem services which describes reactions to the ecosystem's functioning and subsequent change of conditions for a service to occur. Each ecosystem service has an own set of ecosystem processes which are emergent patterns derived from ecosystem functions within the biophysical structure which have to be identified.

Ecosystem service

"Are the [mostly essential] benefits which people obtain from nature" (MEA 2005). Here synonymous with the concepts 'ecosystem goods and services', 'final ecosystem services', nature's contributions to people' found in other literature.

Ecosystem service assessment

"An appraisal of the status and trends in the provision of 'Ecosystem services' in a specified geographic area. The general aim of an 'Ecosystem service assessment' is to highlight and quantify the importance of 'Ecosystem services' to society. 'Ecosystem service assessments' are multidisciplinary in nature, applying and combining biophysical, social and economic methods." (Potschin-Young et al. 2018)

Environmental product declarations

> "describes building materials, construction products, or building components in terms of their environmental impact, based on life cycle assessments, as well as on their functional and technical characteristics. This quantitative, objective, [standardized] and verified information covers the entire life cycle of the building product." (IBU 2021)

Epiphyte

> „[Plants] growing on living plants." (Ghazoul and Sheil 2010)

Framework

> "A structure that includes the relationship amongst a set of assumptions, concepts, and practices that establish an approach for accomplishing a stated objective or objectives." (Potschin-Young et al. 2018)

Functional Groups

> Are species with similar functional traits and strategies. (Ghazoul 2020)

Functional Traits

> "Are aspects of organisms' physiology (metabolic rate, frost tolerance, or photosynthetic rate), morphology (beak size, body mass, leaf area, or wood density), or behaviour (feeding or predator evasion strategies), that influence performance or fitness." (Ghazoul 2020)

Habitat

> "the physical location or type of environment in which an organism or biological population lives or occurs, defined by the sum of the abiotic and biotic factors of the environment, whether natural or modified, which are essential to the life and reproduction of the species." (Považan et al. 2021)

Health (human)

> "A state of complete physical, mental, and social 'well-being' and not merely the absence of disease or infirmity. The health of a whole community or population

is reflected in measurements of disease incidence and prevalence, age-specific death rates, and life expectancy." (Potschin-Young et al. 2018)

Healthy ecosystem

"One that is able to exist, reproduce and perpetuate in a given environment by maintaining a perennial structure (i.e. growth, organization and biodiversity), and that can implement processes of resistance against adverse external threats, such as plant and animal pests, and climatic effects, in order to quickly repair eventual damages and reproduce itself." (EEA 2016a)

Human wellbeing

"A state that is intrinsically (and not just instrumentally) valuable or good for a person or a societal group, comprising access to basic materials for a good life, health, security, good physical and mental state, and good social relations." (Potschin-Young et al. 2018)

Instrumental value

"Value that something has as a means to an end (e.g. game animals used for food)." (Potschin-Young et al. 2018)

Intrinsic value

"Intrinsic value is the value something has independent of any interests attached to it by an observer or potential user." (Potschin-Young et al. 2018)

Mutualism

"A symbiotic, or mutually beneficial relationship." (Ghazoul and Sheil 2010)

Mycorrhiza

"Fungi closely associated with plant roots and usually involved in a mutually beneficial symbiotic relationship with the plant." (Ghazoul and Sheil 2010)

Natural capital

The environmental stocks of natural biotic (living) and abiotic (non-living) resources which provide ecosystem services. (Preston and Raudsepp-Hearne 2017)

Planetary boundaries

Are a concept which defines nine boundaries that are fundamental to the stability and resilience of the Earth system (Stockholm Resilience Centre 2022)

Primary production

“Production of organic compounds from CO_2 through (mainly) photosynthesis.” (Ghazoul and Sheil 2010)

Provisioning ecosystem service

“Those material and energetic outputs from ecosystems that contribute to human ‘well-being’.” (Potschin-Young et al. 2018)

Regulating ecosystem service

“All the ways in which ‘ecosystems’ and living organisms can mediate or moderate the ambient environment so that human ‘well-being’ is enhanced.” (Potschin-Young et al. 2018)

Resilience

“is the capacity of an ecosystem to absorb and recover from shocks and disturbances while maintaining overall ecosystem structure and function. […][It is also] the time taken for a system to return to an equilibrium state following a perturbation, or the amount of disturbance that can be absorbed before an ecosystem flips into a new persistant state that is structurally and behaviourally different.” (Ghazoul 2020)

Restoration (ecological)

> "The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 2022) to regain its ecological functionality.

Root mats

> "Tightly woven and/or interlinked roots and hyphae that sometimes form on the soil surface." (Ghazoul and Sheil 2010)

Secondary forest

> "Woody regrowth vegetation in areas where forest cover was previously removed, destroyed or absent." (Ghazoul and Sheil 2010)

Species abundance

> "The total number of individuals of a taxon or taxa in an area, population, or community." (MEA 2005)

Succession

> "Sequence of changes in the composition and/or structure of an ecological community following disturbance or environmental change." (Ghazoul and Sheil 2010)

Supporting ecosystem service

> "Are those that are necessary for the production of all other ecosystem services." (MEA 2005)

1. Introduction

This is the decisive decade for humanity to safeguard the stable conditions and resilience of earth's life support system for societal livelihoods.

Since 2009, nine key processes of earth's life support system to humanity have been identified and assessed on a safe operating space within which the continuation of development throughout generations can be assured (Stockholm Resilience Centre 2022). However, almost all yet quantified planetary boundaries are exceeded with an increased risk of irreversible changes to that stability and resilience of the system due to anthropogenic activity (Figure 1). The arguably most publicly present and discussed boundary and indicator is climate change which diverts attention away from the overall conditions and prospects for the life support system aside from climate change consequences caused by human activity.

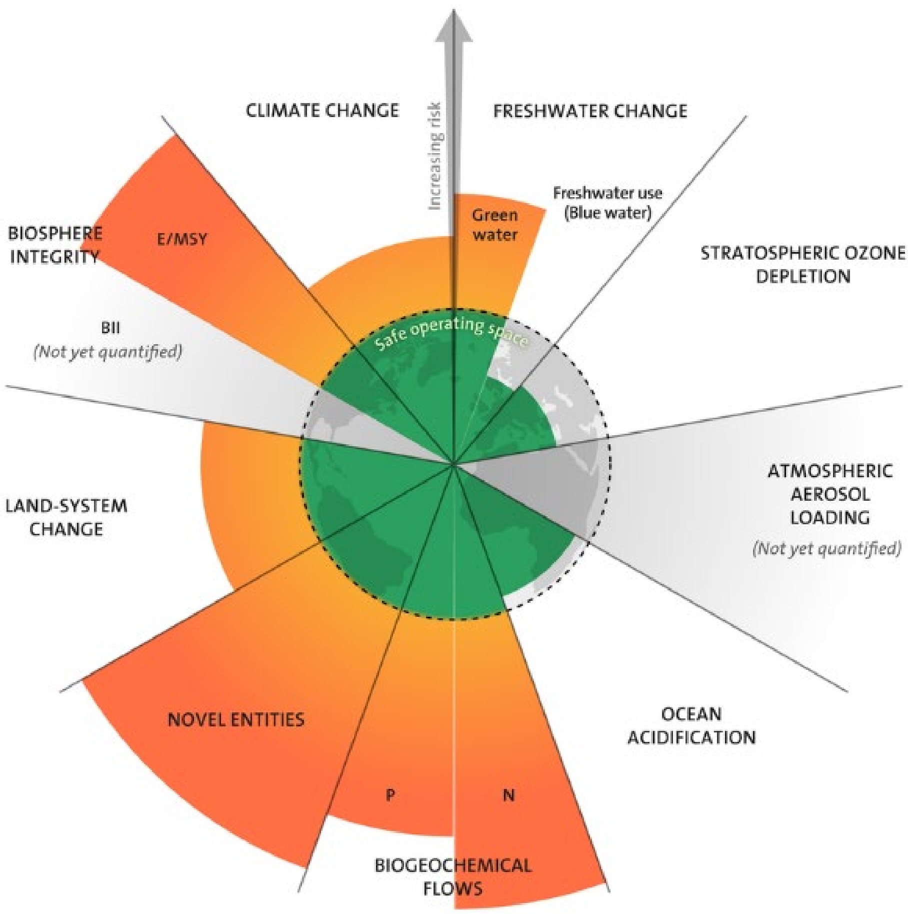


Figure 1. Currently exceeded planetary boundaries. Image by Azote for Stockholm Resilience Centre (Potsdam Institute for Climate Impact Research 2022), based on analysis in Steffen et al. (2015b), Wang-Erlandsson et al. (2022) and Persson et al. (2022)

Despite decades of warning by the scientific community to limit global warming to the boundary of 1.5°C, it is likely that this threshold will be exceeded and that without the implementation of further effective policies greenhouse gas (GHG) emissions will increase and lead to a median global warming of 3.2°C by 2100 (IPCC 2022b). This will entail a worldwide increase in severe weather events, climate catastrophes, shortages in food and water supply and collapse of ecosystems which deepen social inequalities, more intensely affect the poor and drive millions of people into poverty (IPCC 2022a). “The global economic benefit of limiting warming to 2°C is reported to exceed the cost of mitigation […]“, however for all modelled pathways this requires immediate and large scale reductions of GHG emission across all sectors (IPCC 2022b).

However, aside this climate change reality, Steffen et al. (2015a) have underlined the striking relation of human development and economic prosperity on the exploitation of fossil resources and the degradation of natural environments with “The trajectory of the Anthropocene” (Figure 2). It is shown that in “a single lifetime – humanity […] has become a planetary-scale geological force” whose activities inseparably affect the earth system (Steffen et al. 2015a).

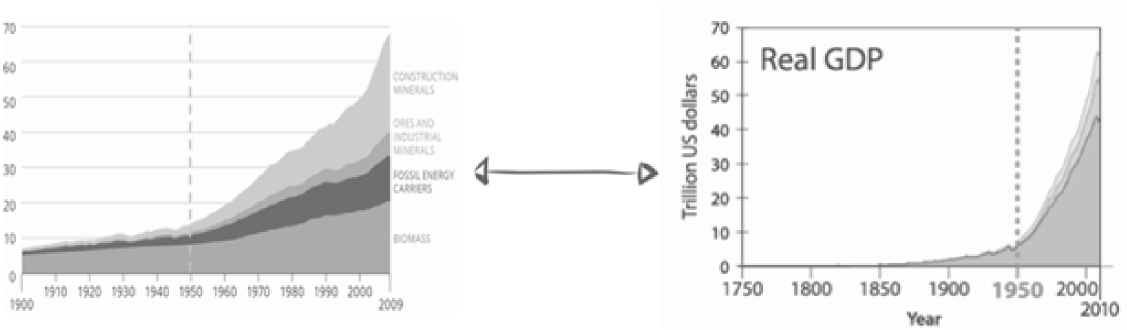


Figure 2. Coupling between resource consumption (EEA 2016b) and economic development (Steffen et al. 2015a)

Depletion, pollution, land use change, climate change, the loss of ecosystems and its services are not only qualitatively but also quantitatively known, and scientific evidence is clear on the consequences for human life with current trajectories.

The biosphere is humanity’s life support system because nature supplies essential services, so called ecosystem services, for human existence and good quality of life (IPBES 2019). Its integrity is the second core boundary besides climate change upon which all other planetary boundaries depend most (Häyhä et al. 2018).

Thus, human development cannot continue at the expense of deteriorating these foundations (see Chapter 1.2). However, breaking this tie and taking planetary stewardship by decoupling development from natural resources and impact on the environment has yet to be achieved (Steffen et al. 2015a; UNEP 2011) (Figure 3).

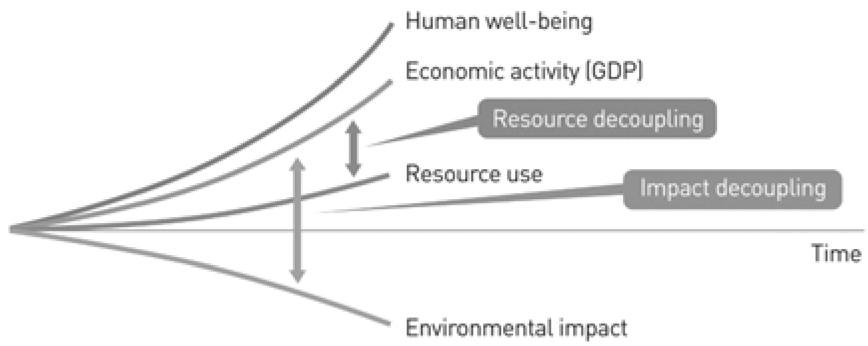


Figure 3. Decoupling natural resource use and environmental impacts from economic growth (UNEP 2011)

Nevertheless, the continuation of human wellbeing at large depends on societal transformations to rebuild our resilient biosphere and "reconnect [human] development to the Earth system foundation through active stewardship of human actions into prosperous futures within planetary boundaries" (Folke et al. 2021). Stemming from the fundamental understanding of the interactions and intertwined nature of ecosystems and human systems, the same scientific reports of the intergovernmental panels on climate change (IPCC) and biodiversity and ecosystem services (IPBES) strongly support the key role of nature conservation, ecological restoration and ecosystem based solutions and management, in order to achieve such transformation.

1.1. The built environment's role in a transformation

While only covering 1-3% of the earth's surface, urban areas are inhabited by the increasing majority of the global population (by 2050: World 68%, Indonesia 73%, Europe 84%) which not only generate about 80% of global GDP but also consumes three quarters of global energy and material flows (United Nations 2018; EIB 2018; UNEP 2013; Metabolic 2017). The built environment as an industry sector itself consumes half of the world's natural resources and emits 40% of global greenhouse gases (WorldGBC 2021;

European Commission 2022b). Cement production alone accounts for 7% of global GHGs (Czigler et al. 2020).

This displays city's unique role and importance to achieve a transition because human activity within the built environment (BE) and the construction of the BE itself has far reaching impacts and consequences outside the urban boundaries. More than 75% of the European population already live within urban areas (United Nations 2018) and it is mostly their consumption-related contributions to the different planetary boundaries per capita which exceed European production footprints and global averages significantly, thereby continuing an externalization trend and increasing environmental pressures in other parts of the world (Häyhä et al. 2018). The dependence on the Earth's life support system and subsequent land requirement to sustain people living in a city is much larger than its own footprint (Bushnell 2021). For the city of Vienna, for instance, Lauk et al. (2022) have found that this footprint is about fifteen times larger, with an agricultural land requirement of 0.35ha per person, besides about two thirds of that being located in foreign countries.

Thus, there is a clear nexus between the built environment and its inhabitants driving land conversion, climate change and biosphere degradation through the adverse impacts inflicted by consumption decisions which disregard the health of and ultimate dependence on the natural environment. A study by Arup has outlined the impacts of the BE on the different planetary boundaries (Bushnell 2021). The BE strives to build for people and their wellbeing, however it fails to understand and address the foundation of human development and welfare. The planning and construction of human environments is yet to holistically account for the multitude of planetary challenges and not to solely focus on decarbonization, despite its unquestionable importance (see also BBSR study from 2020 on the environmental footprints of buildings in Germany and the necessary reductions to stay within planetary boundaries).

"Urban areas can create opportunities to increase resource efficiency and significantly reduce GHG emissions through the systemic transition of infrastructure and urban form through low-emission development pathways towards net-zero emissions. […][This can be achieved] only if emissions are reduced within and outside of their administrative boundaries through supply chains, which will have beneficial cascading effects across other sectors" (IPCC 2022b).

“[Because] The question no longer is how to reduce the negative impact of our actions, but instead how each and every action can contribute to a positive future […] [,] [a] built environment as a means of regenerating, co-creating and evolving social-ecological systems from the local to the global scale […] has several implications for the production of the built environment for how it is created, the technologies used, and how it is evaluated” (Du Plessis and Brandon 2015).

The built environment as a discipline has therefore an extended responsibility and exceptional role but also because people spent almost all of their time in man-made surroundings considering that people spent most of their time indoors (Ortiz-Ospina 2020) and 75% of the terrestrial ice-free surface has already been modified by human activity (IPBES 2019). While redefining human development and accomplishing synergies between sustainability agenda efforts (Bushnell 2021), this opens the opportunity to also act as educator and role model to raise awareness on the societal dependence on healthy and functioning ecosystems and their services through its significant, even though indirect, influence on people by shaping their surroundings.

1.2. Biodiversity’s role in a global safety net

Biodiversity and the diversity of interactions can be seen as a bank of solutions to make best use of available resources but most importantly as a safety net to secure the continued functioning of the whole ecosystem (Ghazoul 2020). It increases the resilience against shocks. In the face of a heavily altering climate, this resilience is important to sustain and regenerate the health of the ecosystem on which human wellbeing depends (see also Chapter 2.3 Ecosystem service cascade).

Definition:

Biodiversity is the diversity of life which describes the biological diversity of species, genetic diversity or of entire ecosystems as habitats (Weisser 2020). If productivity and variation, and thus resources and the conditions to obtain them, within a system increase, the possibility of new ecological niches arises. This increases the likelihood of a further diversification based on a range of newly required traits to persist, and an increase in biodiversity. (Dorber 2021; Ghazoul 2020)

"The tendency for biological diversity to increase over evolutionary time, within and among communities, and the adverse effects of new kinds of disruption on a community's diversity suggest that ecological communities are organized in ways that favor high diversity, just as a thriving economy supports a diversity of occupations. Biological diversity, like diversity of human occupations, develops in response to trade-offs in ability to exploit different resources under different conditions. Disrupt the links of interdependence by, for example, eliminating a forest's pollinators and seed dispersers, and diversity will collapse, even if the factors originally promoting its evolution are still operative." (Leigh and Rubinoff 2005)

Box 1. Bird species diversity for plant species survival and ecosystem resilience

An example to illustrate the importance of biodiversity for the functioning and resilience of an ecosystem is the seed dispersal of a plant by a bird. Should this one bird perish, possibly due to continued deforestation and destruction of its habitat, so will the plant along with it and all the processes and services it has performed. If in contrast there are multiple species of birds which will have specialized on the fruit of the plant which carries the seed, the extinction of one will not have the same consequence, since the seed dispersal and thus further establishment and existence of the plant species is secured by the other bird species which interact with it (see Figure 4). So "Redundancy within functional groups provides insurance. The loss of some species can be offset by an increase in the activities of others in the same functional group" (Ghazoul 2020) which here is 'seed dispersers'.

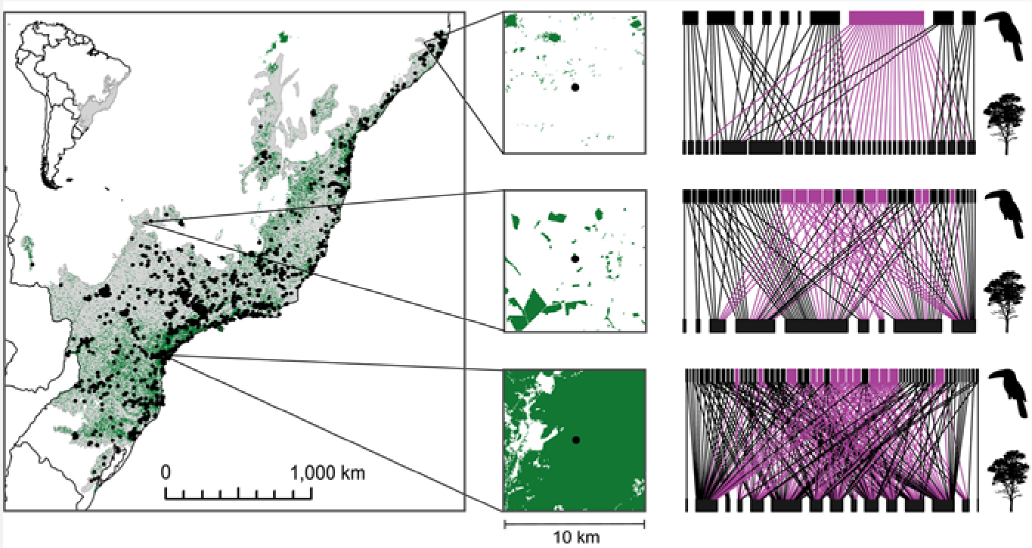


Figure 4. Fragmented tropical forests lose mutualistic plant animal interactions from Marjakangas et al. (2020)

The reality is that there is globally a drastic decline in species populations. In the period from 1970-2016, abundances have decreased by 68% (WWF 2020). Also, species are far more rapidly driven to extinction with for example about cumulative 2% of mammals driven extinct since 1500 compared to a cumulative of 0.125% species based on estimated, naturally occurring background rates of 0.1-2 extinctions per million species per year (IPBES 2019). Since 1700, 21% of the global biodiversity has been lost (Figure 5), beyond a planetary boundary and biosphere integrity threshold of maximum 10% decline in the biodiversity intactness index (WWF 2020). The recent IPCC (2022a) report has found that further 29% of all remaining terrestrial species are threatened with extinction and there is a high to very high risk of biodiversity loss for ocean and coastal ecosystems at a global warming of 3°C. This likely leads to an irreversible mass extinction.

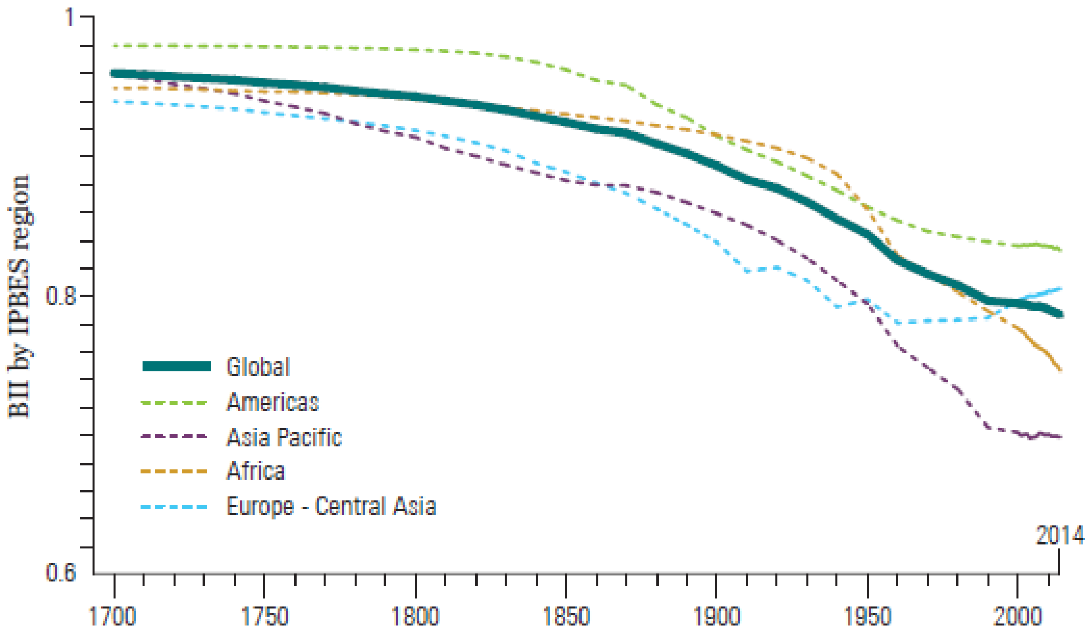


Figure 5. Biodiversity intactness index (BII) decrease since 1700 from WWF (2020)

“[Furthermore,] only ~0.002% of global GDP is invested in biodiversity conservation […][and currently,] out of US$667 billion in quantified green stimulus proposed by G20 countries and ten other nations (<5% of all COVID-related stimulus), only US$141 billion relates to improving biodiversity status or protecting ecosystems, while almost twice as much (US$262 billion) will lead to pollution or habitat destruction likely to negatively impact biodiversity” (UNDP 2021).

The main drivers of biodiversity loss are (in order of magnitude): land use change, over-exploitation of natural resources, climate change and pollution (IPBES 2019). The BE further exerts pressure and drives biodiversity as outlined in the previous chapter through exceeding planetary boundaries but as also specifically described by the Ellen MacArthur Foundation (2021) and Pedersen Zari (2014) (Figure 6).

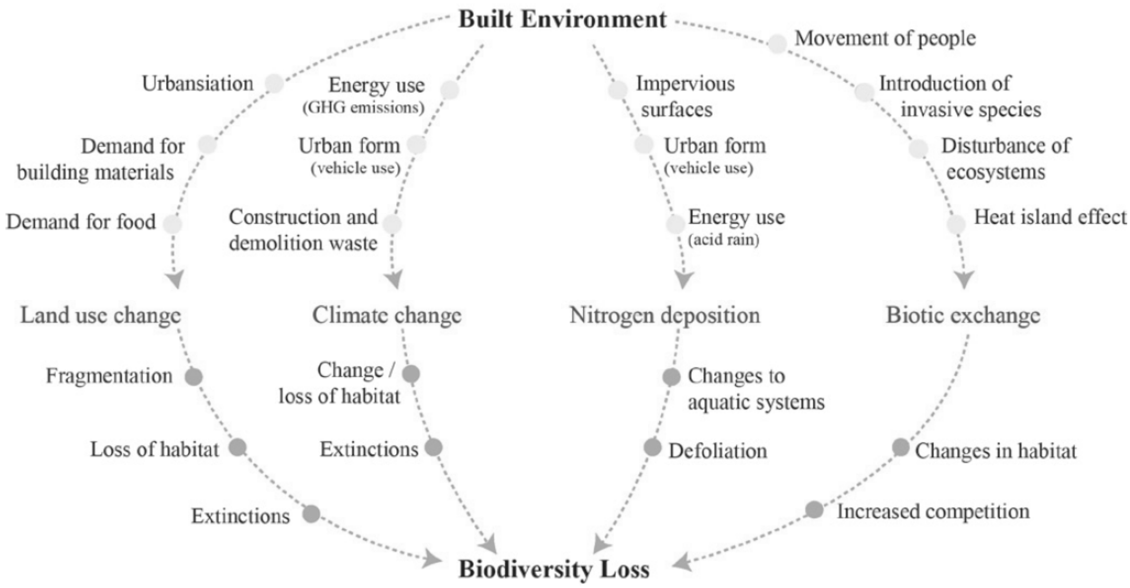


Figure 6. Built environment driving biodiversity loss from Pedersen Zari (2014)

A global safety net, conserving about half the terrestrial land area is required to sustain and protect human’s life support system by reversing global biodiversity loss, preventing the appearance of net carbon emitters from appearing and increasing natural carbon sinks (Dinerstein et al. 2020) (Figure 7). As nations, especially Indonesia besides Russia, Brazil and the United States of America have an outsized role in protection of their biodiversity.

The study confirms that important biodiversity hotspots coincide with important areas for carbon storage which consequently supports the notion that biodiversity protection is also climate change mitigation. This further supports that nature conservation and restoration are able to provide synergistic effects to tackle these challenges. Nevertheless, it needs to be emphasized that “It is less costly to conserve Nature than to restore it once damaged or degraded, all else being equal. […][and that] in many cases there is a strong economic rationale for quantity restrictions over pricing mechanisms” to precautionary deal with markets and the risks of degradation (Dasgupta 2021).

A public awareness about the importance of healthy ecosystems for human wellbeing through the delivery of essential services has yet to emerge. Biodiversity, which is so fundamental to health, has only begun to gain traction as a term outside of the ecological discipline. In 2017, the UK GBC has ambitiously set out the goal to becoming ‘second nature’.

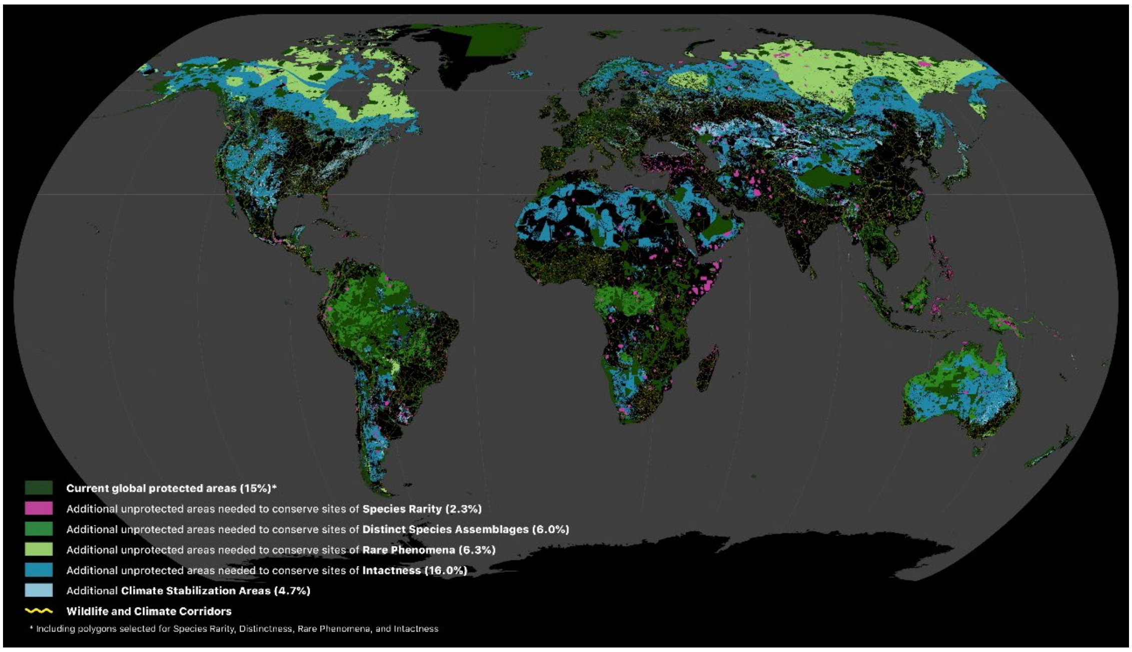


Figure 7. Global safety net conserving 50.4% of the global surface from Dinerstein et al. (2020)

Still, the missing proper understanding and rudimentary translated meaning across disciplines has resulted in mainly poor ecological quality projects for many reasons but ultimately inhibiting a mutual human and natural development (Pedersen Zari 2018). Even current green building standards fail to properly address biodiversity goals and enable net-positive buildings in this regard (Catalano et al. 2021).

Green envelope design and water retention landscaping are design elements which have fortunately gained increasing interest as nature based solutions to combat urban heat island effects and increasing stormwater requirements. However, these are as single entities seldomly part of a holistic transformation to increase natural capital and revert previous environmental damages caused by human actions.

1.3. Aim of this thesis

“Reorganisation is a common pattern in the human past” (Steffen et al. 2015a)

“Nature puts us human in our place. It provides us with life, takes it away, and will be there long after the last human.” (Chan & Satterfield in Potschin et al. 2016)

Knowing of this necessity to co-evolve, the built environment (BE) has the responsibility and important role to transform, secure and safeguard the foundations of human well-being by also building for the health of the natural environment and regenerate nature’s supplies to the people that is built for. This could be a “positive building” legacy. The notion of ecosystem services (ES) or nature’s contributions to people can bridge the gap between the importance of a healthy functioning natural world and the human benefit (Chapter 2.3) to tackle the triple planetary crisis of climate change, nature loss and inequality by transforming the built environment and practice.

It is hypothesized that:

1) Developing the built environment changes the provision of ecosystem services.

And

2) Built environment practice could regenerate and strengthen human wellbeing while co-evolving with nature.

The goal of this thesis is to raise awareness for the fundamental role of nature's services to humanity, the disregard in BE planning and its consequences for human wellbeing. Moreover, the goal is to display the potential of addressing multiple societal challenges and aspirations simultaneously by accounting for ecosystem services. Lastly, the definition of tangible approaches to assess different scales and optimize practice based on the provision of ecosystem services is targeted.

This identifies the following main research questions which guide the structure and process of this research work and are answered by the development of two methodological approaches (Chapter 3).

RQ1: How does ES provision differ in urban to natural environment?

RQ2: How does the BE impact ES provision?

RQ3: How can the BE provide ES by its building actions?

Holistically dealing with the ecosystem services concept to inform and alter design and development decisions is a novel approach for which only few scientific and mostly theoretical explorations by a few authors are currently available in relation to building practice (as to be seen in Chapter 2.6 Ecosystem service analysis for the built environment).

2. State of the art

“We are the first generation that has a clear picture of the value of nature and its integral link with human well-being. We are also the last generation that has the opportunity to prevent the collapse of our planet’s biodiversity in the face of habitat destruction and climate change.” O’Higgins et al. (2020) adapted from Living Planet Report of Grooten and Almond (2018).

2.1. Ecosystem service timeline

Ecosystem services (ES), as benefits which people obtain from ecosystems (MEA 2005), is a relatively young concept which has appeared in various forms since the 1970s (Maes and Burkhard 2017) (Figure 8). Yet, it is said to be “one of the most powerful concepts to have emerged over the last two decades. [Because] It is shaping our understanding of the role that biodiverse ecosystems play in the environment and their benefits for humankind” (Potschin et al. 2016).

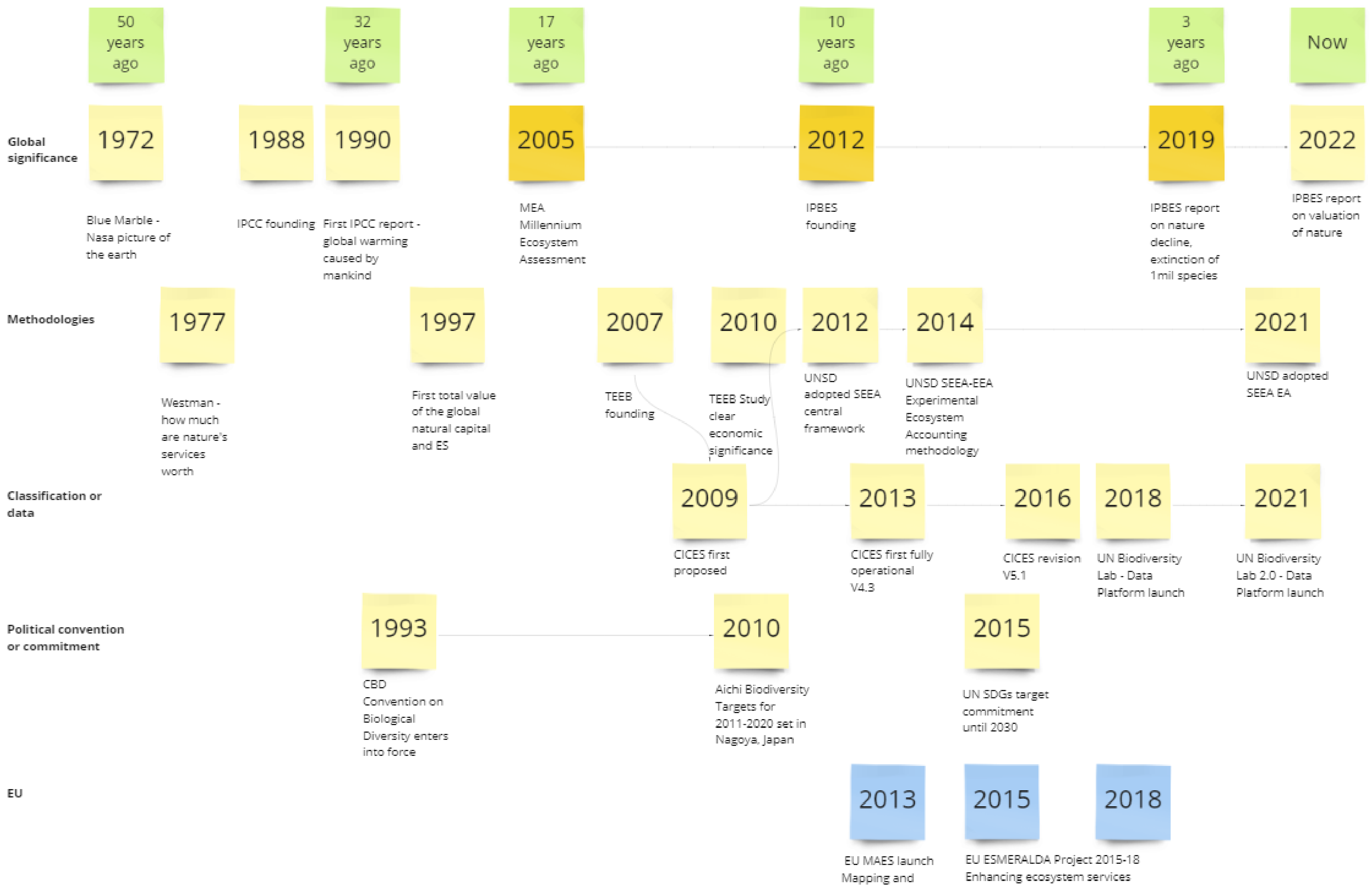


Figure 8. Selected timeline events of ecosystem services development

A trigger, especially in public opinion and in support of the development of the planetary boundaries framework, might have been the first picture of the entire earth in 1972 by NASA which visually expressed the finiteness of our living area and resources (Figure 9) (Ghazoul 2020). This realization and visual evidence of physical limitation tied to the developing understanding that nature on earth provides society with the essentials for life is thus only 50years old.

Figure 9. "Blue Marble" - The first picture of the whole earth (NASA 1972)

Another significant milestone has been the Millennium Ecosystem Assessment (MEA or in other literature also abbreviated as MA) in 2005 which for the first time assessed the state of the earth's ecosystems and identified the drivers behind its deterioration and decline, linking the social-ecological systems. In response to these research outcomes and as pendant to the IPCC, the IPBES was founded in 2012. Its last report in 2019 gained large public attention and reported on the dangerous and unprecedented decline of nature and one million species threatened with extinction (IPBES 2019). IPBES coined the term Nature's contributions to people (NCP) as synonym for ecosystem services to enhance public and political communication and understanding. For the same reason, ES categories are grouped to: (1) regulation of environmental processes, (2) material and assistance and (3) non-material NCP. Therefore, both, MEA and IPBES based studies, can be found depending on the selected framework and subsequently slightly differing categorization (Díaz et al. 2018).

ES research and mapping continuously increases and diversifies, as to be seen in Figure 10 and Figure 11. Some of the most recent approaches, such as indicators and non-monetary valuation besides computational modelling, are only little more than a decade old (Valencia Torres et al. 2021).

A significant milestone within the EU is even younger and has been the launch of the MAES project on the **M**apping and **A**ssessment of **E**cosystems and their **S**ervices in 2013 (Maes and Burkhard 2017). Yet, 'a fundamental understanding of ecosystems and the environment is lacking in some areas of planning, especially urban planning" which has to still take up the increasing knowledge on ecosystem services in practice (Thompson et al. 2021).

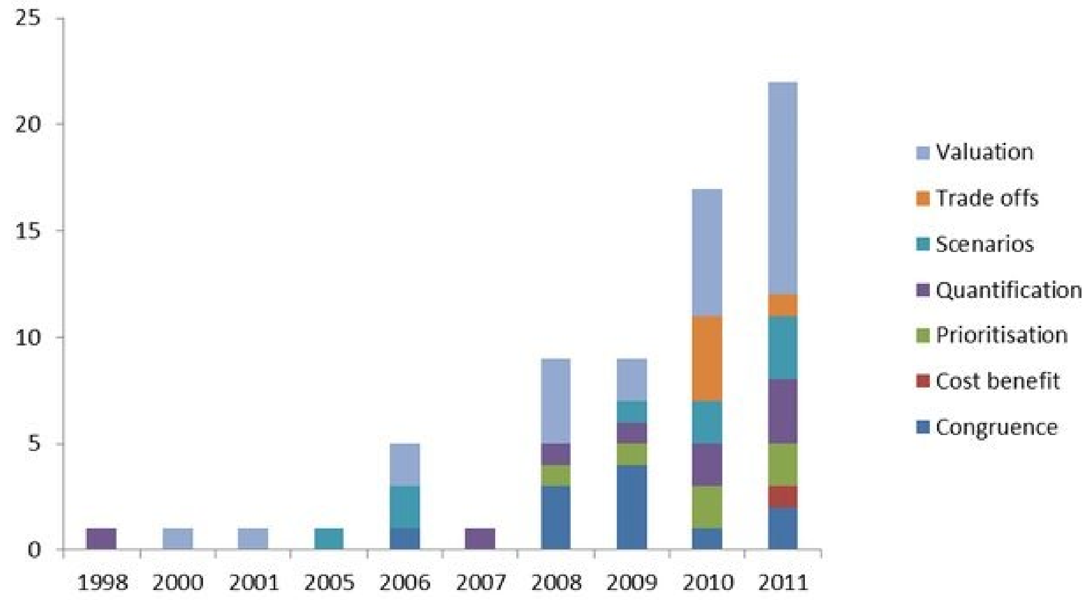


Figure 10. Amount of studies per year and motivation for ecosystem services mapping from Benis Egoh et al. (2012)

Figure 11. Emerging ecosystem services themes and approaches since 1977 from Valencia Torres et al. (2021)

2.2. The four ecosystem service categories

In this thesis, the original categorization and framework of the MEA is used, as it is seen as the most appropriate to communicate ecological understanding while being also sufficiently understandable for built environment (BE) professionals.

Ecosystem services (ES) can thus be categorized into four categories which are highly interlinked and relate to the constituents of human wellbeing (MEA 2005) (Figure 12). The most publicly comprehensible are the 'Provisioning ES' which incorporate materials, food or water. Another publicly understood ES is Recreation in natural environments as for example in parks. This is a 'Cultural ES'. The remaining two categories are 'Regulating' and 'Supporting ecosystem services'. (Fish, Saratsi et al. in Potschin et al. 2016)

Definition: Ecosystem services categories

Supporting ES: "Are those that are necessary for the production of all other ecosystem services. They differ from provisioning, regulating, and cultural services in that their impacts on people are often indirect or occur over a very long time, whereas changes in the other categories have relatively direct and short-term impacts on people." (MEA 2005)

Regulating ES: "All the ways in which 'ecosystems' and living organisms can mediate or moderate the ambient environment so that human 'well-being' is enhanced." (Potschin-Young et al. 2018)

Provisioning ES: "Those material and energetic outputs from ecosystems that contribute to human 'well-being'" (Potschin-Young et al. 2018). "These are the products obtained from ecosystems " (MEA 2005)

Cultural ES: "All the non-material, and normally non-consumptive, outputs of ecosystems that affect physical and mental states of people. Cultural 'Ecosystem services' are primarily regarded as the physical settings, locations or situations that give rise to changes in the physical or mental states of people, and whose character are fundamentally dependent on living processes; they can involve individual species, habitats and whole ecosystems. […] Spiritual and religious settings are also recognised. The classification also covers the 'existence' and 'bequest' constructs that may arise from people's beliefs or understandings." (Potschin-Young et al. 2018)

There is a hierarchy to these four categories by definition of the attributed ES. Supporting services such as habitat provision are essential for regulating services like pollination which in turn is tied to food provision. Depending on the societal context food can then in turn represent a cultural service which is grounded in cultural diversity and meaning attributed to it.

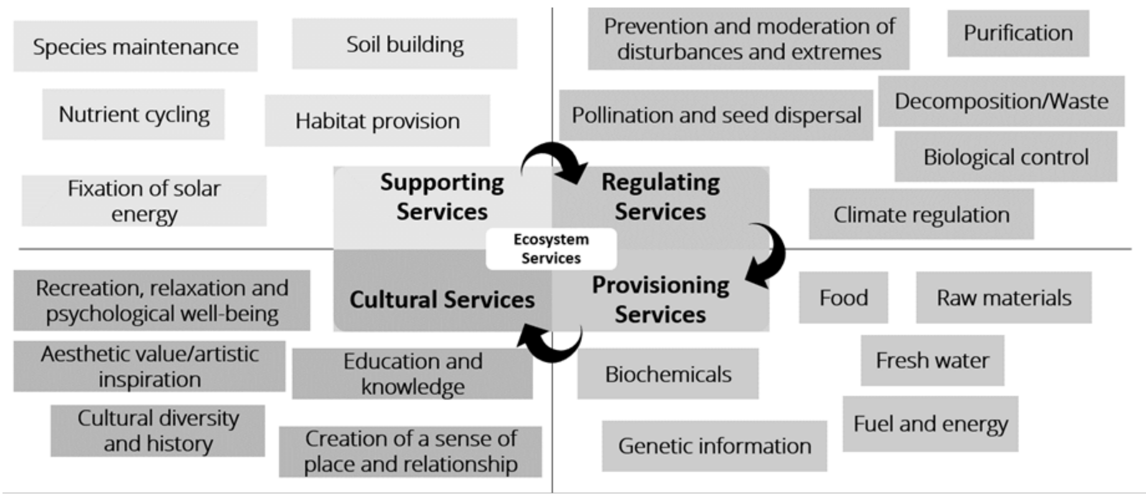


Figure 12. Categorization of exemplary ecosystem services based on (MEA 2005; Pedersen Zari 2018), Design by Katharina Hecht (2021)

Table 1. Complete list of ecosystem services according to (MEA 2005)

Ecosystem service category	Ecosystem services
Supporting services	Soil formation Photosynthesis Primary production Nutrient cycling Water cycling
Regulating services	Air quality regulation Climate regulation Water regulation Erosion regulation Water purification and waste treatment Disease regulation Pest regulation Pollination Natural hazard regulation
Provisioning services	Food Fiber Fuel Genetic resources Biochemicals, natural medicines, pharmaceuticals Ornamental resources Fresh water

Cultural services	Cultural diversity Spiritual and religious values Knowledge systems Educational values Inspiration Aesthetic values Social relations Sense of place Cultural heritage values Recreation and ecotourism

Habitat provisioning had initially not been defined as one of the identified ecosystem services by the MEA (2005) but its importance and the correlation of its degradation and loss to ES deterioration was already clearly described, leading to later uptake and recognition as a supporting service.

Besides interlinkages there are also trade-offs between different ecosystem services. A common trade-off for example is the increase in food production through intensifying agriculture and land use which diminishes water availability as another provisioning service but also the ability to sequester carbon (regulating service) and to regulate nitrogen (supporting service). This means that in this case an increase in provisioning service entails a decrease in regulating and supporting services. Therefore, there are not only linkages between and within the ES categories but similarly trade-offs which is an important characteristic to take into account when working with this concept. More common trade-offs are listed in the MEA (2005).

Trade-offs are a natural and common occurrence in nature which fosters diversity, such as in the functional trait (see Glossary) diversity of species where for example one plant species is able to rapidly acquire nutrients and grow fast while the other species is conservative with nutrients, slowly grows but has an improved defensibility against climatic changes or herbivores – plant eating animals (also see Chapter 4.3.2 Ecological knowledge) (van Bodegom and Price 2015; Ghazoul 2020). Therefore trade-offs are also beneficial, because "more diverse plant communities can provide higher levels of multifunctionality and [in turn] higher levels of multiple ecosystem services" (Potschin et al. 2016).

Therefore, decision making has to ensure that a sufficiently broad set of ecosystem services is assessed to identify and evaluate trade-offs. This evaluation in turn has to equally take a variety of values for the different ecosystem services into account because the maximization of one will come at the decrease of the other and only a diverse set of values is likely to recognize that a balance in ecosystem services maintains the ecosystem's balance to the overall and long-term optimum.

2.3. Ecosystem service cascade

Ecosystem services (ES) are the result of an ecosystem's biophysical structure and functioning to enable certain ecosystem processes (EP) that make up an ES. The services are in turn the bridge between the environment, nature, and the social and economic system which derives human benefits and values from the service provision.

The cascade model originates from Haines-Young and Potschin (2010) and schematizes this chain of derivates from nature towards the value human's attribute to its services (Figure 13). It is at the basis of the assessments conducted in this thesis.

The biophysical structure is created by the assemblage of life-forms, its biodiversity in plants, animals and organisms as ecosystem agents (EA), and their always dynamic interactions also with the abiotic (non-living) conditions like the climate, which in turn governs ecosystem functioning (Orians et al. 1996). Even though that the overall structure between ecosystems might be similar due to comparable communities, their specific species composition and thus EA differ for the same EP. Also for every ES, there is a different set of EP which is to be identified (see Chapter 4.3.5 Ecosystem service profiles).

Box 2. Emphasis on why does biodiversity matter?

"Ecosystem functions are the effects of biota on the biological, physical, and chemical properties of the environment, including the fluxes of energy, nutrients, and materials through environments. Associated with this are ecosystem services, the natural processes that contribute to human wellbeing […] Ecosystem functions and services arise from interactions among species and their environment." Therefore is biodiversity conservation not only detrimental for its own sake but crucial for the continued provision of human benefits. (Ghazoul 2020)

Thus, in order to understand ES provision, the ecosystem context has to be studied to identify its main characteristics based on this cascade.

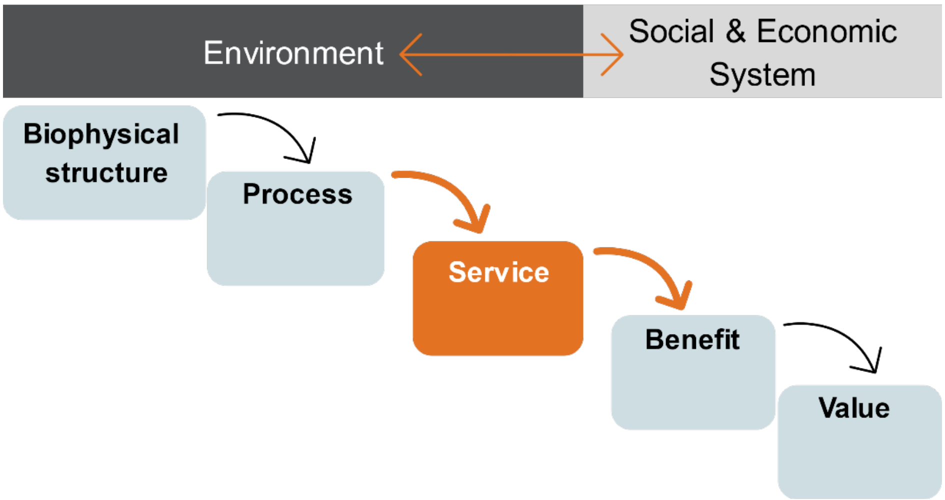


Figure 13. Ecosystem service cascade model adapted from Haines-Young and Potschin (2010)

2.4. Ecosystem service indicators

In order to tangibly work with the ecosystem service (ES) concept the services have to be measurable with the aid of indicators. In the long term, this facilitates the possibility to monitor and assess the ES's performance. Extensive indicator sets have been defined for all ES categories and a service's corresponding human benefit in the Canadian ES Toolkit (EST) by Preston and Raudsepp-Hearne (2017). Maes et al. (2016) defined indicators related to the urban ecosystem for provisioning, regulating and cultural ecosystem services, as well as best available indicators across different ecosystems for EU reporting and standardization purposes. These later aid in the identification of suitable data sources to assess ES provision (see Chapter 3.2.1).

Based on these different literature sources for ES indicators and understanding of underlying ecosystem processes the following primary and secondary indicators can exemplary be identified for three supporting ecosystem services (Table 2).

Table 2. Primary and secondary indicators for three supporting ecosystem services

Ecosystem Service	Primary Indicator	Secondary Indicator	Source
Habitat Provisioning	- Topography/characteristic requirements for reproduction	- Characteristics/ biophysical structure of habitat - Species abundance	(Preston and Raudsepp-Hearne 2017)
Nutrient Cycling	- Nutrient ratios/balance/concentration - Decomposition rate - Texture/structure of soil	- Soil maturity index - Biodiversity micro food web/ invertebrate communities - Erosion rates or eutrophication (indicator for loss/dysfunction)	(MEA 2005)
Water Cycling	- Intercepted rainfall [m^3/a] - Water retention capacity by vegetation and soil [t/km^2] - Soil water infiltration capacity [cm][cm/h] - Soil water storage capacity [mm] - Surface runoff [mm]	- Surface/ groundwater - Drinking water provision [$m^3/ha*a$] - Non drinking water provision [$m^3/ha*a$]	(Maes et al. 2016)

2.5. Ecosystem service valuation

The valuation of ecosystem services (ES) is a discipline on its own and can be based on many different approaches but with two main outcomes, being a monetary or non-monetary valuation. Yet, “the challenges of constructing of an agreed international standard are considerable, and will no doubt continue for many years, in many cases the process of (both monetary and non-monetary) valuation itself presents major challenges” (Flood et al. in (O’Higgins et al. 2020).

The first initiative to draw international attention to the benefits provided by nature was The Economics of Ecosystems and Biodiversity (TEEB) which provided its first study and the clear economic significance in 2010, building upon the first attempt and definition of the Common International Classification of Ecosystem Services (CICES) (Maes and Burkhard 2017). The CICES is based on the previously described ecosystem service cascade model (Chapter 2.3). Its main difference is that it does not recognize supporting services but clearly outlines its classifications and how they specifically relate to the Millennium Ecosystem Assessment (MEA) and TEEB categorization and naming of ecosystem services (Haines-Young and Potschin 2018).

The monetary valuation of ecosystem services estimates economic values based on current market forces to communicate with the prevailing gross domestic product (GDP) system to account for nature’s value in decision making and indicate “the magnitude of these services relative to other services provided by human-built capital at the current point in time” (Costanza et al. 2014). This is necessary because “economic progress measures continue to rely on GDP to inform development paradigms, policies and related programs” and its consequences are causing the present day, global environmental and social challenges (Sangha et al. 2022). “This ability to follow biophysical estimates through to economic value has allowed decision makers to begin having conversations they did not previously engage with, and lead to new policy outcomes” (Flood et al. in (O’Higgins et al. 2020).

Nevertheless, despite more than 50 valuation methods and approaches available, IPBES (2022) reports that less than 5% of valuation publications include uptakes in policy. Furthermore, Ersoy Mirici (2022) interestingly identified a lack of economic analysis of green infrastructure and ES provision in urban planning by exploring scientific publications within the Scopus database, which makes ES valuation even more relevant for built environment (BE) practice.

There are different methods to obtain an economic value for an ES which mostly focus on use values (Figure 14), such as the attribution of costs by determining the willingness to pay (WTP) for water or raw material provisioning (direct use) or hazard regulation services through natural shoreline protection by avoiding storm, wave and flooding damages (Quasi option). The first example represents market-based instrumental values which have been prioritized for economic and political decisions besides non-market, relational or intrinsic values of nature (IPBES 2022).

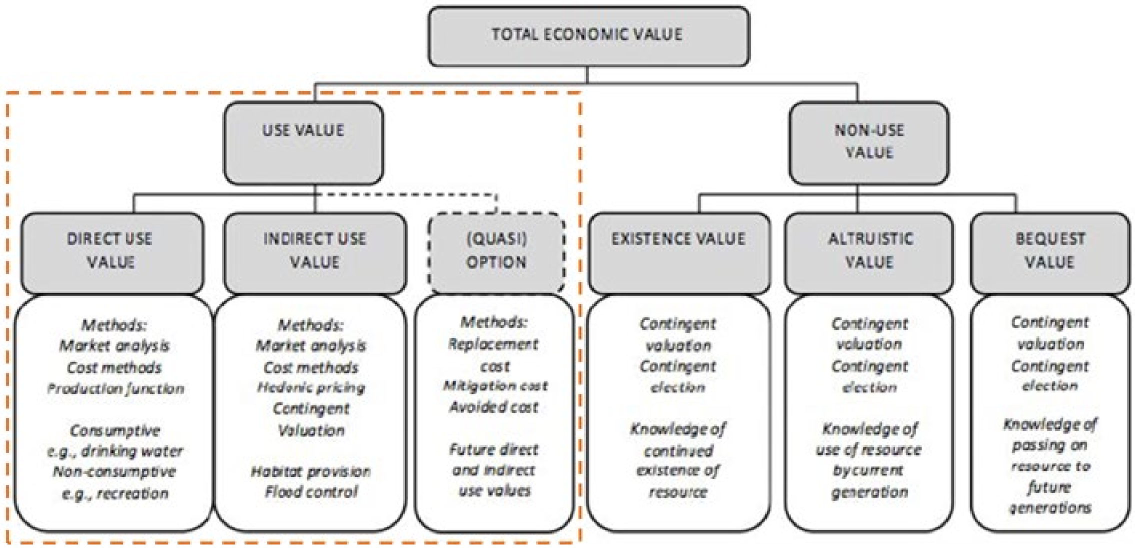


Figure 14. Focus of economic valuation studies, adapted from Preston and Raudsepp-Hearne (2017)

While valuing individual services is possible, even for losing an ES, it is misleading because of the interdependencies between services and the greater values at stake (Westman 1977). Therefore, decisions should not be based on a narrow set of ES but account for their multitude and diverse values (IPBES 2022). If such is done, “economic estimates of services, conservation and restoration benefits tend to outweigh those private benefits” (Bradbury et al. 2021).

A related term that is increasingly used in the economic valuation of ecosystem services is natural capital which describes the environmental stocks of natural biotic (living) and abiotic (non-living) resources which provide ecosystem services (Preston and

Raudsepp-Hearne 2017; UCCRI 2022)(Figure 15). “Natural capital accounting is the process of calculating the total stocks and flows of natural resources and services in each ecosystem or region” (Považan et al. 2021). Because ecosystem contributions to national economies have not been accounted for, the United Nations Statistics Department (UNSD) started the System of Environmental -Economic Accounts (UN SEEA EEA) in 2014 which guides and encourages countries to assess their natural capital and changes in ecosystem services (de Jong et al. 2016). It is also considered to be a suitable approach for ES-spatial planning but its use is limited due to science-policy guidelines and lack of practical application examples (Rozas-Vásquez et al. 2019).

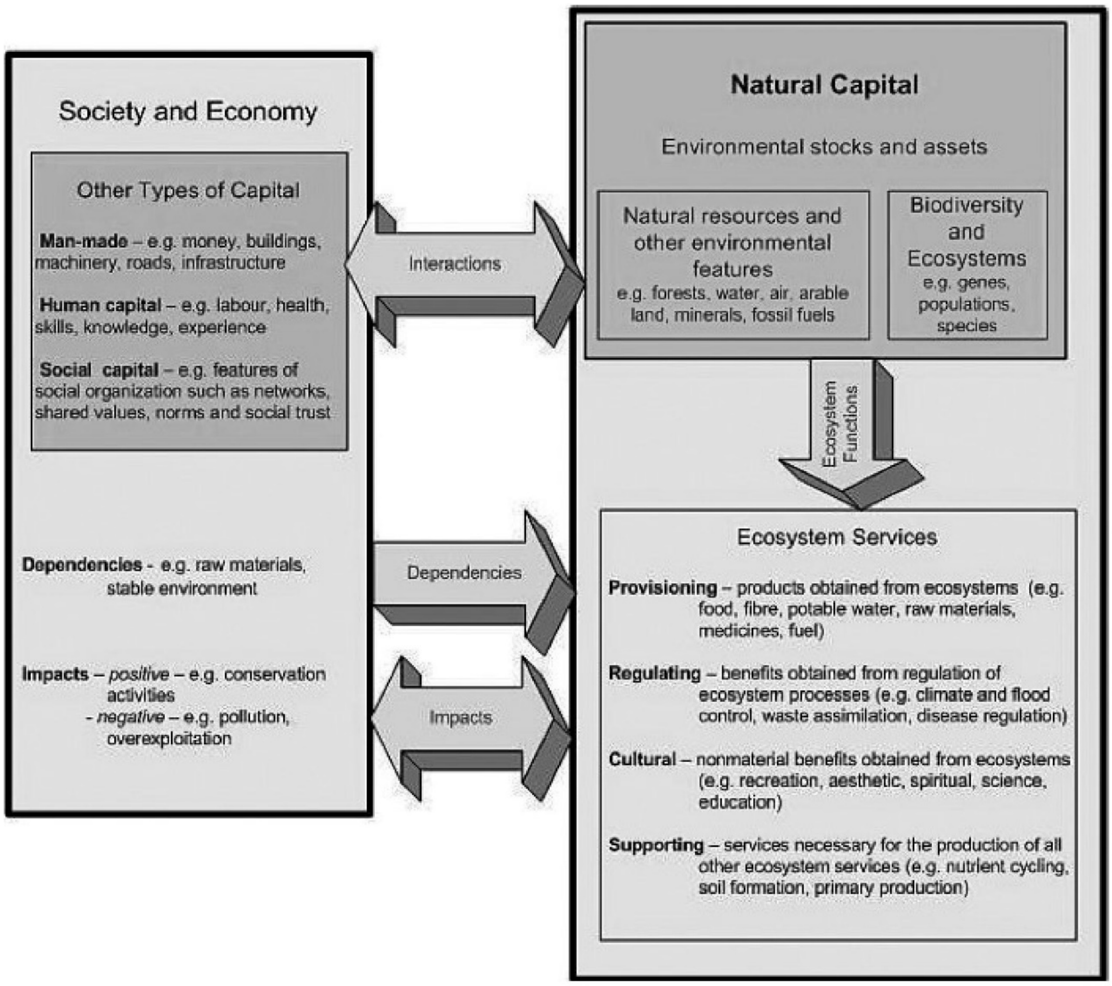


Figure 15. Natural capital in relation to ecosystem services and human capital (Preston and Raudsepp-Hearne 2017)

Therefore, also from this economic conceptual model it becomes clear that growth at the cost of natural capital is not sustainable and the impairment of the environment leads to significant losses and costs for society, as also supported by the "Naturkapital Deutschland" assessment (Hansjürgens et al. 2018). Since many low income countries and the low income global population tend to directly rely on natural capital, protecting and regenerating these assets thus also supports the alleviation of poverty (Dasgupta 2021). Indonesia is among the top ten countries with highest GDP dependency on biodiversity and ES as identified by Retsa et al. (2020) who have also assessed the fragile and intact states of biodiversity and ES for 195 countries besides their GDP dependencies.

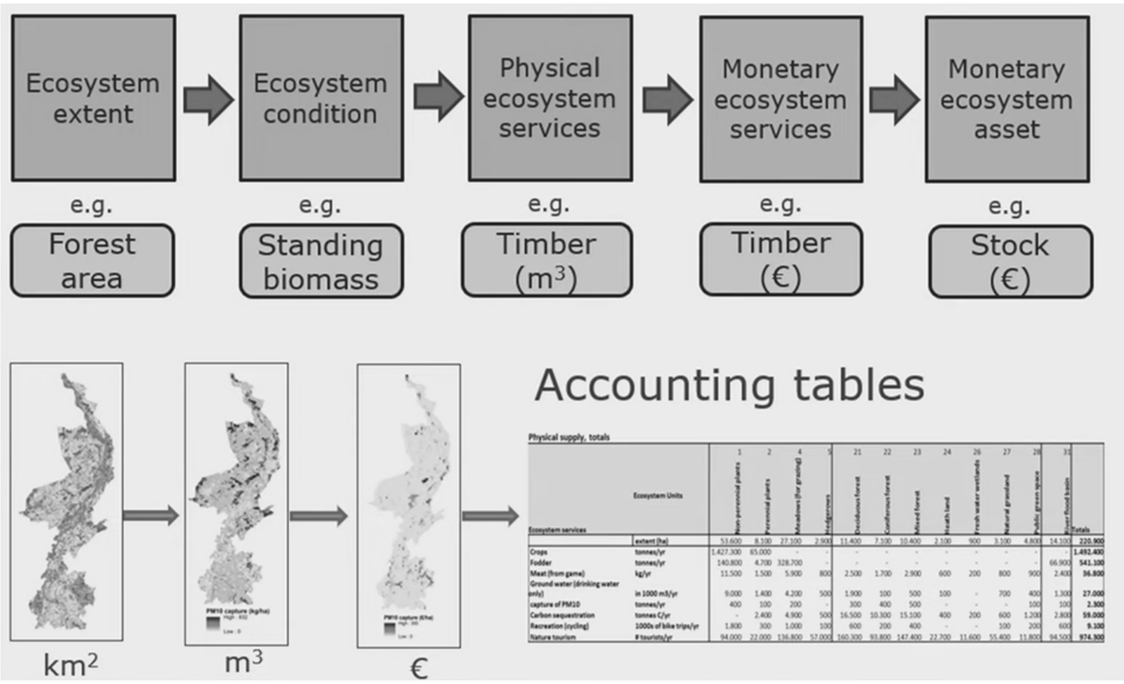


Figure 16. UN SEEA Ecosystem Accounts from Hein (2019) displaying a pilot project for Limburg province, the Netherlands, by Remme and Hein (2016) and de Jong et al. (2016)

For the year of 2000 the value of global ES was estimated to be four and half times larger than the Gross World Product which, at that time, meant about 347 trillion $/year compared to a global GDP of 75 trillion $/year (Costanza et al. 2014). Following these valuations, it can thus also be identified that global land use change is responsible for losses of 4-20 trillion $/year between 1997 and 2011 (Costanza et al. 2014). According to the 2nd Global Land Outlook (UNCCD 2022), 40% of land degraded directly affects half of the global population while it is also known that more than half of the global GDP (44 trillion $) is moderately or highly dependent on ES (WEF 2020) (Figure 17).

However, once again and the same authors of economic valuations continuously emphasize this, these are virtual costs to indicate and raise awareness about ES's importance, yet their actual value would be infinite due to the fact that they provide humanity's living conditions and life without them would not be possible (Costanza et al. 2014). Thus, it is important to recognize that estimating ecosystem services or nature's true value is likely to never be obtained (Westman 1977) and monetary ES assessment's main role is thus as supporting tool (Považan et al. 2021).

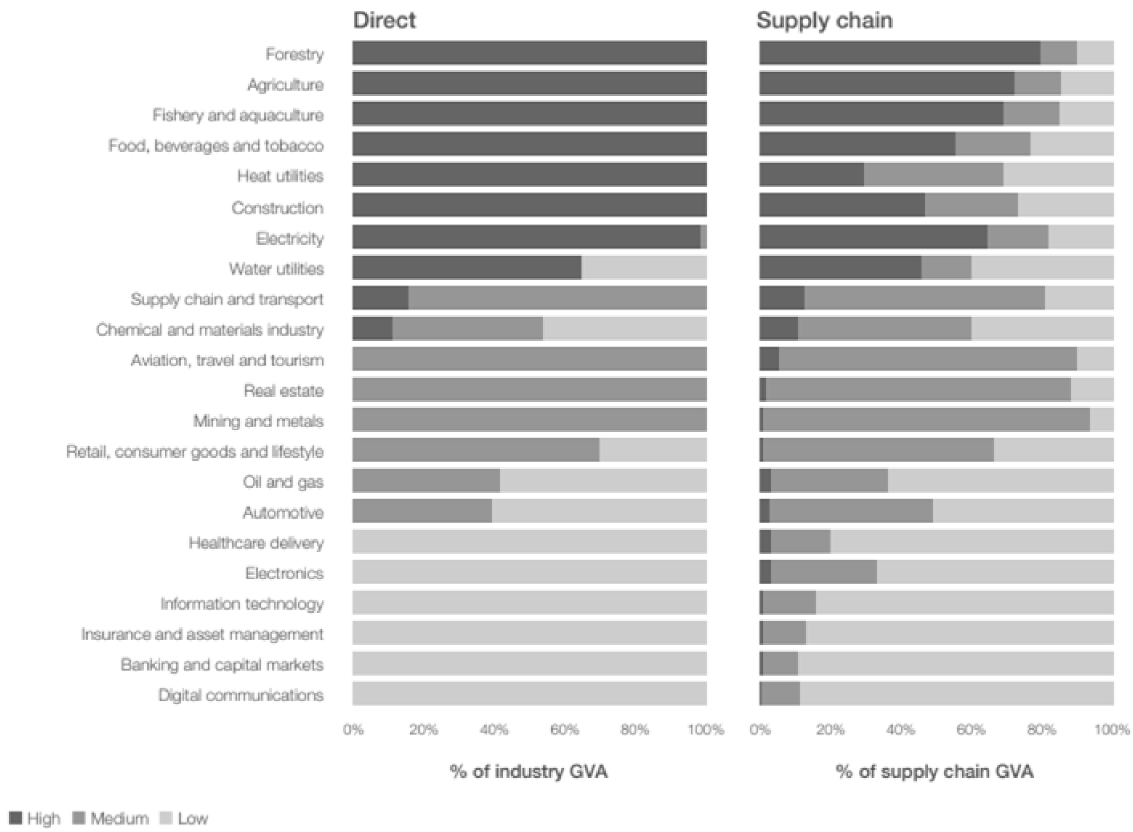


Figure 17. Industry dependency percentage of direct and supply chain Gross Value Added (GVA) (WEF 2020)

Moreover, it becomes clear that "Our economies continue to fail to adequately value ecosystem services" (Sangha et al. 2022) overall and the recent (IPBES 2022) report underlines that "many of nature's values are often ignored in favor of short-term profits and economic growth."

To redefine the term development for the improvement of society and human wellbeing within planetary boundaries and resource limitations, key reforms, such as incorporating principles of sustainable scale, efficient allocation and fair distribution of resources and linking development to the state and use of natural resources, are required as identified by Sangha et al. (2022).

The (IPBES 2022) also states that "Achieving sustainable and just futures requires the recognition and integration of diverse values of nature into political and economic decisions." It proposes a novel typology to understand and account for different value perspectives (Figure 18) and offers an overview of the differences between various valuation method families with each their own strengths and weaknesses (see Appendix Figure 76).

This makes the case for being aware of the variety of stakeholders and their objectives as well as identifying the different beneficiaries across space and time to only understand impacts but also the diversity of values attributed to nature and its ES (CCI and BirdLife International 2011; Fedele et al. 2018). Subsequently this entails that valuation cannot be restricted to solely monetary value but needs to account for the non-monetary values (Maes et al. 2016) which are especially relevant in socio-cultural ES assessments (Považan et al. 2021). "They are often based on collective and interactive procedures – e.g. workshops, meetings, structured interviews or questionnaire methods. So, it is not so much about determining the exact value […], rather than attaining approval, or agreement on a particular assessment or solution" (Považan et al. 2021) (see Figure 19).

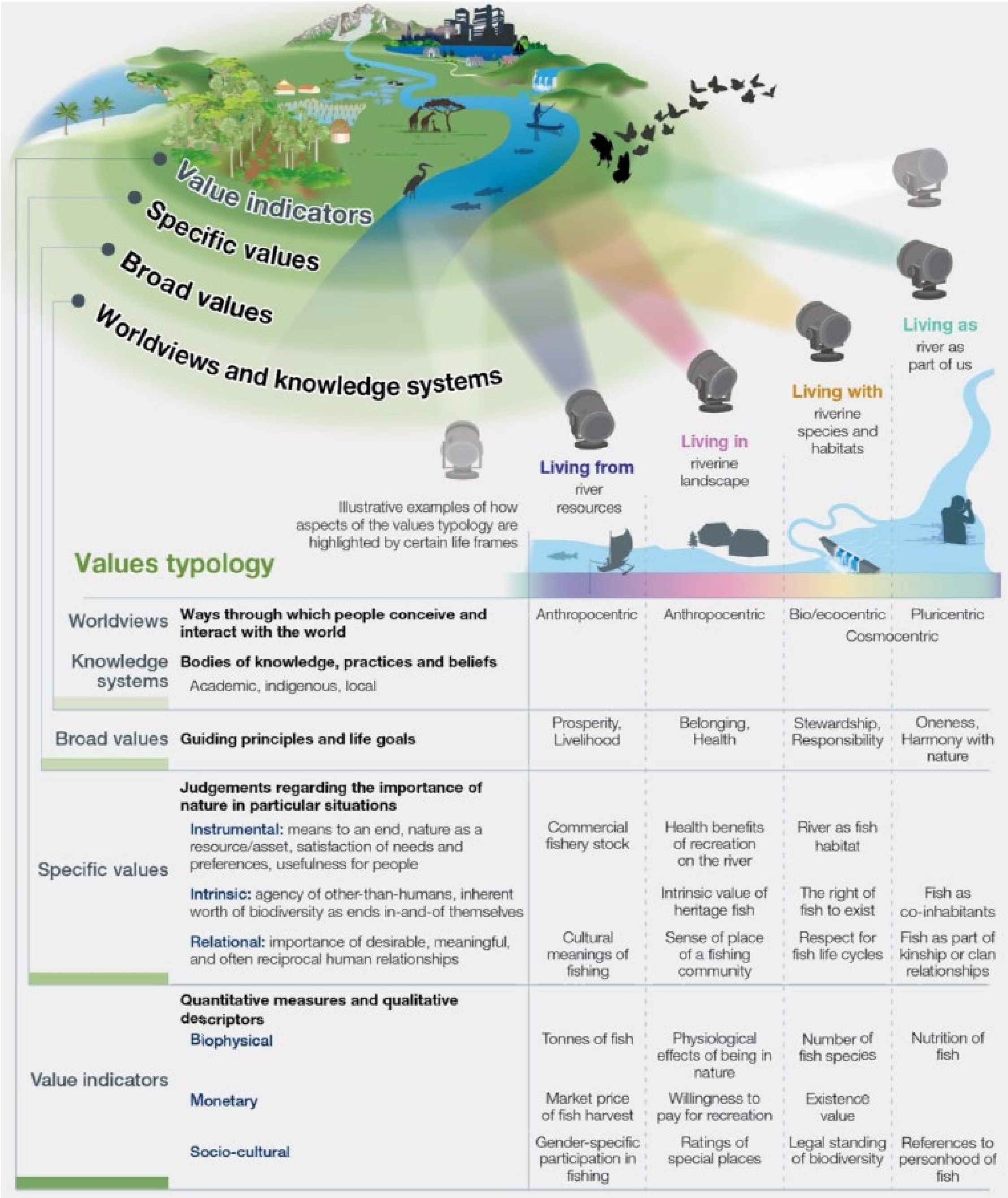


Figure 18. Novel value typology and key concepts to understand the diverse values of nature from IPBES (2022)

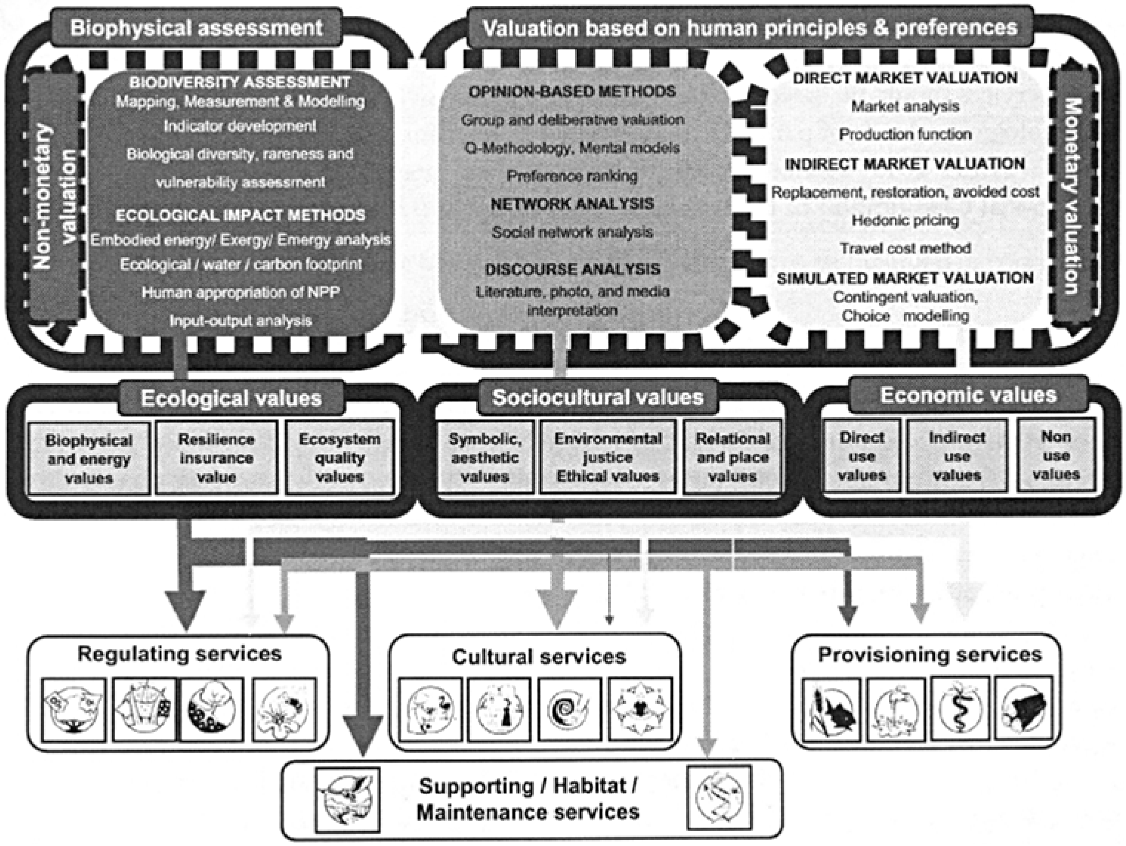


Figure 19. Ecosystem services, value types and valuation methods from Potschin et al. (2016)

2.6. Ecosystem service analysis for the built environment

The pioneering research of Dr. Maibritt Pedersen Zari and her submission for achieving the doctoral degree (Pedersen Zari 2012) first described an '*Ecosystem Services Analysis*' approach (which was also abbreviated ESA) in which the ecosystem services (ES) domain is connected to the built environment (BE) for the improvement towards a more regenerative practice. Pedersen Zari later publishes a visual presentation of the approach in which she formulates it into four steps as presented in Figure 20.

In this master thesis two methodological approaches are presented (Chapter 3 Methodology) which have been informed by Pedersen Zari's publications and thus share similarities. These will be outlined in the following along with the novel contributions made by this master thesis to the research field and the still limited executed assessments to translate the frameworks into theoretical case studies or practice (Figure 21).

Pedersen Zari suggests comparing an existing ecosystem with the pre-developed ecosystem as a first step. This is also an integral part of the in this thesis presented quantitative and qualitative approach. It belongs to the initial definition of the context and aids as reference for a desirable performance (this works reasoning is presented in Chapter 3.2.2).

The second step of Pedersen Zari's framework determines measurable rates of provision for both ecosystem situations for seven ES: Habitat provision, nutrient cycling, purification of air, water and soil, climate regulation, provision of fuel, provision of water and provision of food. In this paper's quantitative approach this is limited to only five of these (excl. purification and provision of fuel). However, due to retrieving this measurement data from a global and continuously extended data platform their information is quickly and easily retrieved and has the potential to provide the data for a much wider range of ES (see Chapter 3.2.1).

Furthermore, the here presented quantitative approach extends these results, which are already usable for setting "site-specific optimal ecological performance goals for development" as suggested in Pedersen Zari's step three, with a monetary valuation dimension (see Chapter 3.2.3). Communicating the values of ES has been one of Pedersen Zari's identified challenges before integrating the ES concept into BE design (Pedersen Zari 2019b).

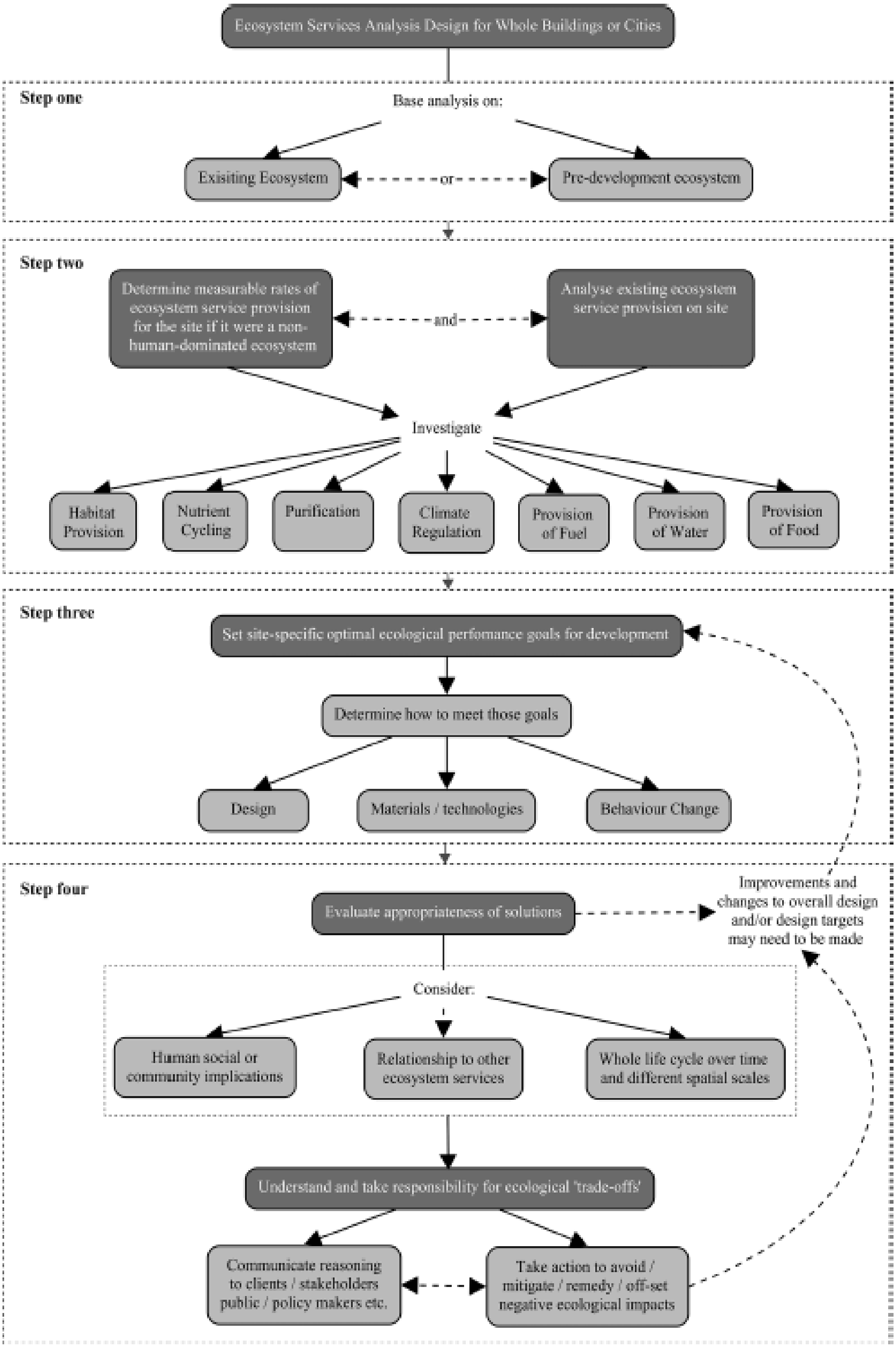


Figure 20. Ecosystem services analysis framework proposed by and taken from Pedersen Zari (2018)

A first case study for the city of Wellington, New Zealand, has already been displayed in Pedersen Zari's doctoral thesis but the conclusions and a potential redefinition of the future city planning agenda based on the comparison and differences of the urban environment to its pre-developed natural state in ES provision have been further a focus of a later (Pedersen Zari 2015) publication. Curitiba and Havana are added as two other case studies executing the '*Ecosystem Services Analysis*' in Chapter 6 *'*Applying ES biomimicry to urban contexts*'* of the first published book 'Regenerative urban design and ecosystem biomimicry' (Pedersen Zari 2018) or in Pedersen Zari's following paper 'Devising urban biodiversity habitat provision goals' (2019a). These city analyses are to the authors knowledge, to this date and merely to this scale, the only applications of an ES assessment with the intent to increase ES provision towards an identified reference to regeneratively transform BE practice and agendas.

The quantitative approach in this thesis, conducted two high level case studies in the relation to the city of Jakarta, Indonesia and Garching, Germany (see Chapter 5.2 for results).

In 'Incorporating an understanding of ecosystem services into built environment design and materials selection' (Pedersen Zari 2017) and 'Ecosystem services impacts as part of building materials selection' (Pedersen Zari 2019b), Pedersen Zari has offered insights into common material uses (concrete, glass, timber, stone, steel, straw) and their potential production and extraction impacts on her seven selected ES. This is executed research which adds transparency and decision information to Pedersen Zari's step three related determination of how ecological performance goals for a development might be met or not with building materials.

How a design is possibly able to do so and how this appropriateness could be evaluated related to Pedersen Zari's step four, is the target of the here presented qualitative approach which assesses ES changes on specifically a design-level. Even though qualitative, it considers the whole lifecycle as suggested by Pedersen Zari and enables an actionable workstream, which as in the quantitative approach, has the potential to be extended with a valuation dimension to further tangibly communicate societal wellbeing impacts (see Outlook Chapter 6.4). Furthermore, in this particular showcase of the qualitative approach, three supporting ES have been chosen and their relation to the many other ES described (see Chapter 4.3.4).

Through its setup of being based on the definition of ES profiles which detail the ES cascade (see Chapter 4.3.5), the qualitative approach integrates an understanding of ecological structures, processes and functions into design which was previously identified as crucial knowledge and lack to current ecosystem-level biomimicry in urban design (Blanco et al. 2021).

Lastly, Pedersen Zari proposes several strategies to translate ecosystem processes into design (Pedersen Zari 2012; Pedersen Zari 2018) and has mapped those for easier uptake (Pedersen Zari and Hecht 2019). The qualitative approach of this thesis results in lifecycle specific ES provision requirements as well as a generalized and scale unspecific checklist for ES provision which complements this support for BE practice (see Chapter 5.3.2). The later presented work also reviews two supposedly ES beneficial nature-based solutions (NbS) based on these requirements and thus further contributes to the scientific discourse and alleviation to key barriers (Pedersen Zari and Hecht 2019) as practical examples (see Chapter 5.3.3).

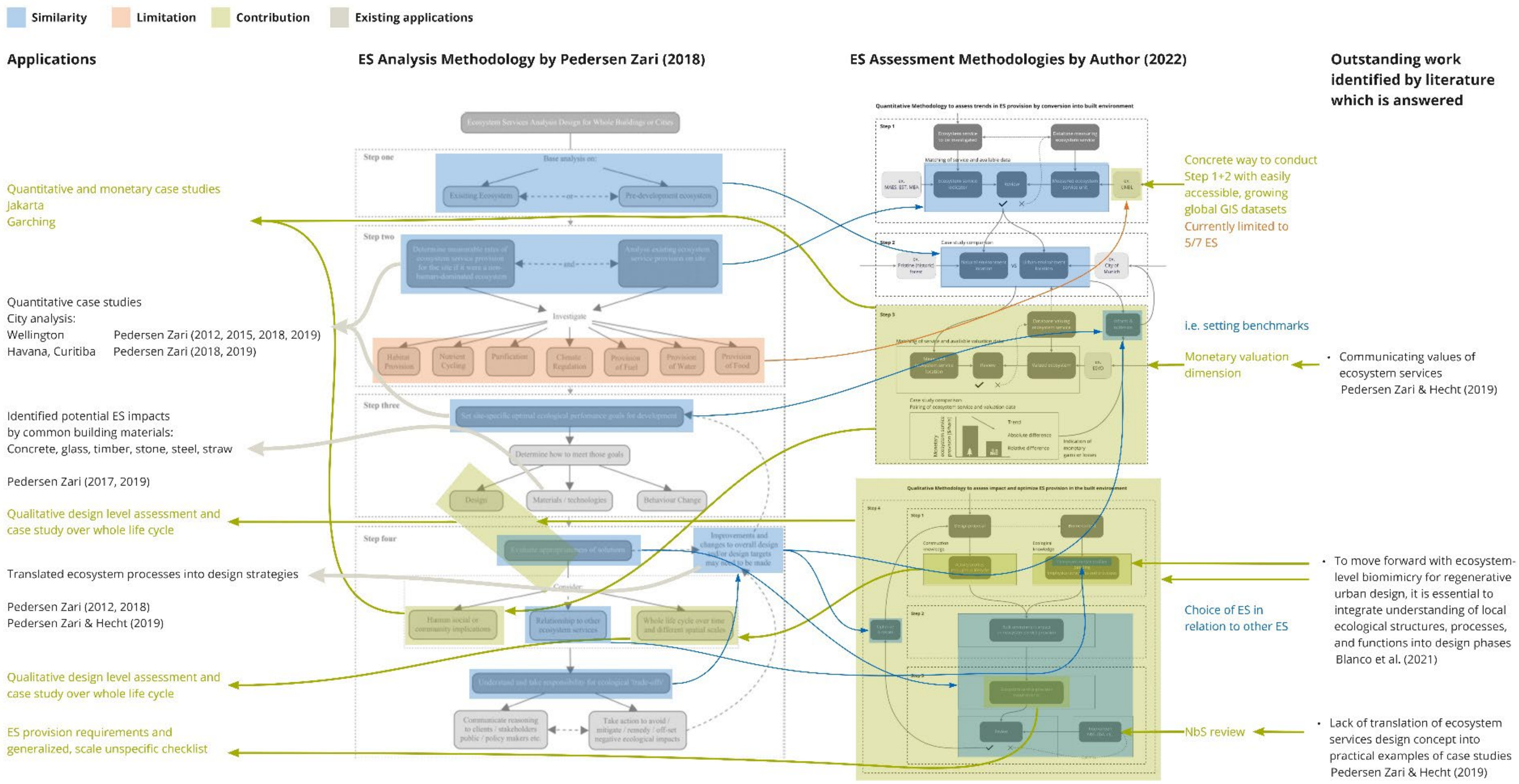


Figure 21. Similarities, limitations and contributions in comparison to 'Ecosystem Services Analysis' by Pedersen Zari

3. Methodology

3.1. Summary

This thesis proposes two approaches to assess and inform the design and planning of the built environment (BE) on different scales with different levels of detail and required background knowledge.

The first approach quantifies the provision of six ecosystem services (ES) based on freely accessible data without requiring any background knowledge in its use once adequately matched. It offers a high-level insight into the differences of urban and natural environments. This explores research question one. Moreover, this can be coupled with current economic valuation of the investigated ES, resulting in $/ha/year divergences. The purpose of the approach is to display trends of BE practice and illustrate human wellbeing tradeoffs in regard to differing ES provision by construction development.

The second approach qualitatively assesses the impact of a development proposal on the natural environment and its provision of three supporting ES. It offers a design-level insight throughout the entire building lifecycle. However, extensive knowledge on BE activities related to the proposal and ecological knowledge for specifying the ES cascade in the investigated ecosystem are required. This entails the definition of construction activity and ES profiles which are then overlayed on each other. The purpose of the approach is to identify the specific impacts of a BE action resulting in ES provision changes which affect human wellbeing.

Derived from the qualitative assessment approach, design shortcomings and requirements for the provision of the three supporting ES, habitat provision, nutrient- and water cycling, are identified. This guidance responds to research question three with the purpose of designating tangible ES provision options for the BE to contribute to human wellbeing.

3.2. Approach One: High-level quantitative assessment

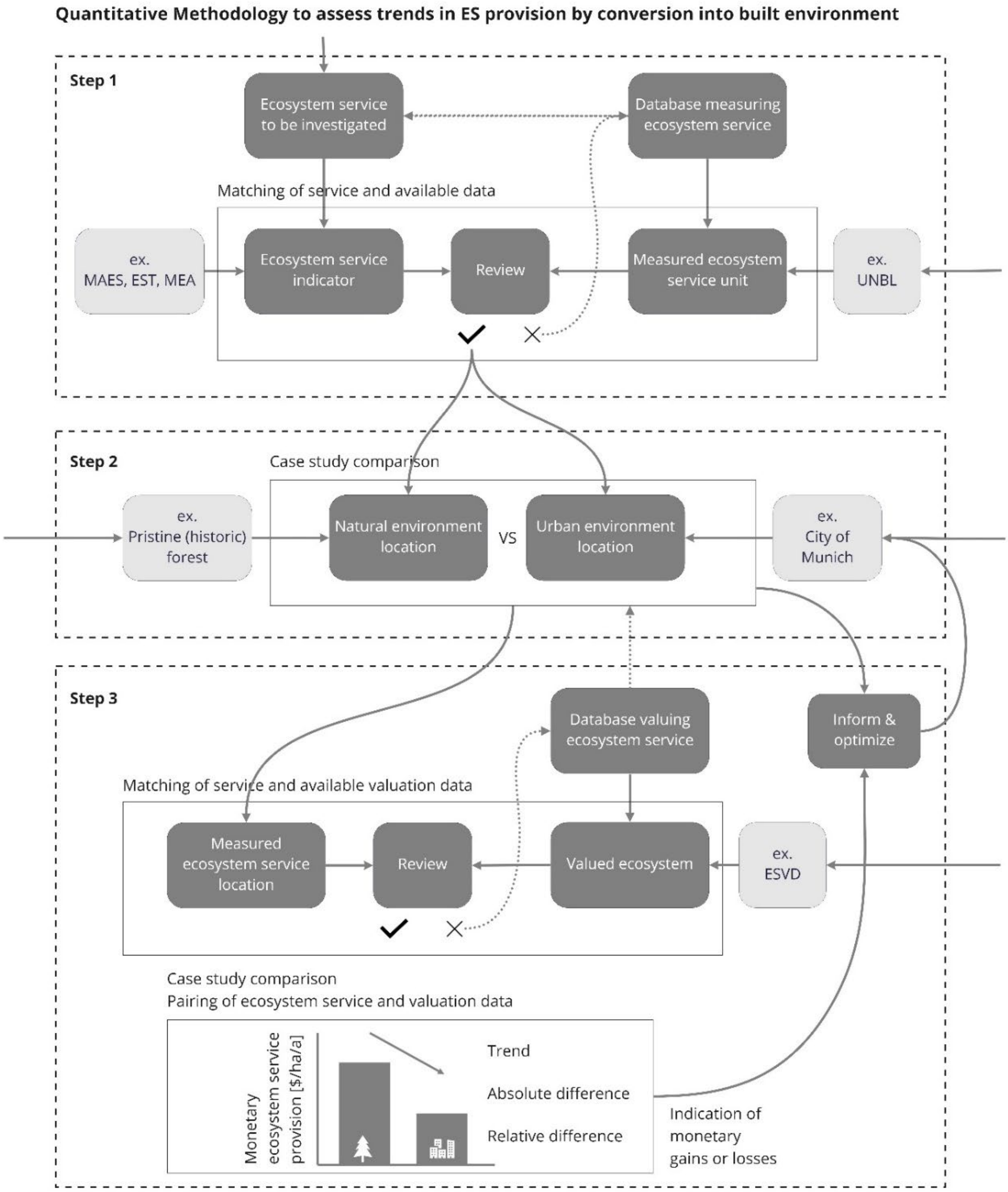


Figure 22. Process diagram for a high-level quantitative ecosystem service assessment

The first approach is separated into three steps: matching the available data with the ecosystem services which are to be investigated, identifying trends by a selected case study comparison and lastly coupling these with monetary data available (Figure 22).

3.2.1. Step 1

The focus has been set on a quantification approach which is freely accessible and easy to use for non-specialists once ecosystem services (ES) are adequately matched with available data. This is to enable quick and uncomplicated uptake by and orientation for practice in expanding the information basis prior to decision making.

A selection of eleven ES is made from the complete list of ES (Chapter 2.2, Table 1) based on their identified relevance to the built environment (BE) (Pedersen Zari 2014) and their supporting character to other ES (MEA 2005). Based on the previously identified indicators (see Chapter 2.4), specific datasets with corresponding data are then attributable to the selected services. This matching is possible for six of these eleven ES (Table 3) which form the basis for further analysis.

Data is taken from the free and open source (UN Biodiversity Lab 2022) (UNBL) platform which centrally collects over 400 global spatial data sets on several different environmental and human development topics from different authors and institutions. The Geographic Information System (GIS) data is readily converted and thus visually accessible without requiring any GIS knowledge.

Table 3. Selected ecosystem services for quantitative assessment

Selected ecosystem service for quantitative assessment	Matching dataset from UNBL	Ecosystem service category	Source
1.Habitat provision	Yes	Supporting	(MEA 2005; Pedersen Zari 2014)
2. Nutrient cycling	Yes	Supporting	(MEA 2005; Pedersen Zari 2014)
~~3. Air purification~~	No	Regulating	(Pedersen Zari 2014)
4. Climate regulation	Yes	Regulating	(Pedersen Zari 2014)
~~5. Provision of fuel~~	No	Provisioning	(Pedersen Zari 2014)
6. Fresh water	Yes	Provisioning	(Pedersen Zari 2014)

7. Food	Yes	Provisioning	(Pedersen Zari 2014)
~~8. Water cycling~~	No	Regulating	(MEA 2005)
~~9. Soil formation~~	No	Supporting	(MEA 2005)
~~10. Photosynthesis~~	No	Supporting	(MEA 2005)
11. Primary production	Yes	Supporting	(MEA 2005)

This enables the attribution of available data on quantifiable ES to a geographical point of interest. An advantage is that the chosen platform covers global datasets, increasing useability and applicability for a global audience.

3.2.2. Step 2

In this research, two sites, a natural and urban location, are chosen to compare and identify trends in ES provision by conversion into urban built environments. The natural, unmodified site serves as reference point for the pre-development potential in ES service provision. In BE practice, this could also be called the baseline, as commonly established for energy performance analysis for example. However, it is important to acknowledge that there is no fixed ecological state due to the dynamic changes and successions continuously occurring within an ecosystem. Therefore, the data is only a specific point in time and should thus, from an ecological perspective, be appropriately seen as a reference.

Box 3. Why is a natural ecosystem chosen as reference?

The use of an undeveloped and ideally anthropogenic-influence-free site as reference point is suggested in relation to the exceedance of planetary boundaries (see Introduction) which is caused by human activity. Since cities with its majority of global inhabitants are responsible for these environmental impacts on the earth’s life support system then current BE practice is to be seen as a driver and representative of these exceedances. If a safe operating space for human development and existence is to be attained, nature, through its 3.8 billion years of evolution, is likely to correspond to the best available and optimal allocation of resources and thus provision of ES as a reference (Figure 23).

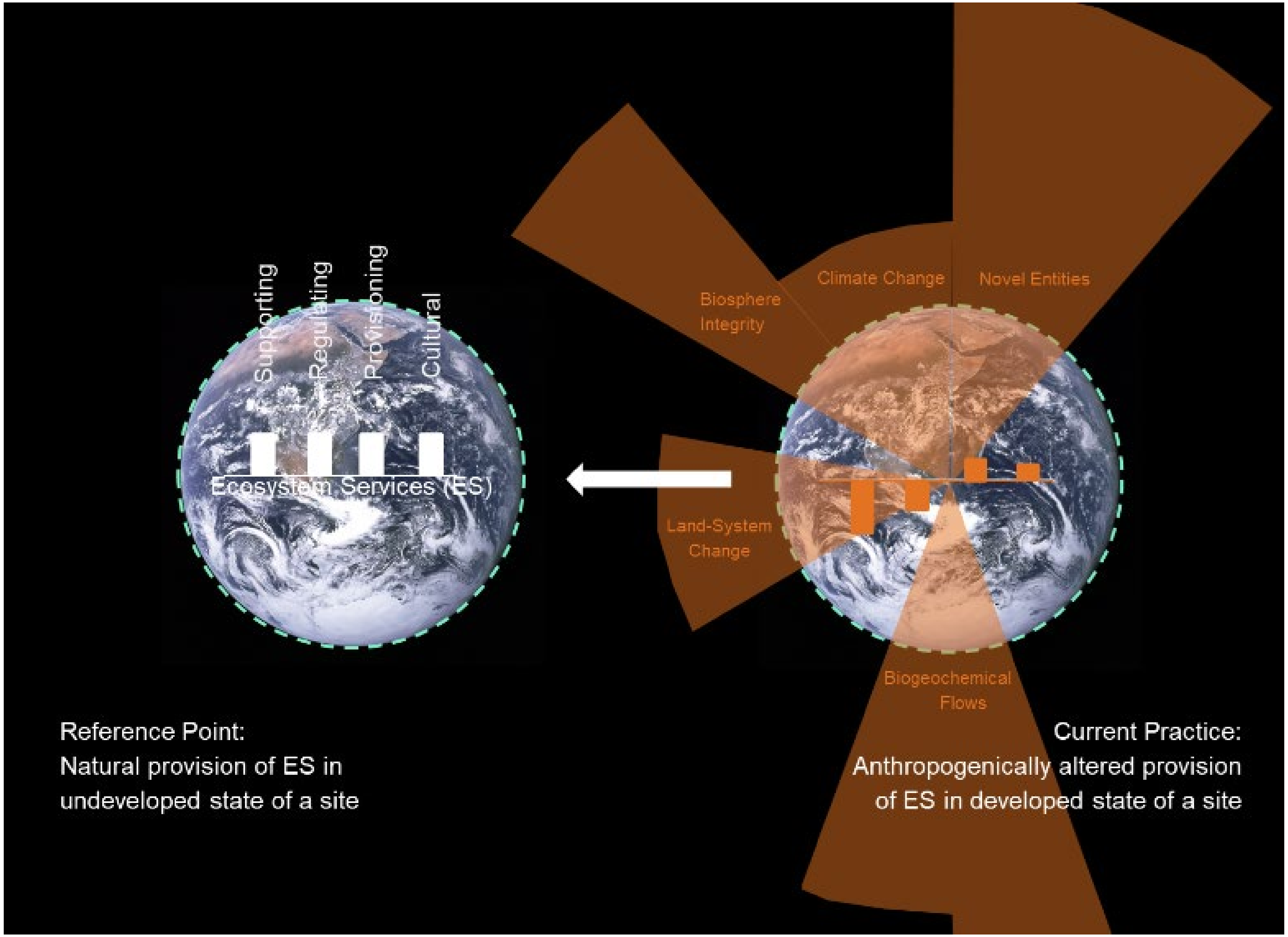


Figure 23. Nature, undeveloped and ideally human influence free, as reference point for ES provision to stay within planetary boundaries with built environment development. Graphics based on (NASA 1972; Stockholm Resilience Centre 2022)

The corresponding data on the provision of the six ES on both sites is then documented and compared. Column charts with a trendline between the natural and urban location indicate the losses or gains by conversion for each service. The relative change and difference between the two sites is deducted as well for further processing or conclusions for decision making.

3.2.3. Step 3 (Optional)

The benefits of ecosystems to people are attributable to ES provision due to the bridging definition of the ES concept (see Chapter 2.3 Ecosystem service cascade). Likewise, the inhibited provision can be shown as loss to human wellbeing. The valuation of ES benefits or lack thereof is a continuously progressing discipline on its own as described in Chapter 2.4 Ecosystem service valuation. Monetary valuation based on a service's importance for the economic system or demand by markets is one tangible way to indicate ES societal relevance.

Therefore, the relative losses caused by conversion from natural to urban environments are multiplied with these currently known standardised monetary values which were identified per area of natural environment for a specific ES. This research utilizes the Ecosystem Services Valuation Database (ESVD) (Brander et al. 2021) developed by (Groot et al. 2012), where different monetary valuations (currently > 6,700 records) are continuously provided across biomes globally based on scientific studies (currently >950). These are given in international $ of the year 2020 (abbreviated with 'int$') per hectare (abbreviated with 'ha') and per year (abbreviated with 'a' for annum).

This pairing of information enables an indication of the magnitude and also financial strain posed on society by establishing the built environment according to current practice.

Box 4. Caution with the use of ESVD data

Used and resulting monetary values should not be seen as absolutes because they are based on relatively few studies with a variety of specific ecological and socio-economic contexts which do not necessarily represent the two investigated sites in this research. This is also pointed out during the use of the ESVD. It is i.e. difficult to match ecosystem conditions even per biome because about 58% of the data records do not provide such information for comparison, as has been recently identified by (Hernández-Blanco et al. 2022).

Due to the limited monetary valuation data, the scope of assessable ES might narrow further with this additional analysis step as it is dependent on source availability related to the investigated context.

3.3. Approach Two: Design-level qualitative assessment

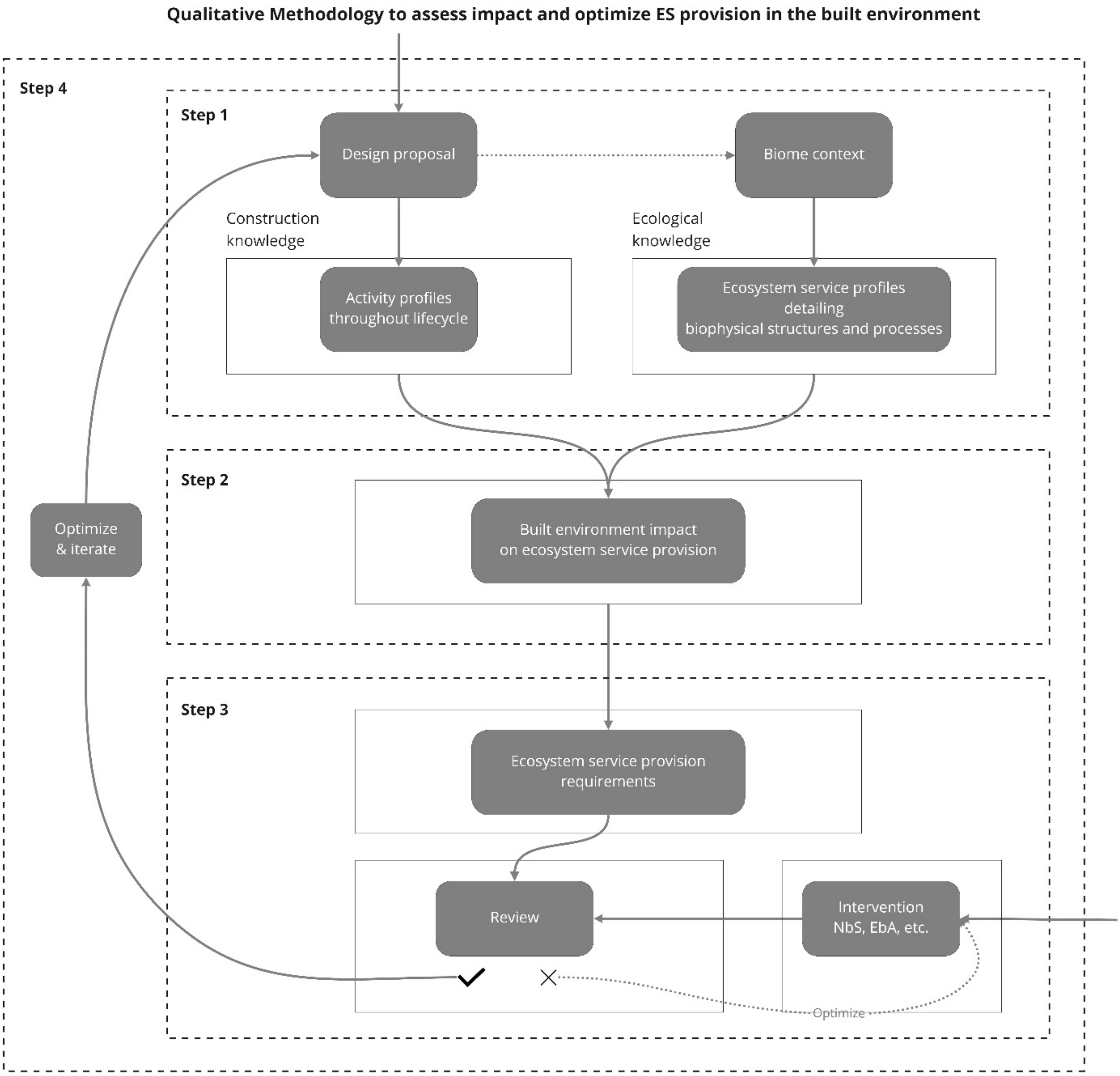


Figure 24. Process diagram for qualitative ecosystem service assessment on design level

The second approach is seperated into four steps: assessing a design in its ecosystem context, identify construction impacts throughout the lifecycle, capitalize on shortcomings and define ecosystem service (ES) provision requirements which can then be used for an optimization of the design by iterating the assessment approach (Figure 24).

3.3.1. Step 1

This second approach is targeting a more in depth analysis of specific development proposals to understand the causes for expected or already inflicted changes in ES provision by the related built environment (BE) actions. To also operationalize responsibilities and align this methodology with practice, the design proposal is dissected and examined according to its different lifecycle stages. Additionally this partition enables a comparability and reviewability with its drawbacks and benefits to increasingly operationalized lifecycle assessments (LCA).

Therefore firstly, based on the European standard DIN EN 15978 and the selected design proposal, construction activity profiles can be ascribed to each lifecycle stage from A1 (Raw material supply) to D (Benefits and loads beyond the system boundary), such as for example transport by road or foot (A2) or site preparations and setting of the structure (A5). These will unavoidably have consequences for the Biophysical Structure (BS) of the investigated ecosystem setting. For instance damage to the vegetation cover and integrity of top soil. To summarize and visually simplify this information, it is suggested to create a schematic graphic per lifecycle stage of construction within the designs biome context.

Secondly, ecological knowledge is required to define the cascade model (Chapter 2.3) for each ES to be assessed. This means identifying the main ecosystem processes (EP) that are preconditions for the provision of that ES and locating their occurrence. These EP which are different for every ES, emerge from the BS of the ecosystem which also has to be thoroughly understood.

Ideally, this is detailed further and distinguished primarily between the five animal kingdoms (Animalia ~ animals, plantae ~ plants, protista ~ single celled organisms, fungi ~ mushrooms, monera ~bacteria) as first defined by Robert Harding Whittaker in 1969

(Hagen 2012). There are more divisions and specifying might occasionally be possible down to the animal phyla, group, order, family or genus.

They are the ecosystem agents (EA) forming the BS and which are ultimately responsible for a process by their interactions (see Chapter 4.3.3). Even though desirable, this is secondary and priority lies on understanding and simplifying the general workings of an ecosystem for an appropriate and sufficient knowledge transfer to inform BE practice. However, the possible degree is hereby based and also limited on the biome specific ecological knowledge available.

Therefore, an ES profile detailing the approximate location and required processes for the provision of the ES concludes this first step.

3.3.2. Step 2

Thereafter, the defined design proposal impacts per lifecycle stage on the BS can be directly tied to influences on specific ecosystem processes of an ES by pairing the construction activity and ES profile.

Due to this methodology it is thus possible to identify shortcomings in ES provision and their causes across all lifecycle stages (A1-D) of the design proposal. Specific attention lies on the ability or inability for the specifically required ecosystem processes for an ES to occur. The construction activity directly or indirectly influences the BS and its EP. The social & economic system dimensions of the ES cascade are not assessed but could theoretically be tied to the identified qualitative changes in ES provision.

3.3.3. Step 3

Based on this understanding of shortcomings of the design proposal on ES provision, requirements for an improved ability to provide the conditions for ES supply can be summarized into a review list for construction interventions throughout a buildings entire lifecycle. This enables clear guidance on what has to be achieved by a change in construction approach, its management or design to reduce impacts and improve conditions for an ES to occur and be provided to the human benefit. Furthermore, these requirements enable the review of specific interventions such as nature-based-solutions (NbS) or ecosystem based adaptations (EbA) and their ability to provide desirable conditions.

3.3.4. Step 4

The last step entails implementing the newly gained information and optimization solutions into the previously analyzed design. By iterating these process steps, a design should gradually improve in its ES provision performance and impact on pre-existing ES.

4. Conduction

4.1. Summary

For the first methodologically presented quantitative approach, two cases are investigated: the Campus Garching on historically converted temperate forest in Germany and the planned relocation of the Indonesian capital Jakarta to a globally important biodiversity hotspot, the island of Borneo (Chapter 4.2).

The second qualitative approach is illustrated with an application to a design proposal for a first development in the Indonesian tropical rainforest for which the detailed process of defining construction activity and ecosystem service (ES) profiles is described (Chapter 4.3). This is followed by the overlaying of profiles to identify built environment (BE) impacts and shortcomings on ES provision.

Resulting requirements are then used to review two common nature based solutions (NbS), green roofs and facades (Chapter 4.3.8), which are shortly described.

4.2. High-level quantitative assessment

This approach is applied to two different contexts and minor research questions.

4.2.1. Indonesian case study

a) How does the potential of ES provision change on the island of Borneo, if its tropical rainforest is replaced by a new capital city which is built similar to the current capital Jakarta.

Box 5. Why is Indonesia relevant?

The Indonesian decision to relocate its capital (BBC 2022) is highly relevant for the BE discourse because it reflects the conflict between natural capital in form of intact ecosystems and its degradation for human development. In this case land is not mainly converted due to population growth but because of evading the sinking city with its more than 10 million inhabitants (The Associated Press 2022). This represents the struggles of many communities and island nations which are facing rising sea levels due to human induced climate change. Nevertheless, the question remains whether with a new city development more societal value can be generated than is lost by conversion. Indonesia has been identified as an important nation with an outsized role (65.8% of its national area) to conserve its globally significant biodiversity hotspots and to contribute to a global safety net (Dinerstein et al. 2020)(see Chapter 1.1). Especially on Borneo, scientists have suggested conservation areas fundamental to its maintenance (Struebig et al. 2015) which collide with the seemingly planned new capital location in East Kalimantan (Souisa and Salim 2022) (Figure 25). Besides the significant contributions to carbon sequestration and water-related ES by customary forests, continued deforestation by land conversion also threatens the indigenous communities who depend on the forest's goods and benefits (Leo et al. 2022).

Figure 25. Globally significant biodiversity hotspots coinciding with planned location of new Indonesion capital adapted from Global Safety Net (2022)

The chosen natural reference site (East Kalimantan, Borneo) and urban location (Jakarta, Java) are indicated on Figure 26.

Figure 26. Case study locations Indonesia. Adapted from Vectormaps (2022)

For each of these sites data is retrieved for the six matching ES from the UNBL platform (Figure 27) (the remaining used data maps are provided in the Appendix Figure 78).

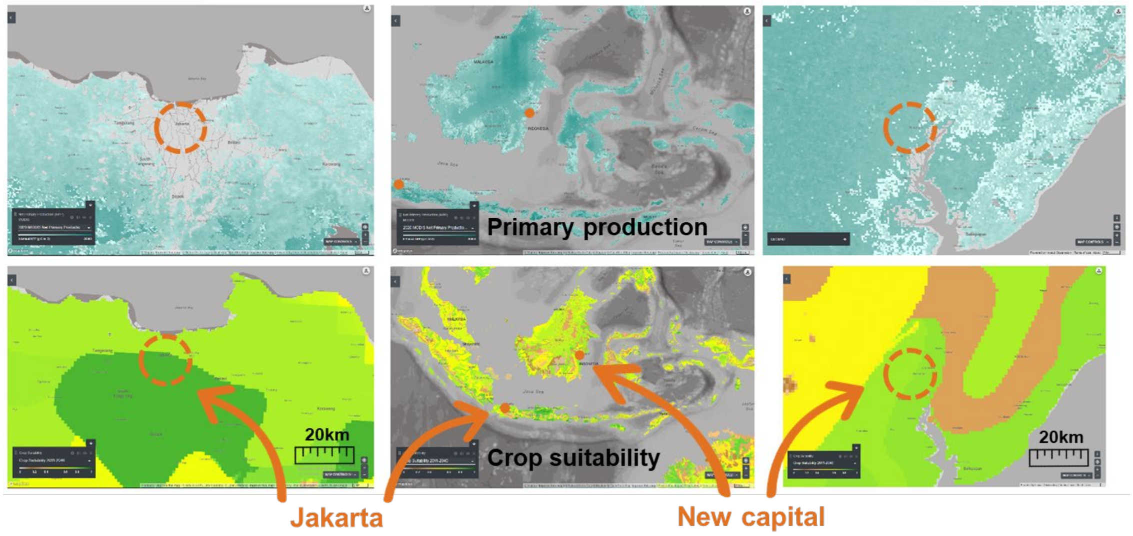


Figure 27. Exemplary data maps on two ecosystem services for the Indonesian case study locations. Compiled and adapted from UN Biodiversity Lab 2022)

These are then compared alongside each other and first trends can be identified for each service.

These differences in provision are coupled with the available data related to the ESVD. Hereby, three different suiting scales as data sources are distinguished. Monetary ES valuation data on the tropical rainforest biome from a global scale as described by (Groot et al. 2021), as well as based on the online ESVD (Brander et al. 2021) and more specifically for the Indonesian tropical rainforest biome as identified in Appendix four of

Groot et al. (2021). The latter two provide mean standardised values for only five out of the six ES, while the first also provides a value for the lacking nutrient cycling ES. This makes it possible that all previously observed trends can be further defined through monetary indications.

Only the monetary changes in differing water provisioning services cannot be assessed despite available valuation data because the provided measured data is in a qualitative scale format and therefore a further processing based on quantification is not possible.

4.2.2. German case study

a) How has the ES provision changed by developing the Campus Garching on previously historically existing Western European temperate forest?

Box 6. European forest and selected site

Forests used to cover 80% of the European land surface (EEA 2018) which halved by the late 17th century due to exploitation (EEA 2006) and continued domestication. The benefits and ES attributed to forests are manifold, such as the provision of timber and freshwater, air purification and soil protection but also climate change mitigation by carbon sequestration (EEA 2018, 2015). Its multiple tangible and intangible contributions to human wellbeing across the four ES categories within Europe are discussed and summarized in (EEA 2016a) (see Appendix Figure 50). A study on the economic value of ecosystem services for the EU28 in 2012 identified that almost half of the value that is generated originated from woodland and forest ecosystems (Vysna et al. 2021). Mostly this contributed to the directly perceived human benefit in form of nature based recreation as second largest monetary valued ES.

Despite human modification of more than 96% of European forest's, they are nevertheless considered as one of the best ecosystems to conserve biodiversity (EEA 2016a). With a remainder of more than 40% forest cover at present, Europe is still one of the most forest-rich regions worldwide (EEA 2015). However, as many other ecosystems, it is facing increasing pressures due to climate change but also increasing demand for its resources (EEA 2018, 2016a; The Biodiversity information system for Europe 2022a).

Historically the city of Munich has continuously expanded beyond its old town borders into the surrounding agriculturally used fields (Uhlmann 2008) which through former appropriation to sustain its inhabitants has been converted from originally dominant forest.

Only since the 20th century, the city of Garching, which is about fifteen kilometres northeast of Munich, has undergone such development from a farming village (Stadt Garching 2022). The campus Garching of the Technical University of Munich is an example for this transformation. Applying this assessment to the Bavarian context thus enables the fundamental review of trade-offs made during historic settlement development and city expansion in light of ES provision. This retrospective based on currently available knowledge can put current practice and interventions into question by establishing a new theoretical baseline.

The natural reference site to represent data on the pre-existing forest is taken from a Bavarian forest in the south of Munich which has been identified and chosen based on its high biodiversity intactness and low human disturbance data. The two sites are shown on Figure 28. As in the previous context, data on the six matching ES is retrieved from the UNBL platform for both of these sites and are then compared to each other (Figure 29) (the remaining used data maps are provided in the Appendix Figure 79). For the economic valuation coupling, data on only the global and European forest biome are available. Both retrieved from the online ESVD (Brander et al. 2021). As previously discussed, the water provisioning ES cannot be assessed in monetary terms due to mismatches in data format. Furthermore, the coupling with the European data is restricted to an assessment of only primary production, climate regulation and food provisioning services. This makes the global valuation data better suitable to assess monetary trends for at least five out of the six selected ES.

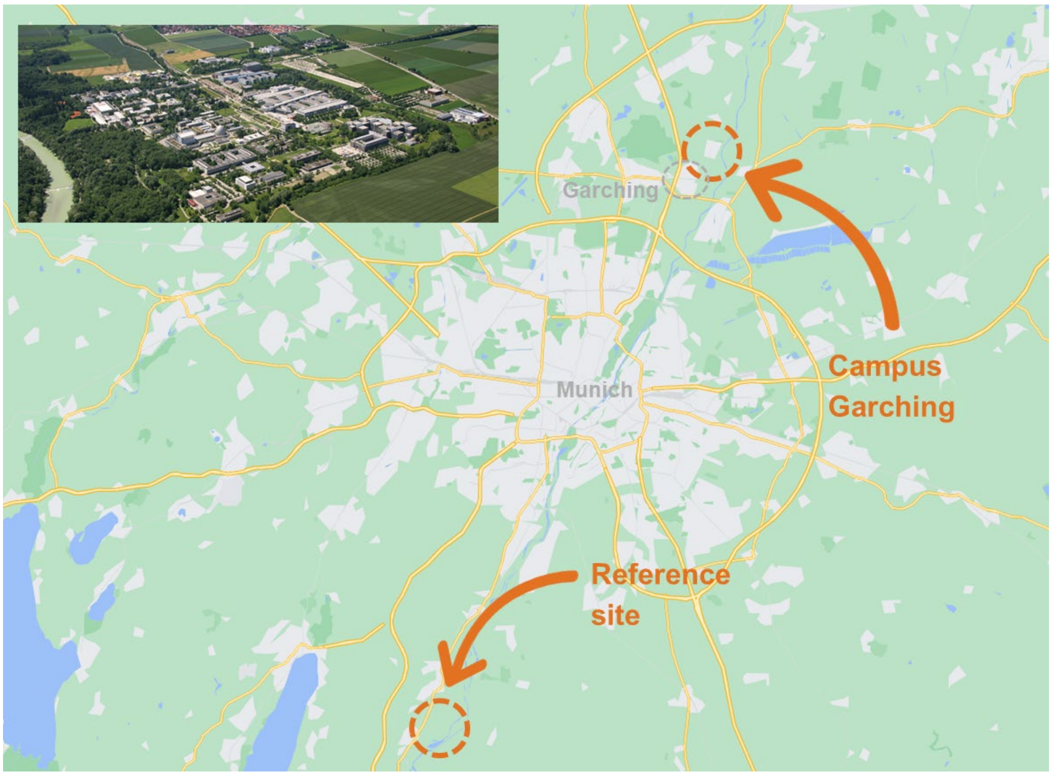


Figure 28. Case study locations around Munich. Adapted from Google Maps (2022), image from TUM (2022)

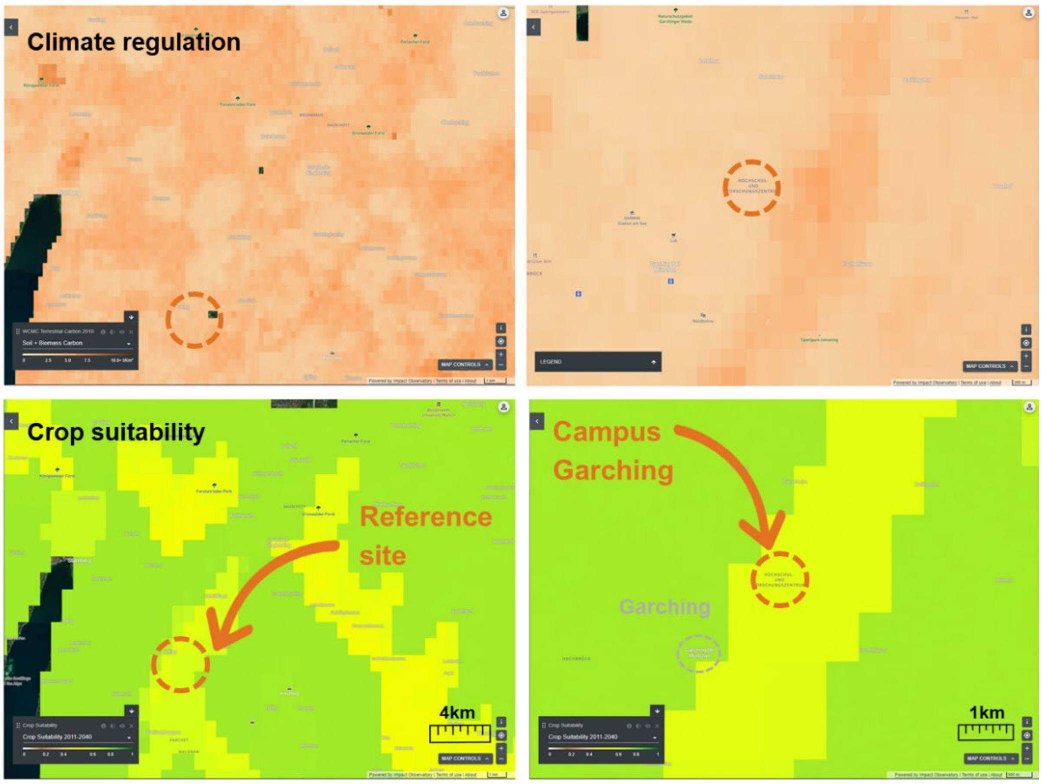


Figure 29. Exemplary data maps on two ecosystem services for the Munich case study locations. Compiled and adapted from UN Biodiversity Lab 2022)

4.3. Design-level qualitative assessment

4.3.1. Construction activity profile

This approach is applied to a theoretical first development proposal on an Indonesian archipelago by (Bacheva, Pepin 2022). Focus is set on the buildings which are situated in the tropical rainforest on the architectural plans because it is the biome which is investigated in this research. Since all the buildings are designed based on the same method and set of elements, it is rather an assessment of the approach and subsequent impacts of construction processes tied to the realization of the architects ideas.

The investigated design is thus representatively analysed to anticipate first development impacts and to gain insight for the Jakarta/Borneo case study from the previous assessment approach, if it were to be developed similarly at first. As to be seen on Figure 30 and Figure 31, the proposal is not a highly urbanized design in contrast to the city of Jakarta's dense climax state. It rather represents a more gradual development of first human settlements in tropical climate, as it is closer to historic informal settlement establishments mostly based on local, renewable, biobased building materials. Nevertheless, a due diligence of the design's architectural and statical feasibility and performance by the author has been out of the scope of this research.

It's main characteristics are (Bacheva, Pepin 2022):

- All timber construction structure
- Local, differing quality and type of wood
- Small dimensions and young trees preferred as source
- Design for disassembly, simple construction methods
- Wall elements from timber and rattan (lianas) in timber frame
- Merely roof cover and rainwater collection gutters (corrugated steel) and foundation (coral) not from wood
- Hand tool based, no heavy machinery, built on site
- Mainly natural ventilated buildings, one seaweed insulated HVAC room

- Extensive green roof and climbing plant façade curtain elements
- Photovoltaic panels and battery system for electricity supply, off grid
- Elevated paths and buildings, one floor
- Piping and cabling under elevated floors
- Buried water and septic tank

Figure 30. Impression of the investigated design proposal's scale, image from Bacheva, Pepin (2022)

Firstly, each construction activity associated to this design is documented per lifecycle phase as defined by the European standard DIN 15978 (Deutsches Institut für Normung e.V. 2012). Associated and thus analysed activities mostly match the ones described by and to be assessed for the standard.

The assumptions made in comparison to the definitions by the standard are shown in Table 4.

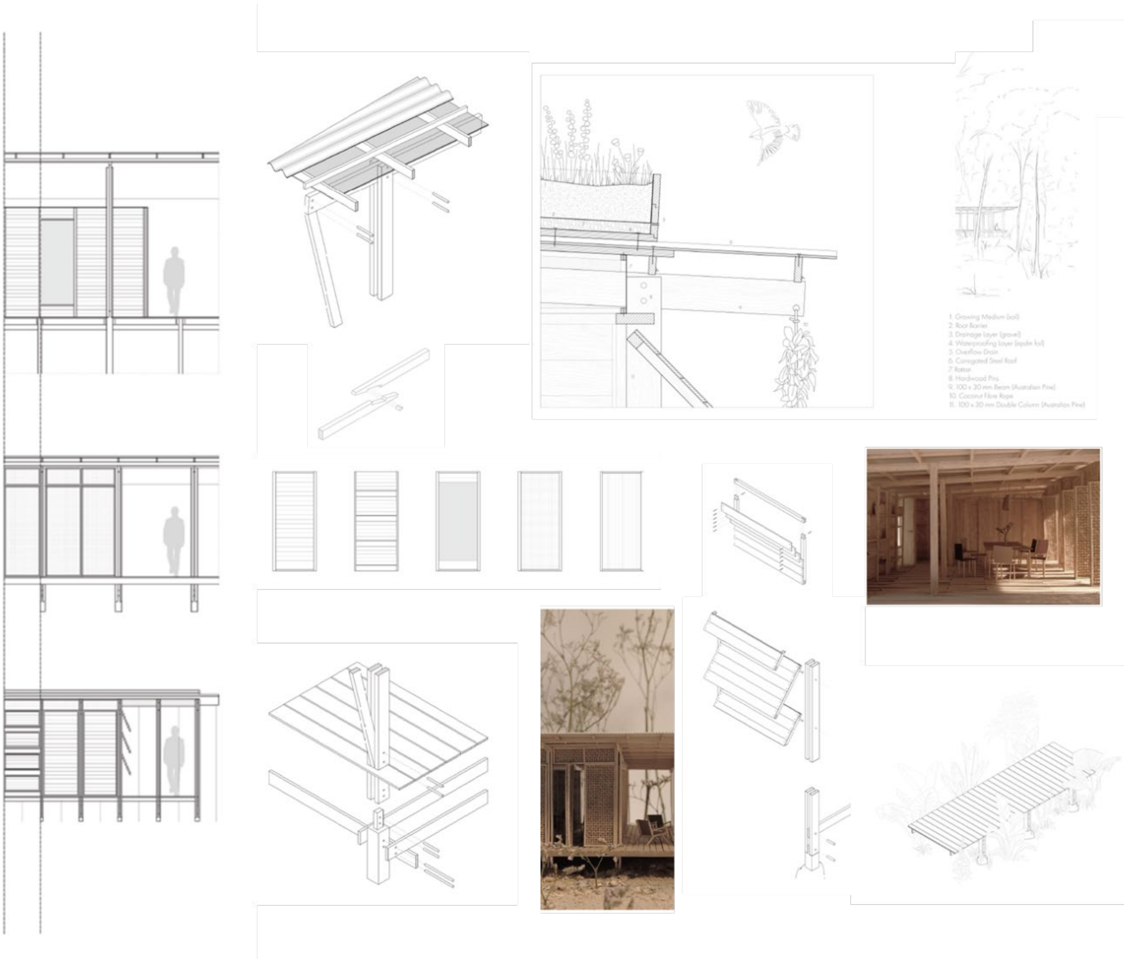


Figure 31. Impressions of the investigated design proposal's characteristics, individual images from Bacheva, Pepin (2022)

Table 4. Alignment of design assessment to DIN EN 15978

Lifecycle phase and chapter in DIN EN 15978 (Deutsches Institut für Normung e.V. 2012)	**Assumptions made for assessment of the design described in this research. With a focus on deviations from the standard definition indicated on the left.**
Definition A1-C4 and D beyond system boundary of investigated building	Same understanding. A1-C4 is local ecosystem impacts of the building and its required area, while D is potential benefits to another building II and its area over the lifecycle of this other project
Definition A4 and A5 Ch. 7.4.3.1 and 7.4.3.2	Not considered are:

	- the ecosystem impacts of non-renewable and non-tropical rainforest related products and materials before they are used - any ecosystem impacts outside of the rainforest ecosystem (which will have to occur on an island by i.e. sea transport, marine and reef/shoreline/mangrove ecosystem impacts However, the impacts of people within the transport process within a tropical rainforest, even if they walk, are incorporated, which is different to the LCA approach where it is not to be taken into account.
Definition A5 Ch. 7.4.3.3	Mostly taken into account - Not considered: manufacturing processes on site because for this case study it is locally in its proximity and thus its ecosystem impacts are solely attributed to the manufacturing phase A3 It is assumed that there are no climatization services provided during the construction process - The water demand and use for the construction process is not taken into account. - Neither are the ecosystem impacts of retrieving water from the tropical rainforest ecosystem. Solely precipitation income, collection and use impacts of the building are considered later on. - Waste disposal during the construction process is not incorporated.
Definition B1-B7 Ch. 7.4.4.1	Same assumption that non-fixed interior fitout and electronics are not considered
Definition B1 Ch. 7.4.4.2 and 7.4.4.3	It is assumed that no painting or coating of mainly wooden structure is required - Particulate matter (PM) impacts on ecosystems not considered because it is unclear to know with certainty what their air concentrations cause
Definition C4 Ch. 7.4.5.5	It is assumed that nothing is left behind as landfill and rather either burned if biobased material or retrieved and reused if mineral based (i.e. screws) Coral foundation piles are left in place and over time do not contribute to any emissions as i.e. landfill garbage

In this approach, it is also tried to incorporate the behaviour and movement of the residents during the use stage of the building to understand subsequent impacts on the ecosystem. However, the activities associated to food sourcing through fishing, hunting, foraging, developing agricultural systems or hygiene related human impacts, such as the salt or mineral inputs to the ecosystem by showering are excluded to this assessment due to the exceedance of the research scope which is focused on buildings. Furthermore, the incorporation of impacts associated to the sourcing, manufacturing and transport of imported materials for the realization of the design to the location, i.e. the photovoltaic panels, HVAC system, piping, tanks, waterproofing, anything non locally manufacturable but used in the development, is not taken into account. Solely their impacts from the time of implementation are considered.

The impacts are listed besides the corresponding activity (Figure 32) and summarized schematically per lifecycle phase of construction within the tropical rainforest ecosystem by a graphic which distinguishes between direct and indirect consequences (Figure 33). The summary schemes for all lifecycle phases can be found in the Appendix (Figure 80-Figure 91).

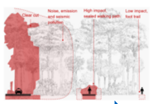
				BE Impact on Biophysical Structure (BS)					
			Overall impact on Biophysical Structure (BS) of (Tropical Rainforest) Ecosystem	Activity I	Impact on Ecosystem I	Activity II	Impact on Ecosystem II	Activity III	Impact on Ecosystem III
Product	*A2*	Transport		**by Road** *Use classification* *-Access roads for raw material supply activity* *-Distribution network roads to manufacturing* *Material classification* *-Unpaved Informal dirt roads for access* *-Unpaved Compacted dirt roads for more frequent use and better drainage to last longer*	**Consequences** -Total surface damage to vegetation cover on ground and top soil by truck and caterpillar movement -Creation of clearances, leaving ground more exposed to sun and rain and increase of forest edges to wind -frequent noise pollution due to traffic -frequent seismic activity due to traffic -Fossil fuel emissions by exhaust -Roadkills of animalia kingdom -Potential unintentional transport of invasive species -potentially human induced alteration of topography/ flattening and compacting of soil additionally affects water uptake and flow	**by Foot** *Intensity and frequency deviations* *-occasional trail for access* *-permanent walking path for distribution*	**Consequences** -low: vegetation cover on ground is pressed down, can bounce back or is not even interfered with by placing steps beside stems and crowns -medium: vegetation cover on ground stays down, dies by impact and is succeeded -high: vegetation cover on ground and soil is destructed by walking and becomes dirt path		

Figure 32. Activity profile and consequences for the ecosystem's biophysical structure exemplary for lifecycle stage A2 Transport for the investigated design proposal.

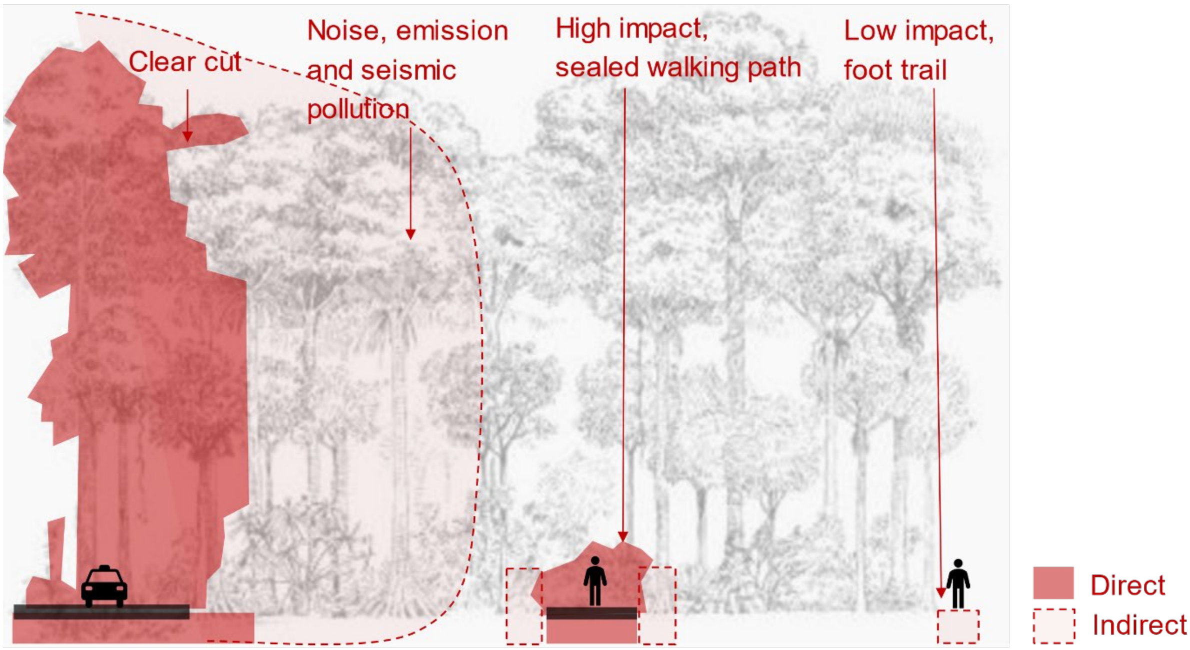


Figure 33. Exemplary summary graphic of impacts on the tropical rainforest's biophysical structure inflicted by the investigated design proposal in lifecycle stage A2 Transport. Rainforest image adapted from Brandon (2014)

There is a difference between the allocation of impacts in the approach of this research and the LCA DIN standard. The standard i.e. requires the allocation of impacts associated to the manufacturing and transport of a replacement element solely to the lifecycle phase B4 (Replacement) of the building (Deutsches Institut für Normung e.V. 2012). In this approach presented here, if anything is to be replaced within the operation of the building, the relevant previous phases (such as A1-A5) are to be reviewed again to understand the accumulating impact of the action. Therefore, in this approach the lifecycle stages and impacts are rather to be seen as additionalities to comprehend the impacts inflicted by each construction action individually but could certainly be summed up and attributed to a single phase as an overall result for the execution of the replacement action.

4.3.2. Ecological knowledge

Ecosystem Services (ES) are derived from Ecosystem Processes (EP) which take place as a result of the complex interaction network of ecosystems.

"To protect tropical diversity, we must understand how it evolves and how it is maintained. To understand how diversity is maintained, we must be able to distinguish the species involved, and we must learn what factors regulate different populations, how different species coexist, and the many and varied ways different species depend on one another." (Leigh and Rubinoff 2005)

Definition:

"Ecology is a science, […] and has become more or less synonymous with 'environmentalism'. […] As a scientific discipline, ecology deals with interactions among organisms and their environment. Ecology seeks to describe these patterns, and understand the processes that give rise to them." (Ghazoul 2020)

Ecological systems are more than the sum of its parts and thus carry an emergent complexity characteristic whose properties originate from the variety of interactions between its individuals and biological processes across spatial scales. This makes them difficult to investigate and comprehensively understand. Yet emergent patterns are possible to be identified because they center around evolutionary theory and natural selection which requires organisms to suitably respond to biotic interactions among themselves and to heterogenous environmental conditions for their survival and reproduction. These evolutionary shaped attributes in physiology, morphology or behaviour are called functional traits which on a large scale affect ecosystem processes and ES provision. Similar traits and strategies in species are defined into different functional groups which each contribute differently and thus provide resilience if there is redundancy within the groups. (Ghazoul 2020)

This analysis and search for the main characteristics of the tropical rainforest is focused on the relevance and its useability for the built environment and is thus a strong simplification of the complex interactions and circumstances known and unknown to biologists and ecologists (Figure 34). Nevertheless, the effort was made to transfer the scientific factual basis as accurately as possible through interdisciplinary exchange, even though it is clear that "We have a long way to go before we understand the dynamics of more complex multi-species ecological systems, at least sufficiently well enough to predict how they might respond to anthropogenic change” (Ghazoul 2020).

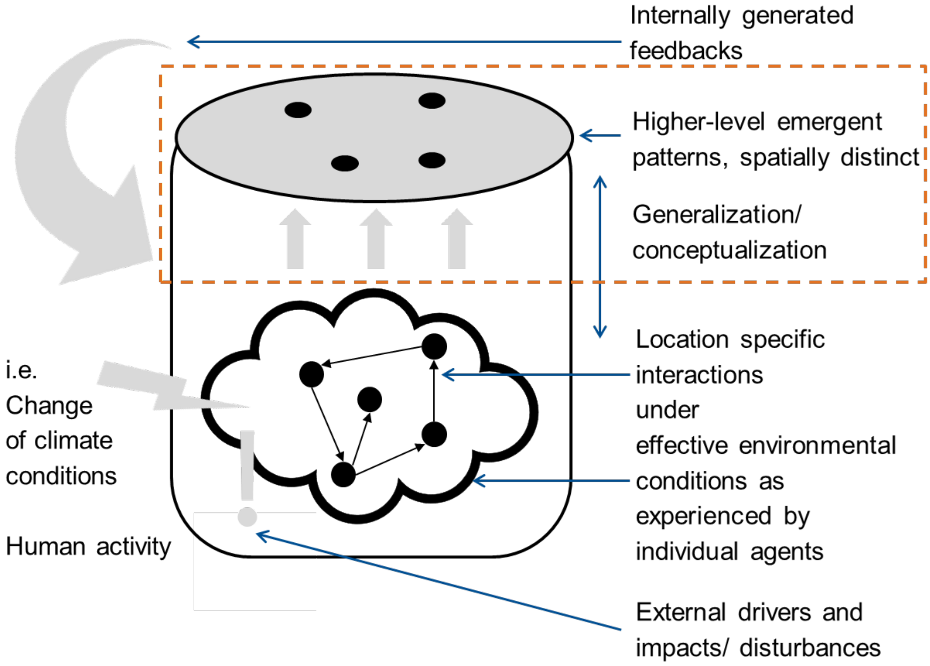


Figure 34. Level of analysis. Adapted conceptual model of complex adaptive systems by Mackey & Su in (Bermingham et al. 2005)

4.3.3. Biophysical structure – Tropical rainforest

Tropical rainforests host more than 50% of the global terrestrial biodiversity and yet only cover between 3-7% of the world’s surface (Khan Academy 2022; Rainforest Alliance 2019; WWF 2022b; Osborne 2000). This makes them especially important for human’s life support system.

Characteristic for a tropical rainforest are its different though interdependent layers corresponding to different heights and environments within the biophysical structure (Figure 35): (from top to bottom) emergent canopy, upper-canopy, lower-canopy, understory and forest floor with its ground cover (National Geographic Society 2022d; Brandon 2014). Below is the soil layer with its root and fungi network.

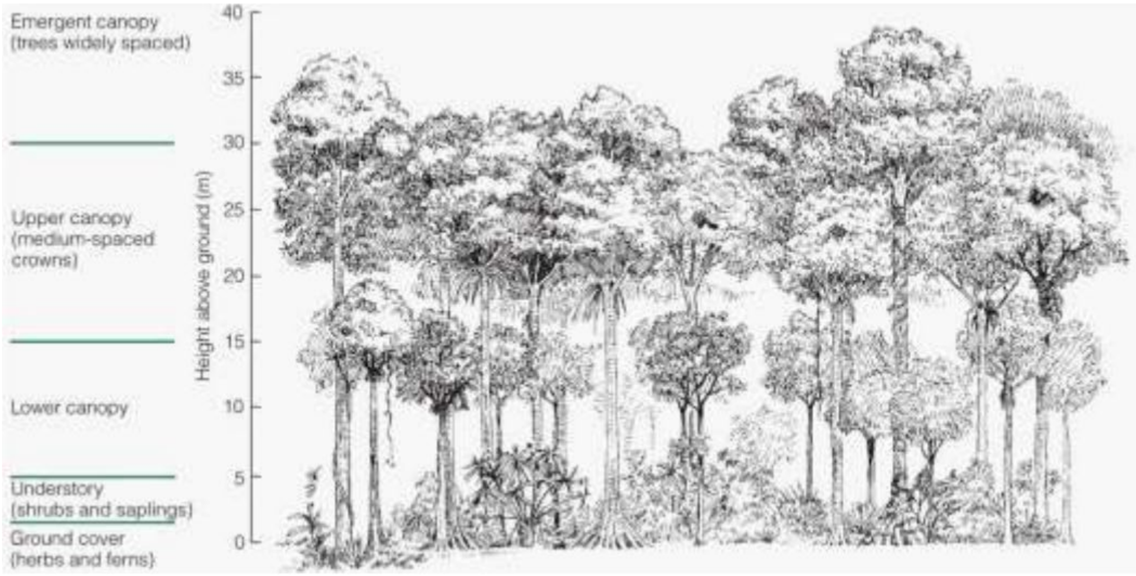


Figure 35. Layers of the tropical rainforest from Brandon (2014)

Each layer has its own distinct living conditions through the variation in available food, water, sunlight and air circulation resources (National Geographic Society 2022d; Ghazoul and Sheil 2010) to which all organisms adapt to fill an ecological niche (Ghazoul 2020).

The emergent canopy layer features the largest trees which as the name suggests, emerge from the roof-like dense canopy underneath and is thus the most wind exposed environment. These are often dipterocarp tree species which in Borneo lowlands represent almost one fourth of all trees and which are a prominent hardwood for construction (WWF 2022a). Emergent trees have an average life expectancy of 200-300 years but can become more than 500years old (found for Costa Rican tropical rainforest in Pfadenhauer and Klötzli 2020)

The upper canopy is contrasting these conditions with blocked precipitation and winds due to the dense leaf cover reaching for the sunlight. These circumstances are the origin for the production of fruit around seeds as key to reproduction for a majority of plants by the attraction of animals which is why the layer is the most resourceful and subsequently species rich layer of the tropical rainforest (National Geographic Society 2022d). This mutually beneficial relationship is also called mutualism (Ghazoul 2020). This plant-pollinator or seed disperser mutualism is especially important in the tropical rainforest because it allows the plants to keep their fast growth traits instead of trading them off for pest defenses in the highly competitive environment (Leigh and Rubinoff 2005). Distinctive for the canopy are for example orchids, ferns, lichens, mosses or also known as epiphytes which can account for 40% of total leaf biomass (Mongabay 2014, 2012d, 2012a).

The understory is characterized by large leafed vegetation, flowers or camouflage tactics to attract as much sunlight as possible since only 0.5-5% reach the floor (Mongabay 2012i; Ghazoul and Sheil 2010), attention by animals for pollination or no attention respectively (National Geographic Society 2022d).

Tropical rainforest soils are nutrient poor because of the very high annual rainfall which leaches the soil but also because of the fast decomposition processes on the forest floor which quickly transfer recovered nutrients through the shallow root-fungi network (National Geographic Society 2022d; Khan Academy 2022; Mongabay 2012i, 2012h; Osborne 2000). This reinforces the positive feedback loop of high primary production due to climatic conditions, large biomass as primary plentiful resource for a high diversity of organisms which in turn accelerates energy recovery through the food web further advancing growth.

Box 7. Food web and levels of organization

"An ecosystem is a unit of study in which energy flows from the sun through autotrophs (producers, such as plants) to heterotrophs (consumers, such as herbivores – plant consuming - and carnivores - meat consuming – animals) and on to decomposers (detrivores, such as fungi and insects) and in which nutrients and materials cycle through the organisms that make up a food web (National Geographic Society 2022c). […] Organism, population, community, ecosystem and ecosphere are levels of organisation of ecological structure and functioning from the individual to global level." (Osborne 2000)

Another important factor to understand which characterizes a healthy and resilient ecosystem, besides its diversity in species, processes and ESs, is its variety in relationships which is certainly interconnected with the other factors. These relationships include competition, reproduction or succession which are fundamental interactions in ecological theory (Ghazoul 2020).

Succession is a "sequence of changes in the composition and/or structure of an ecological community following disturbance or environmental change" (Ghazoul and Sheil

2010). These shocks originate for example from storms, lightning strikes, fires, drought, insect plagues, landslides, earthquakes, other treefalls or human activity which cause gaps in the canopy and other layers (Mackey & Su in Bermingham et al. 2005; Newbery et al. 1998; Osborne 2000). “The gaps created by the disturbances are a major catalyst of community dynamics in tropical rainforests” (Bermingham et al. 2005) because they significantly alter the environmental conditions and resource availability in vertical and horizontal space for organisms. Depending on gap size this has varying degrees of higher nutrient availability due to the fallen biomass and increases in light intensity and duration, which raises air and soil temperatures and decreasing humidity subsequently reshaping microclimate (Osborne 2000) (Figure 36). At the hottest time of the day, air and soil temperature differences between clearings and closed forest were found to be up to 4°C and 15°C respectively (found for tropical forest in Surinam in Osborne 2000).

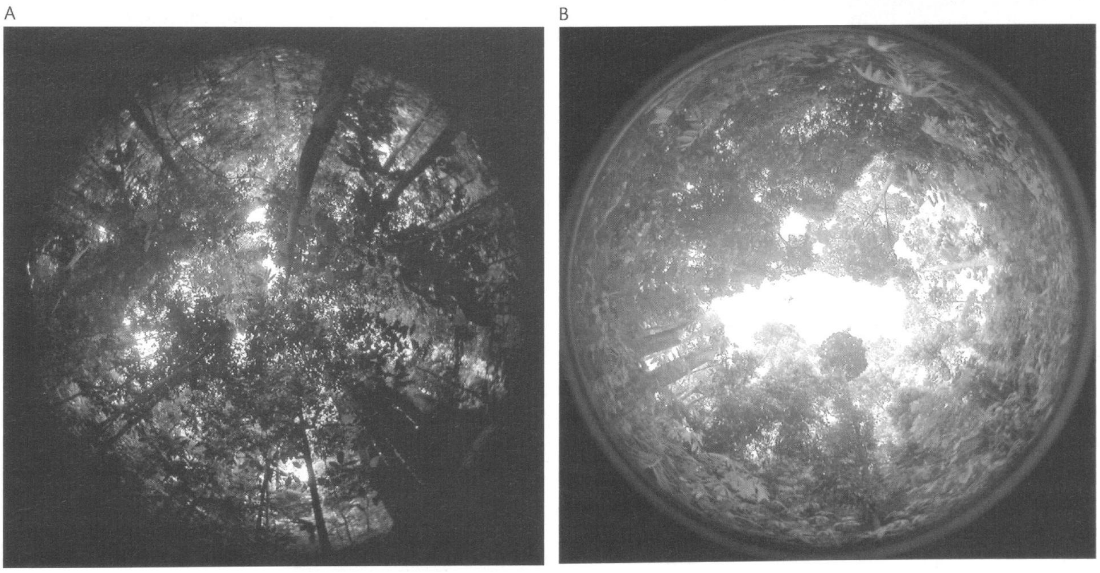


Figure 36. Distinct seedling environments. Non gap (A), gap (B) on Borneo. Images by Julia Born from Ghazoul and Sheil (2010)

The average size and occurrence of a gap is about 100m² once every hectare per year (Teixeira 2021). There are four phases to disturbance subsequent cyclical forest recovery which are 1) the pioneer-, 2) growing-, 3) mature- and 4) aging phase (Teixeira 2021; Pfadenhauer and Klötzli 2020) (Figure 37). As the first phase suggests, gaps are first filled with tree pioneer species and then mix with climax species during the growing phase (Osborne 2000; Pfadenhauer and Klötzli 2020) which is accordingly increasing species. Pioneer species specialize on fast growth in full sunlight, growing several meters a year (Pfadenhauer and Klötzli 2020) at the expense of short life spans while climax species specialize on shaded germination and slow but effective aboveground growth in (semi-) shaded environments (Bermingham et al. 2005; Pfadenhauer and Klötzli 2020; Osborne 2000).

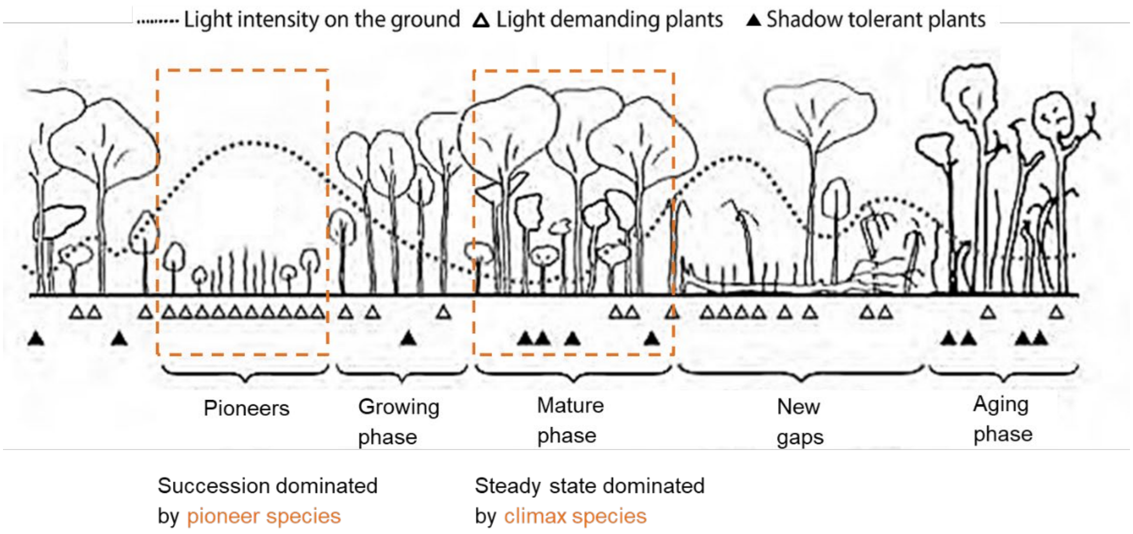


Figure 37. Role of tree pioneer and climax species in succession of canopy gaps. Adapted from Pfadenhauer and Klötzli (2020) and Bruno Senterre and Michael Wagner (2014)

Thus there is a fluctuation in plant community composition which increases biodiversity and biomass over the course of time which are common natural phenomena of succession (Teixeira 2021). This "continues until the addition of new species and the exclusion of established species no longer change the environment of the developing [ecosystem] community" (Teixeira 2021). The maturity phase spatially occupies the largest area (>50% mature phase) and is dominated by long lasting climax species (Teixeira 2021) such as the dipterocarp tree species while the pioneer phase accounts for less than 5% of the area only (Sumatra, Indonesia in Pfadenhauer and Klötzli 2020) (Figure 38).

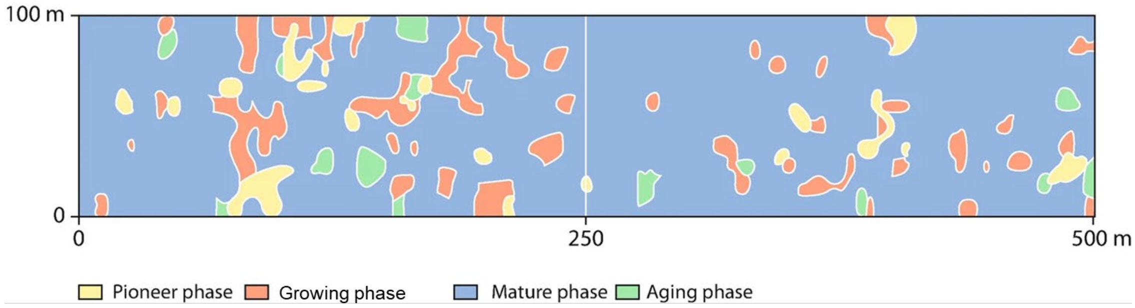


Figure 38. Spatial distribution of the four forest recovery phases. Adapted from Pfadenhauer and Klötzli (2020)

“This mosaic is far more species-rich than an area of equal size that is only comprised of the mature phase. Thus […] [it] is partly responsible for the large number of species in tropical rainforests” (Pfadenhauer and Klötzli 2020) which supports the statement that:

“Shifting cultivation is, at relatively low human population densities, highly sustainable, as cultivation is followed by fallow periods that rebuild soil nutrients. Planted fruit trees encourage birds and rodents that bring in seed of other tree species from surrounding forests, and further enhances forest recovery. The clearance of relatively small patches mimics natural processes of tropical forest disturbance, in which storms and tree falls periodically open up small areas. Small cleared patches even enhance biodiversity by creating a greater variety of habitats.” (Ghazoul 2020)

However, it is not established if succession and secondary forest is capable of replicating the pre-existing climax forest with its functions and subsequent services after deforestation, but if at all, it’ll take more than a hundred years (Osborne 2000) which is important to realize that not all shocks can be recovered, even with enough time.

An ecosystem frequently experiences disturbances and in varying degrees but can through its different agents, interactions and processes retain a dynamic stability in space and time in a non-equilibrium state (Bermingham et al. 2005; Ghazoul 2020). This is until its resilience is exceeded by the intensity of one or the accumulation of many disturbances and an alternative stable state is reached (Figure 39), as it is often consciously or unconsciously imposed by human activity. This is also why “Ecological laws are founded on probabilistic interpretations of nature, [which are] modelled statistically” (Ghazoul 2020) and why “Species-rich forests will develop in areas where disturbance magnitude and frequency are moderate” (Osborne 2000).

Even though rather generalized, this displays the interdependent and individual importance of each layer in the complex biophysical structure and functioning of the tropical rainforest as a whole.

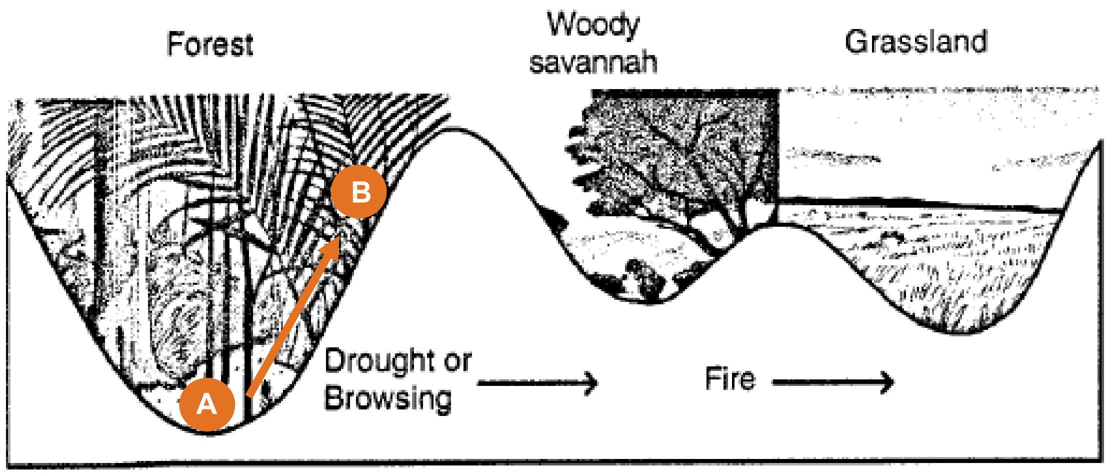


Figure 39. Schematic of alternative stable states. Resilience is reflected by basin depth and current ecosystem state imagined as a ball (A) and under influence of a disturbance (B). Adapted from Ghazoul (2020)

4.3.4. Three investigated supporting services

In this context the following three supporting ecosystem services (ES) are selected and investigated in detail because they are providing the essential life basics and conditions for a number of ES in the other categories: Habitat provision, nutrient cycling and water cycling. At the same time these directly target the societal challenges tied to the exceedance of the planetary boundaries (see Introduction).

Definition:

A habitat is defined as “the physical location or type of environment in which an organism or biological population lives or occurs, defined by the sum of the abiotic and biotic factors of the environment, whether natural or modified, which are essential to the life and reproduction of the species.” (Považan et al. 2021)

The direct loss of habitat by land cover change and subsequent disintegration of the Biosphere by human activity is the main driver and cause for Biodiversity loss (MEA 2005; Pereira et al. 2012; Sala et al. 2000) which influences the nutrient cycle as with biodiversity, biomass is lost and with biomass its nutrients. Therefore the habitat provision ES has been selected for further investigation to be aware of such impacts and counteract current trajectories. This supporting ES further contributes and forms the basis for example pollination, food and pharmaceutical provision.

Definition:

“Water cycles through ecosystems and is essential for living organisms.” (MEA 2005)

Water cycling is impacted by human freshwater use (also called blue water use), the dilution of pollution (also called grey water use) and water demand by domesticated plants and soil (also called green water use) (Abbott et al. 2019). Especially the latter, green water, characterizing the evapotranspiration capacity, is heavily altered by global deforestation and conversion to agricultural crops or livestock use which is further disrupted by the effects of climate change (Abbott et al. 2019) to the extent that it has recently been found to exceed green water variability causing abnormally saturated or dried out soil globally (Potsdam Institute for Climate Impact Research 2022). Abbott et al. (2019) depicts the global water cycle and describes consequences of human interference such as extreme weather, flood damage, altered ocean currents or depletion of groundwater (Figure 40).

Forests have high evaporation and transpiration rates due to its vegetation which indirectly supply 68% of the total rainfall by recycling moisture while in contrast deforested, pasture land has a much lower contribution but instead provides more blue water due to increased drainage (Casagrande et al. 2021). There is therefore a made tradeoff for short-term water availability disregarding the connection to climate and water regulation as well as long term water access. More than three quarters of the global population are at risk of shortages (Abbott et al. 2019) and deforestation is capable of adversely altering local precipitation regimes (Mackey & Su in Bermingham et al. 2005) which is why transparency on these interconnections is required.

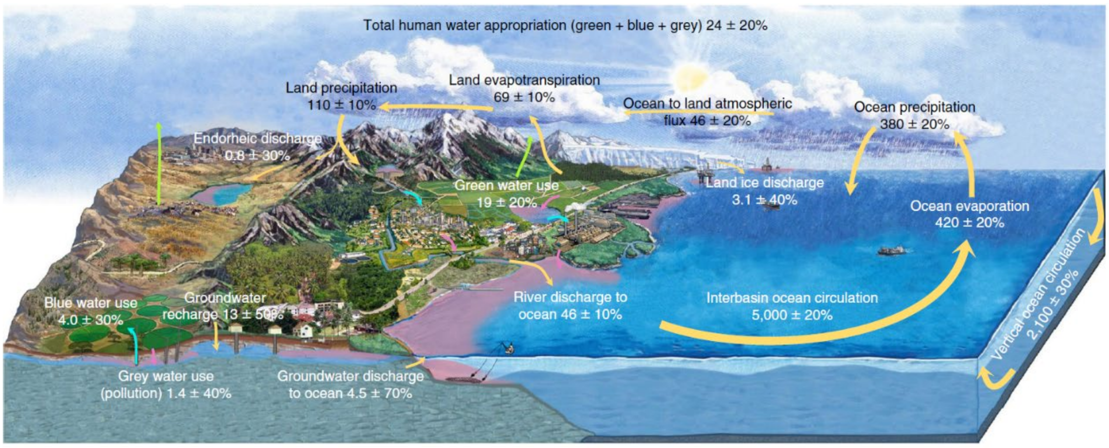


Figure 40. Global water cycle and water fluxes in 10^3 km² per year and uncertainty expressed in %. Grey water use is depicted in pink. Figure from Abbott et al. (2019)

Definition:

"Nutrient cycling describes the movement within and between the various biotic and abiotic entities in which nutrients occur in the global environment." "Approximately 20 nutrients essential for life, including nitrogen and phosphorus, cycle through ecosystems and are maintained at different concentrations in different parts of ecosystems." "An adequate and balanced supply […] provided through the ecological processes of nutrient cycling, underpins all other ecosystem services." (MEA 2005)

The planetary boundaries for biogeochemical flows of especially these two nutrients are far exceeded (Häyhä et al. 2018), almost two fold for nitrogen (200Tg/a) compared to natural fixation (110Tg/a) (Gruber and Galloway 2008) and for phosphorus accumulation (10.5-15.5Tg/a) compared to preindustrial rates (1-6Tg/a) (MEA 2005). Gruber and

Galloway (2008) depict the anthropogenic influence on the global nitrogen cycle and interaction between land, ocean and atmosphere (Figure 41).

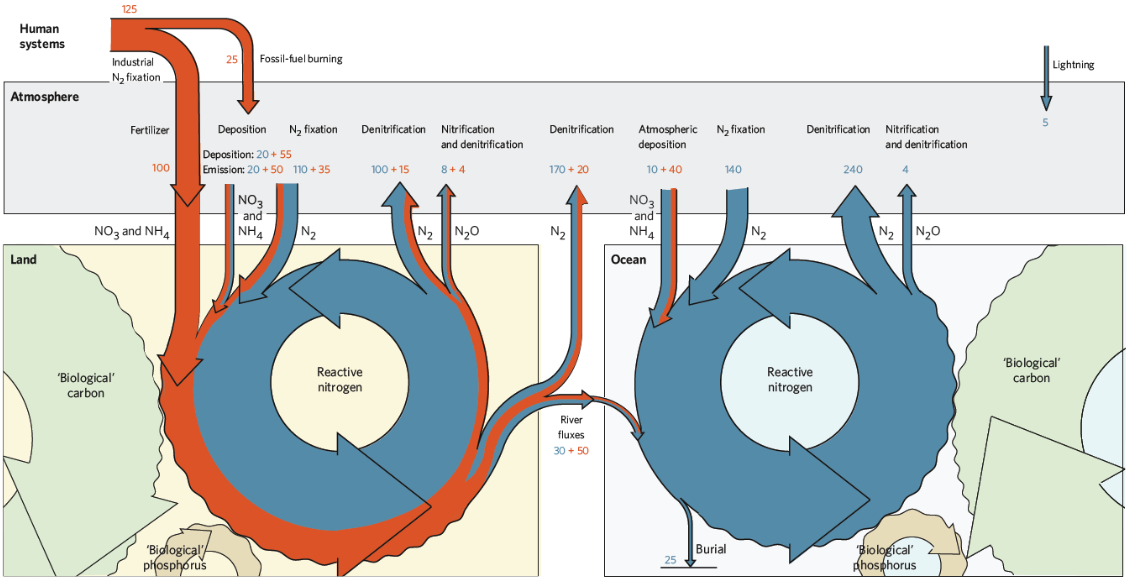


Figure 41. Global nitrogen cycle. Interaction between land, ocean and atmosphere under anthropogenic influence. Numbers in Tg N per year. Figure from Gruber and Galloway (2008)

Fertilization and increase in food production are the driver for human action, yet it is an inefficient man-made management where about 80% of the synthetically reactive nitrogen are leaked to the environment (One Earth 2021) at the cost of eutrophication, acidification and the degradation of freshwater and coastal ecosystems and their respective services (Gruber and Galloway 2008; MEA 2005). Häyhä et al. (2018) have analyzed the planetary boundary exceedances within the EU and identified that recent reduction measures for example in regards to the domestic European nitrogen footprint are considerably outweighed by consumption and externally caused impacts which significantly transgress equal per capita allocation for European countries (Figure 42).

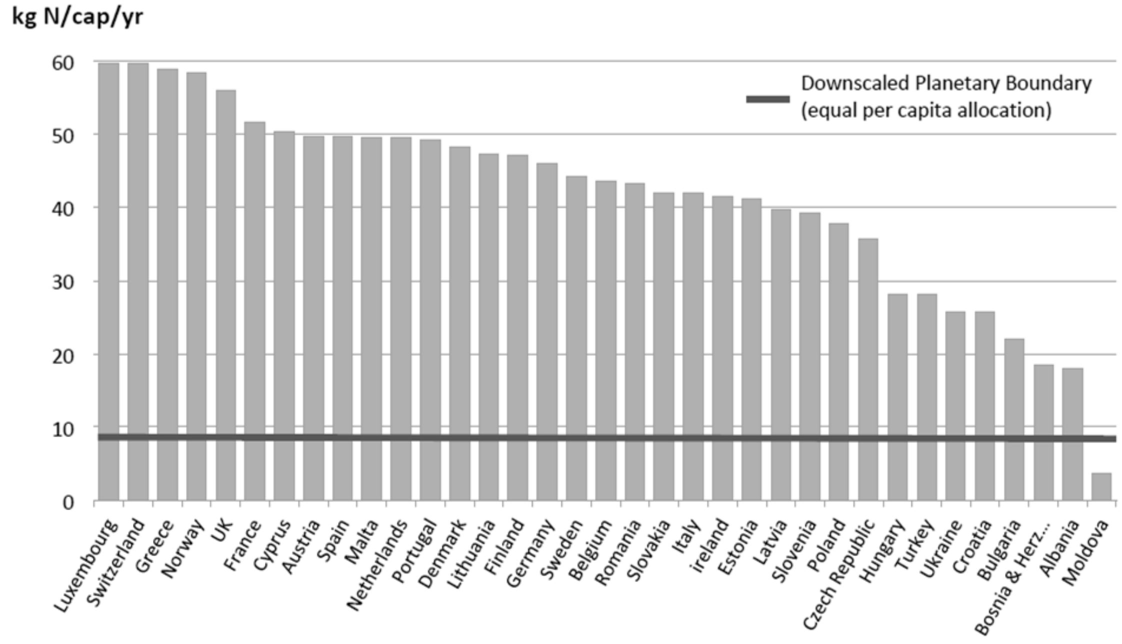


Figure 42. Consumption based nitrogen footprint of European countries from Häyhä et al. (2018)

As essentials for life and prerequisites for the establishment of vegetation, the three selected services can thus also be tied indirectly to plants purification and erosion control abilities as much as to the recreational benefits to people by being exposed to agglomerates in form of forests or parks.

The three supporting services together thus form a strong fundament to assess development impacts on natural capital and its benefits for human wellbeing which link to wider consequences beyond their own ES category and their individual significance (Figure 43).

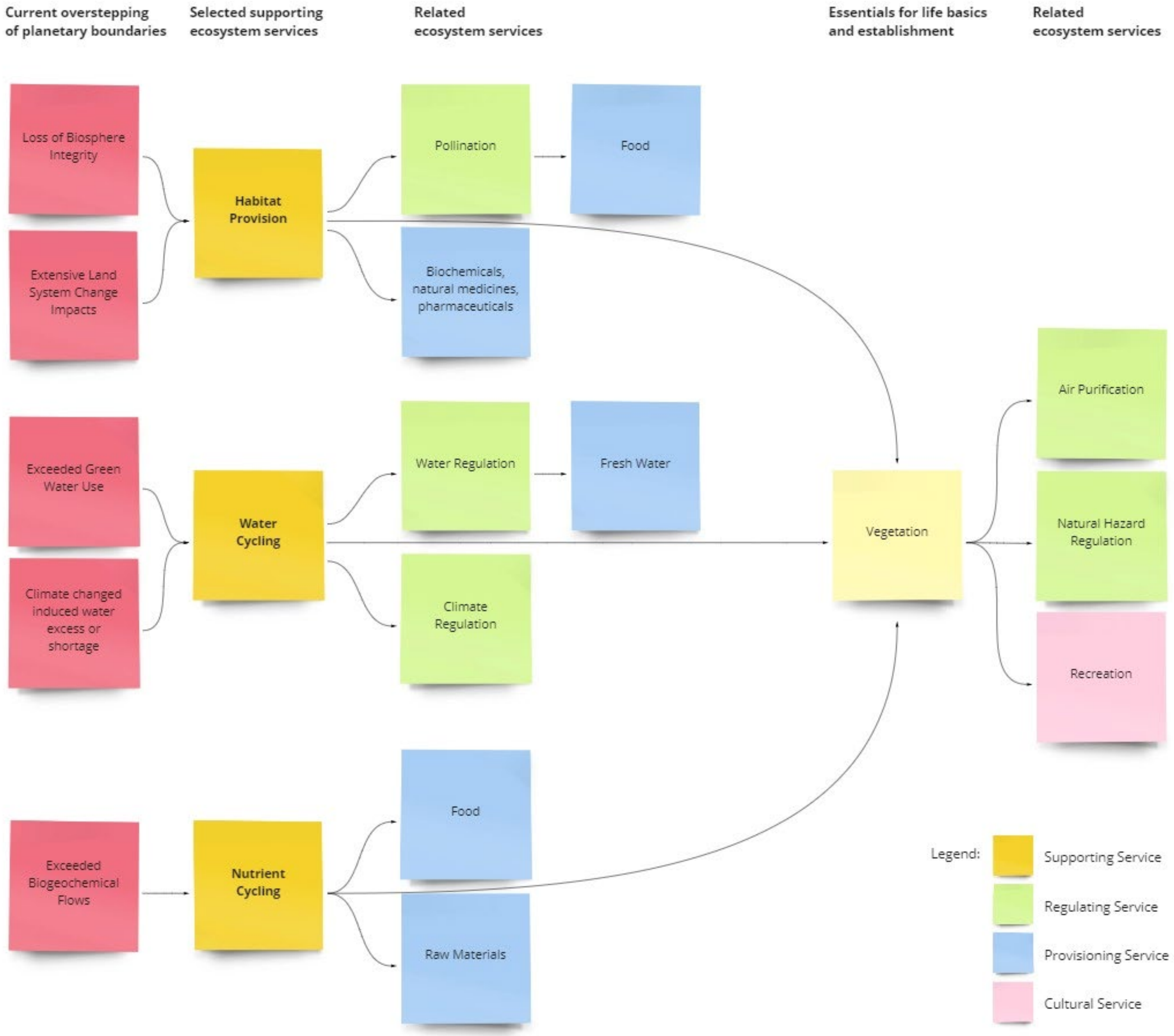


Figure 43. Selected supporting services in relation to planetary boundaries and other ecosystem services.

4.3.5. Ecosystem service profiles

Habitat Provisioning

The limiting and defining factors of this service are the survival and reproduction of a species (National Geographic Society 2022b). Arguably also the stability of this condition is defining its long-term presence overall. If these overarching factors are given a population can be stable and the species be maintained, while frequent disruption of these conditions would hamper this circumstance.

The main components, and hereby defined as processes and prerequisites for the provision of habitat, are shelter, water, food and space (National Geographic Society 2022b) (Figure 44). The characteristics, size, amount and quality of these components to fulfill the suitable habitat conditions differ per species. Thus there are specific conditions for a species in terms of shelter/nesting characteristics, the availability of minimum food and water resources as well as environmental conditions of mating and amount of mating partners within a sufficient area/range/space for all these components/processes to occur.

Only together and in sufficient extent, these processes can form and provide habitat specific to a species.

Based on the previous knowledge of the biophysical structure the canopy layer and forest floor can be identified as main layers which provide the service and processes within the ecosystem. Both of these layers host the majority of large and small species and are therefore the most important habitats where the defined processes evidently occur. For example, epiphytes of the canopy are very important plants of the biophysical structure for this service because they create new ecological niches by retaining water or nutrients or by providing shelter and breeding ground (Mongabay 2012d). The forest floor i.e. provides nutrition by litterfall or an abundance of prey in form of decomposers while the root network offers protection and retained water besides moist soils.

There are undoubtedly many habitats for the rich biodiversity of tropical rainforests. Due to the differing specific condition requirements for each species, the focus lies on the general habitat conditions provided by the tropical rainforest since the focus of this research lies on the processes and main responsible biophysical structures rather than the individual requirements for a species.

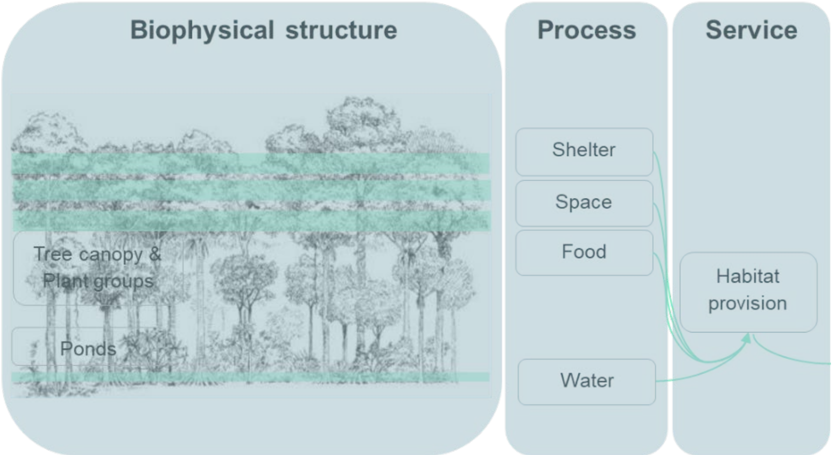


Figure 44. Summary graphic of the main underlying ecosystem processes emerging from the tropical rain-forest's biophysical structure which are the prerequisites for the habitat provisioning ecosystem service.

Water Cycling

The provision of the water cycling ecosystem service is composed of several processes which are precipitation, evapotranspiration, surface runoff, groundwater drainage and change in soil water content (Casagrande et al. 2021) (Figure 45). Precipitation is forming the water budget and baseline income of the system. It is mainly climate driven and thus for the purpose of this study a rather fixed parameter which as a process on a local scale is left unaffected by direct human activity. Therefore it does not appear in further process diagrams. However, indirect impacts on climate regulation by human activity tied to the water cycling's underlying ecosystem processes are taken into consideration. This is related to the components of the evapotranspiration process: interception of rainfall, transpiration by plants and evaporation on surfaces. Evapotranspiration as a compound of these processes is the primary influence of forests on the regulation of the climate by defining the local moisture recycling capacity which determines the microclimate (Casagrande et al. 2021).

The evapotranspiration process is mainly provided by the leaf cover and substantial biomass of the canopy which are crucial for the interception of rainfall, transpiration and evaporation forming the process. The regulation of surface runoff occurs by the topography through the vegetation on the forest floor and emerging extensive root network. The latter is also responsible for retaining or draining water from the soil and thus changes its moisture content which is also dependent on root depth. (as derived by the author from Casagrande et al. 2021's study on rainforest and pasture areas and Ghazoul and Sheil 2010, see Appendix Figure 94)

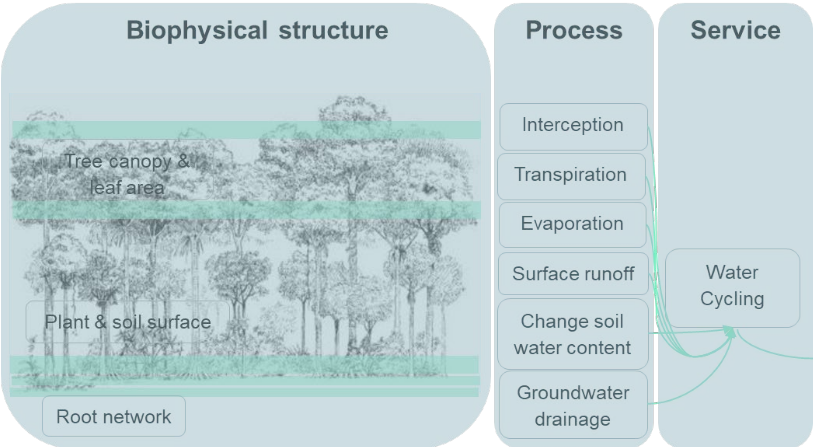


Figure 45. Summary graphic of the main underlying ecosystem processes emerging from the tropical rain-forest's biophysical structure which are the prerequisites for the water cycling ecosystem service.

Nutrient Cycling

The defining processes for the provision of the nutrient cycling ecosystem service are nutrient capture, retention, transfer and re-capture (Orians et al. 1996) (Figure 46). These translate to common notions of budget, storage, exchange and efficiency tied to dealing with resources. Multiple processes can be performed by the same structure and, in contrast to the processes defined for habitat provisioning, the loss of one process does not result in the loss of the entire service. A loss of or damage to one or more processes rather entails a qualitative and quantitative reduction of the service overall.

The common notions of the processes make this circumstance more clear. If the nutrient re-capturing ability within the biophysical structure is compromised, the nutrient cycling service remains present but is consequently less efficiently dealing with the nutrient's available throughout the system. Similarly, though important to point out, if the nutrient capture process is lost, the service and system will keep functioning, however, it will be solely relying on the previously accumulated budget which has been stored within the system, thus is restricted by time.

Orians et al. (1996) describes the main responsible organisms and structures of the tropical rainforest for these processes: Rootmats are essential to all four processes. In combination with the ‘mycorrhizae’, a usually symbiotically living fungi, they are important for the transfer of nutrients to plants. Their recapture ability of nutrients is supported by decomposers including microorganisms as well as nitrogen fixing plants on the forest floor. In the canopy, nitrogen fixing plants and epiphytes capture nutrients from the atmosphere and retain it in different forms. Most nutrients cycling within the system are kept in plant bodies and not in the soil.

For example, one of the many different cycles might be that nutrients are captured by and stored in nitrogen fixers in the canopy. Upon litterfall, these nutrients retained in the tissue are transferred by decomposition on the forest floor. Before release and potential leaching from the soil, these nutrients are recaptured by the root-fungi network which feed them back to the plants and trees of the canopy. Yet another cycle can begin.

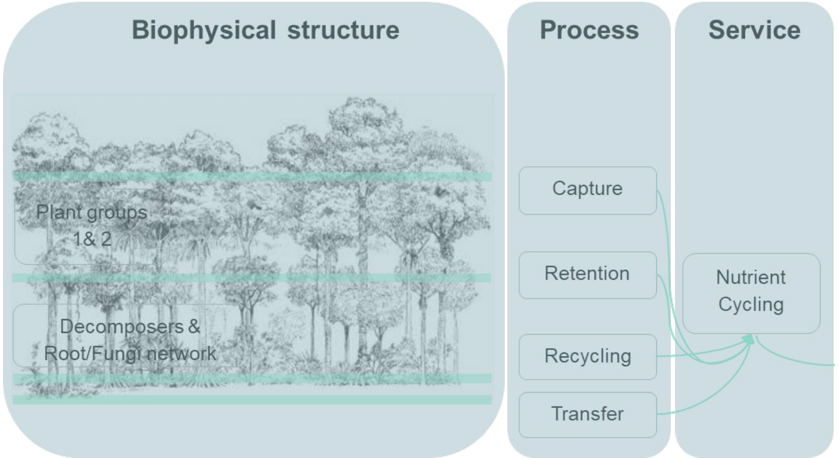


Figure 46. Summary graphic of the main underlying ecosystem processes emerging from the tropical rain-forest's biophysical structure which are the prerequisites for the nutrient cycling ecosystem service

4.3.6. Built environment impact on ecosystem service provision

These identified profiles, fifteen activity profiles of the complete building lifecycle and three ecosystem service (ES) profiles within the tropical rainforest as biome context, are coupled together. This results in 45 distinct design impacts which describe changes in ES provision due to typical building-related activities and their specific influence on the environment (see Appendix 'BE impacts and ES provision requirements per lifecycle phase'). Hereby the summary graphics can be matched which visually represents the main direct and indirect impacts on the biophysical structure (as to be seen in Figure 47 on the far left). This in turn enables the direct relation to the ecosystem processes (EP) attributed to their main occurrence within that structure. Therefore, their change in ability or inability to occur affects the conditions and likeliness of the ES to be provided under that anthropogenic activity. The actual consequences of changes in ES provision on benefit and value of the social and economic system are excluded from the conduction of this qualitative assessment due to scope limitations of this research.

The causes, changes and dependencies are documented in a table for each EP per activity profile associated to one lifecycle phase. By examining all EP entries, an overall impact statement on the expected degree of change in ES provision and its preconditions (as to be seen in Figure 48 on the far right) conclude this step.

For example for the habitat provisioning service (defined on previous page 107), the impacts associated to the clear cut area and road activities of the lifecycle stage A2 (Transport) result in a damage and loss of biophysical structure (BS) and agents which are responsible for the occurrence of all ecosystem processes (Shelter, Space, Food, Water). This means that overall during the transport lifecycles stage of the design proposal the Habitat provisioning ES is likely to be lost since the underlying EP requirements cannot sufficiently be met due to the activity profile and its consequences for the BS in comparison to the undisturbed functioning of the ecosystem (Figure 47, Figure 48). However, as also defined in the activity profile, transport can happen in alternative ways which to a varying degree impact the BS. An occasional, non-compacted and non-sealed foot trail is comparatively low impact and is likely to cause only minor direct and indirect disruptions of the processes without compromising the service despite fulfilling the same construction activity.

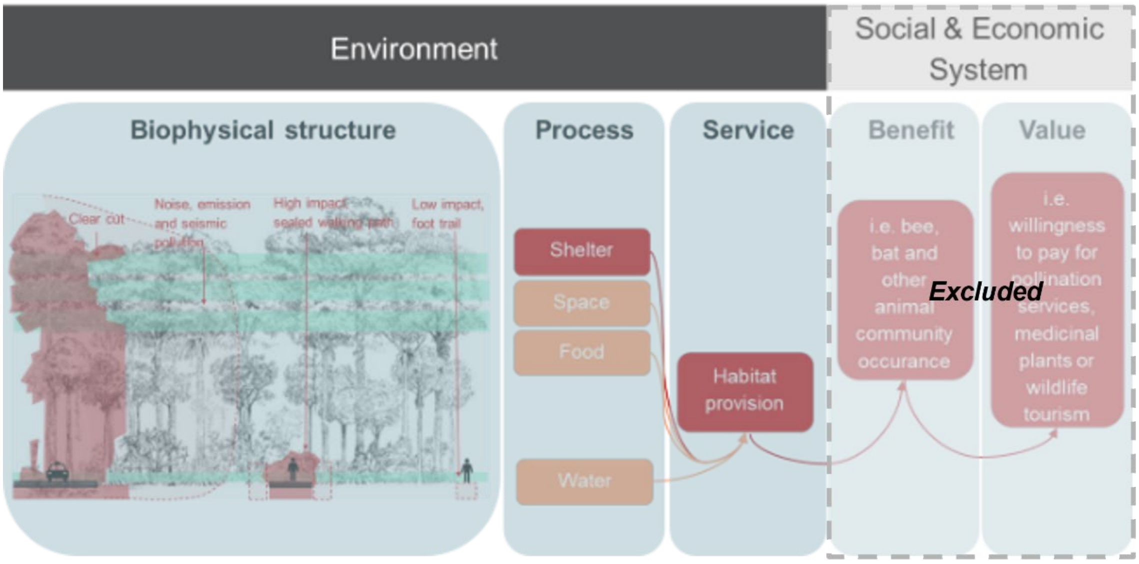


Figure 47. Habitat provisioning ecosystem service impacts by cascading consequences of lifecycle stage A2 Transport activities on the tropical rainforest's biophysical structure.

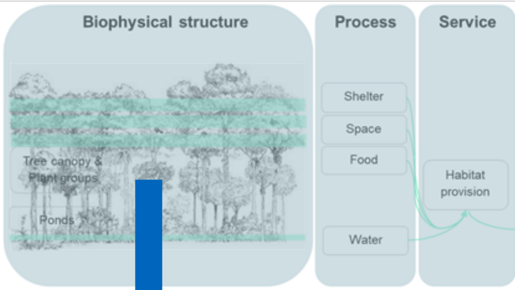
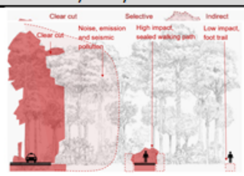
			Legend: *Red=loss* *Green=contribution* *Orange=disruption/decrease* *White=neutral or only slight potential for disruption/decrease* *Overall results emphasize colors*	*Summary & Simplifi-cation of ES provision based on Cascade model*	 				
			BE Impact on Biophysical Structure (BS)	*Ecosystem Service (ES)*	Habitat Provision				
			Overall impact on Biophysical Structure (BS) of (Tropical Rainforest) Ecosystem	*Underlying Ecosystem Process (EP)*	Shelter	Space	Food	Water	Overall impact on ES
Product	*A2*	Transport		*BE Impact on EP & ES*	Lost for road and frequently disrupted	Possible danger due to motorized traffic; frequent disruptions; connectivity might still be given	Quality compromised by pollution of road		Partially lost on individual level and larger affected areas by disruption and degradation/loss of resources

Figure 48. Qualitative assessment of the investigated design proposal's lifecycle stage A2 Transport impact on individual ecosystem processes and overall habitat provisioning ecosystem service based on the lifecycle stage's defined activity profile.

4.3.7. Ecosystem service provision requirements

From this understanding and overall impact statements, ecosystem service (ES) provision requirements can be established for the design proposal's entire building lifecycle. An exemplary requirement overview for the previously described lifecycle phase A2 (Transport) impacts is shown in Figure 40. These requirements serve the purpose to review and optimize the development proposal for reducing adverse changes ES provision and ultimately avoid societal deficits.

The complete table of activity profiles, built environment (BE) impacts on three services and processes by the investigated design and the improvement requirements for ES provision is attached in the Appendix 'BE impacts and ES provision requirements per lifecycle phase'.

Even though this qualitative assessment is based on a specific design proposal, requirements for common practice can be derived and summarized in a checklist guidance document for each service because of its similarity and representativeness to fundamental construction approaches. To transparently communicate and provide comparability for transferability or limitations, the design's main characteristics considered in the impact assessment are listed under 4.3.1 Construction activity profile. It is also discussed and shown that the identified and analyzed activities associated with the design mostly match the ones described by the European LCA standard DIN 15978 which indicates a degree of representativeness, even though that their execution and degree of intensity is likely to differ between development projects.

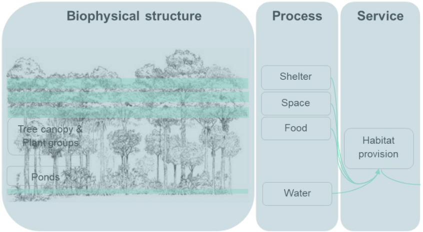
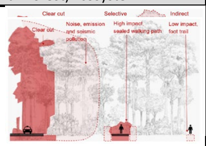
			Legend: *Red=loss* *Green=contribution* *Orange=disruption/decrease* *White=neutral or only slight potential for disruption/decrease* *Overall results emphasize colors*	*Summary & Simplification of ES provision based on Cascade model*						
			BE Impact on Biophysical Structure (BS)	*Ecosystem Service (ES)*	Habitat Provision					Habitat provision by the BE
			Overall impact on Biophysical Structure (BS) of (Tropical Rainforest) Ecosystem	*Underlying Ecosystem Process (EP)*	Shelter	Space	Food	Water	Overall impact on ES	How could this impact be improved/positive, in terms of EP?
Product	*A2*	Transport		*BE Impact on EP & ES*	Lost for road and frequently disrupted	Possible danger due to motorized traffic; frequent disruptions; connectivity might still be given	Quality compromised by pollution of road		Partially lost on individual level and larger affected areas by disruption and degradation/loss of resources	Limit the damage, intensity and scale of direct road impact; enable shelter and space characteristics at least around direct ground losses; minimize usage disruption frequency and danger; avoid pollution

Figure 49. Exemplary requirements for an improved ability to provide the ecosystem processes for the habitat provisioning ecosystem service in lifecycle stage A2 Transport.

4.3.8. Nature-based-solution review

Following the requirement and checklist definition, specific interventions or design solutions such as Nature-based solutions (NbS) are reviewable for suitability. In this research only green roofs and facades have been examined to show the applicability and usefulness of this methodology to this increasing and interrelated domain.

The European Commission (2022a) defines NbS as “Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions.”

Box 8. Nature-based solutions background

Key knowledge gaps and barriers to their implementation are among others, identified by (NetworkNature 2022d) continuously updated evidence base, cost-benefit evaluations and their effectiveness on biodiversity and ES (NetworkNature 2022a). This might be due to the disparity between easier measurable costs of associated one off implementation and ongoing maintenance costs versus hardly quantifiable benefits which amass only over time (The Biodiversity information system for Europe 2022b) and can be distributed over a variety of stakeholders (UK

GBC 2022). Nevertheless there is a large qualitative evidence base and for the evaluations that have been made, significant return of investment trends can be identified (The Biodiversity information system for Europe 2022b) and early adaption is recommended to decrease overall long-term costs in adaptation to climate change (UK GBC 2022).

The (UK GBC 2022) has identified a variety of benefits for different Urban NbS typologies (drainage systems, parks, street trees, green roofs and walls) and showcased the connection to the concepts of natural capital and ES (Figure 50). Thus, NbS progress and success is closely related to the understanding and valuation of ES to which the BE can contribute the case studies, indicators for monitoring and finance models. Incorporating the broad spectrum of ES contribution to societal wellbeing in their assessment further enables a holistic value perspective as opposed to primitive comparisons with engineered grey infrastructure solutions (Mabon 2021). Nevertheless, for the same infrastructure service, a cost effectiveness of 50% and a 28% better value for investment has already been identified (UK GBC 2022).

NbS provide numerous benefits (Figure 51) and are recognized as important opportunities and support to achieving the European Green Deal to address the climate and biodiversity crisis as well as contributing to social justice by benefitting local communities (Balzan 2022; NetworkNature 2022c).

However, criticisms and limitations of Nbs, as summarized and stated by Mabon (2021), are to be kept in mind and foremost it has to be realized that green infrastructure interventions, especially facing unprecedented extreme weather events do not replace or compensate for the nature and life support system lost to urbanization.

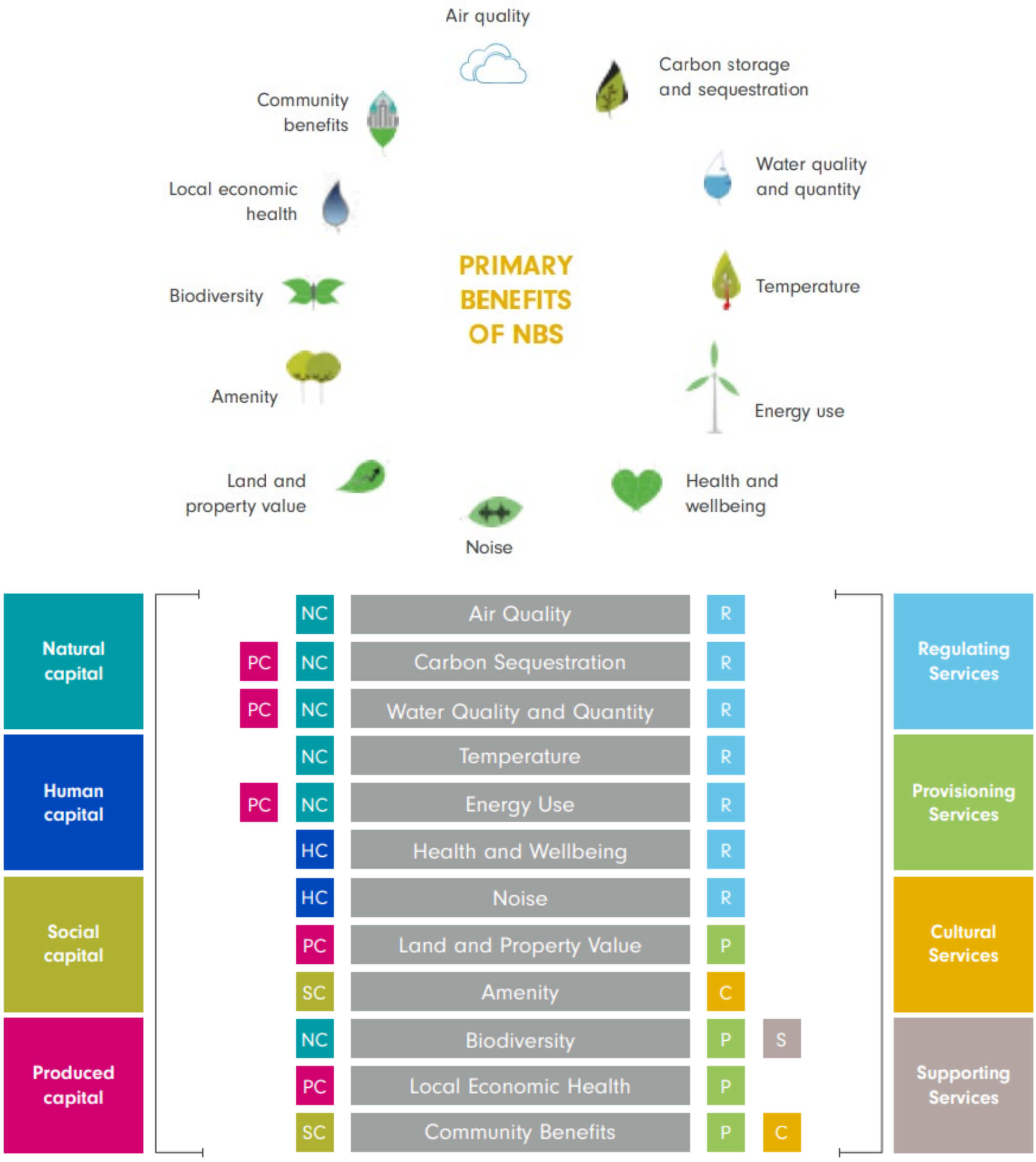


Figure 50. Primary benefits of NbS and their connection to the concepts of natural capital and ecosystem services (UK GBC 2022)

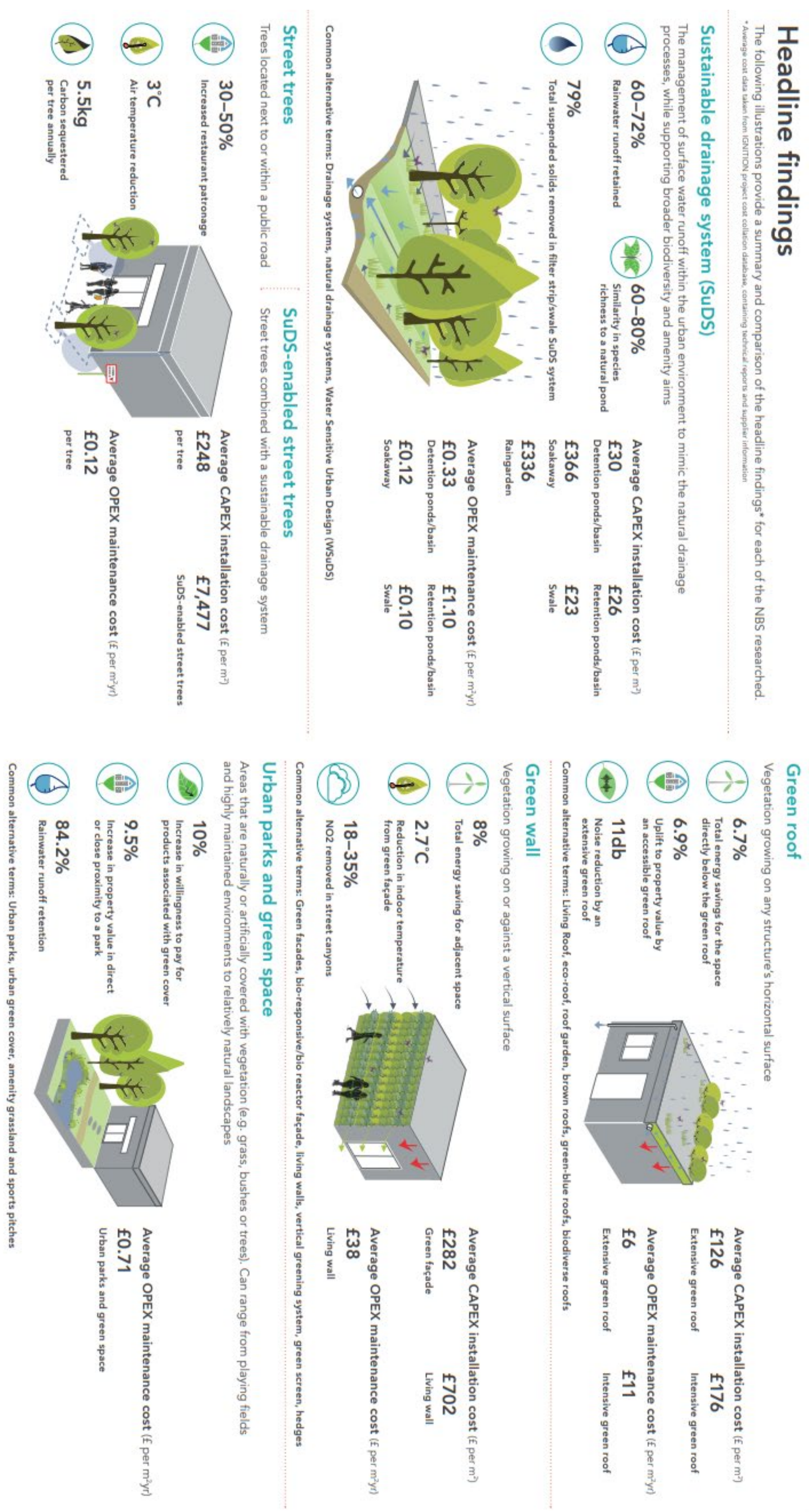


Figure 51. Benefits and costs associated to different urban NbS typologies (UK GBC 2021)

5. Results

5.1. Summary

The results of the high level quantitative study (Chapter 5.2) identify significant decreases in habitat provision, nutrient cycling, primary production, and climate regulation for both of the investigated cases by conversion from tropical and temperate forest to urban environments. This results in 645 and 14,134 Int$/hectare/year societal deficits for the four measurable and monetary valued ecosystem services (ES) (habitat provision, primary production, climate regulation and food provision) out of the initial six. This is respectively for building the planned new Indonesian capital on Borneo in the same way as Jakarta and the German case study on the historical deforestation and conversion process leading to the current Campus Garching. Besides absolute deviations in incurred losses, the overall deficit variation also originates from the different socio-economic contexts and their attributed value to the same service, such as climate regulation. This underlines the beforementioned shortcomings of monetary valuation but nevertheless displays its readiness to offer indications to address ecosystem services also for the benefit of current built environment (BE) discourses such as decarbonization. ES assessment and the comparison to (previously) existing natural environments thus sets a new perspective on the societal value created by construction developments and can aid in the definition of benchmarks to change urban agendas.

The results of the design-level assessment (Chapter 5.3) for the Indonesian tropical rainforest context illustrate the effects for each lifecycle phase and show that various shortcomings are generated by the unawareness or disregard for the functioning of the ecosystem. Subsequently, the respective biophysical structure is disrupted, damaged or entirely lost which is responsible for the changes in occurrence of essential and underlying ecosystem processes for ES provision. These deficiencies are reformulated into a list of ES provision requirements for each lifecycle phase and ES investigated. This guidance is exemplary discussed for the transport and construction phase of the lifecycle along reduction measures as an initiation of an improvement process and further developed to a generalized, scale unspecific checklist. It is an important outcome which enables an additional simplified review opportunity. Its use further highlights the unutilized potential of NbS in usual practice and current limitations in providing ES, also for biodiversity. Furthermore, the transferability to the European despite the initial tropical context is emphasized because of the similarities of temperate and tropical forest structures and thus ecosystem processes for ES provision. Lastly, the ES assessment approach is differentiated from lifecycle assessments (LCA) but it is also discussed how both can complement each other and in Chapter 5.4 why ESA is a crucial novelty to sustainable building.

5.2. Quantitative assessment

The main observation of the results is that the trends are the same in both contexts and that ecosystem services (ES) are to a significantly lower degree provided by the urban environments compared to the natural forest environments analysed. A conversion towards urbanization according to current building practice, which is represented by the cities which have been investigated, can therefore be attributed to a loss in ES provision for the selected ES in at least these two contexts.

The only exception hereby is food provision in the Indonesian comparison. The urban environment provides these services 21% higher than in the reference tropical rainforest environment (Figure 52). However, this originates from the inadequate match of the underlying dataset with the intended assessment purpose for only this specific ES which nevertheless is accepted to extend the demonstration of the presented approach and discuss potential shortcomings (see discussion in Chapter 6.1).

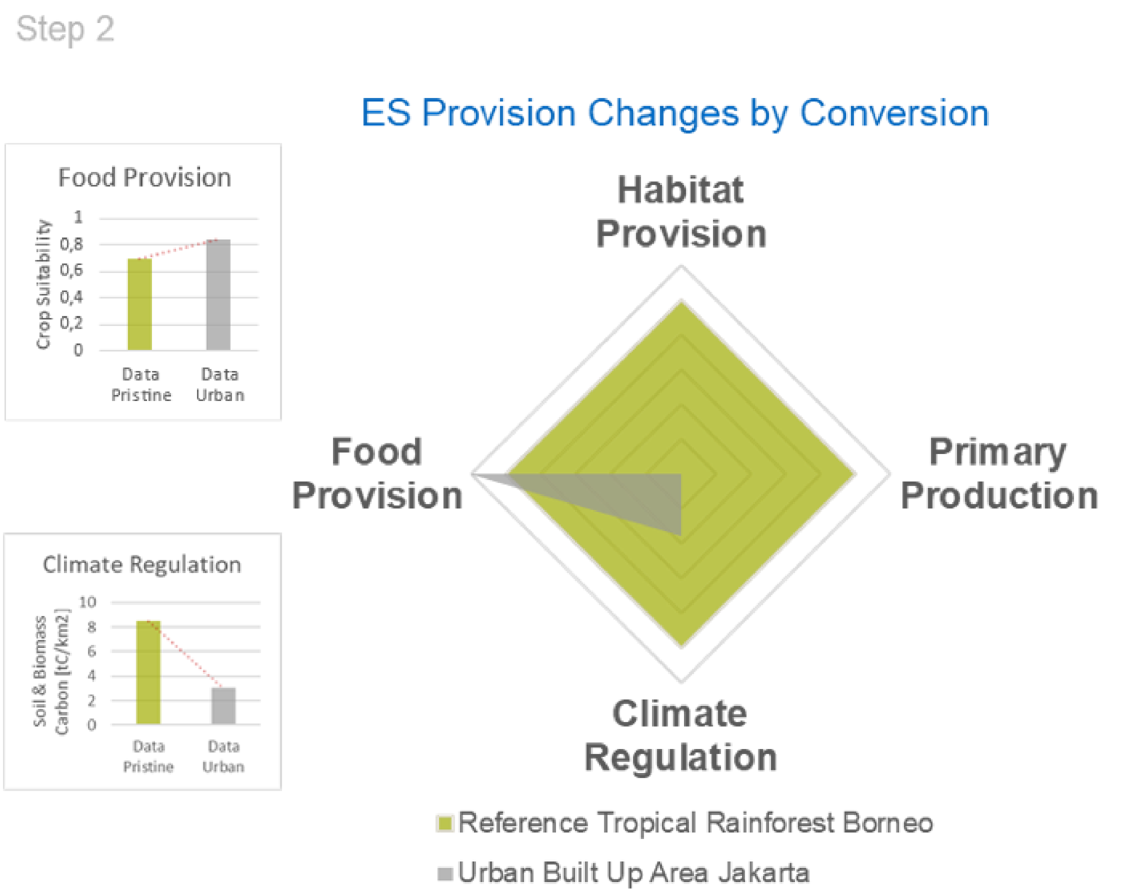


Figure 52. Data summary on ES provision between Bornean tropical rainforest and Jakarta

Comparing the two contexts among each other the following results can be identified.

Especially in the Indonesian assessment the differences in nutrient cycling and primary production between the environments are much larger with 99% and 100% respectively compared to the Bavarian context where variations were 43% and 50%.

In contrast, the climate regulation service differences deviated less with 65% reduced provision in the city of Jakarta and 50% at the Garching campus in comparison to their reference forest ecosystems (see Figure 52 and Figure 53)

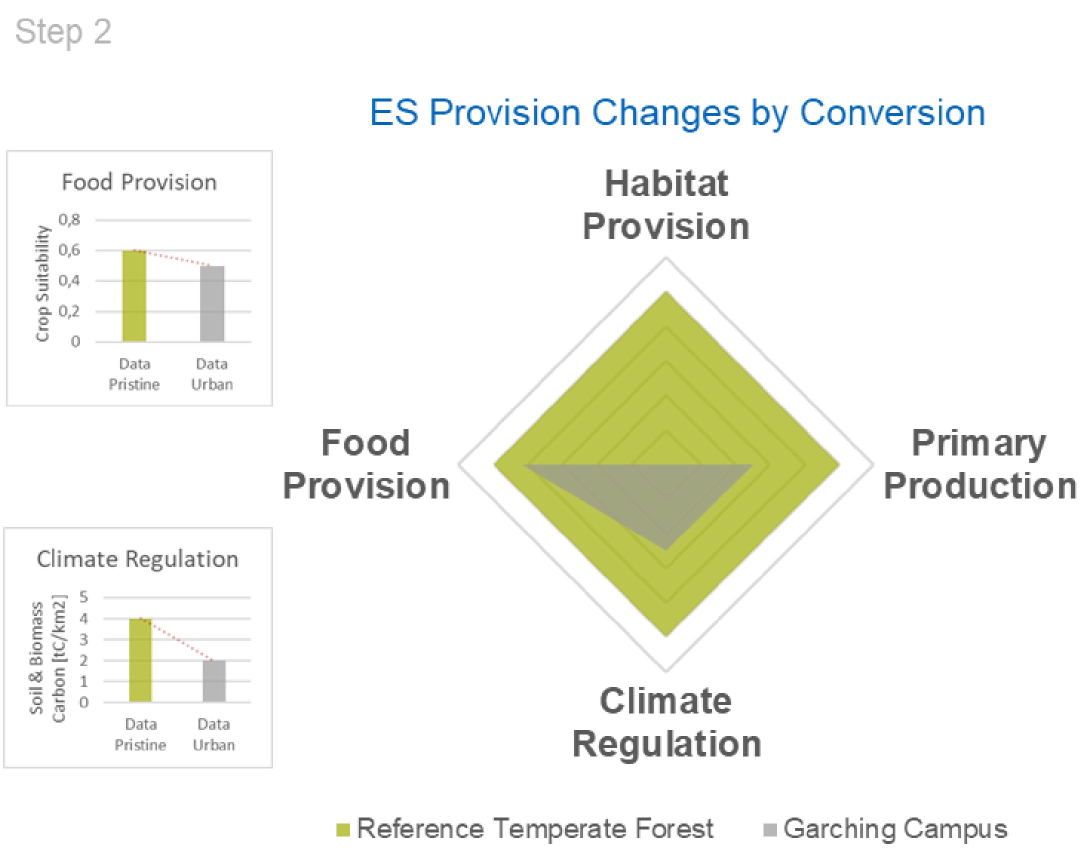


Figure 53. Data summary on ES provision between Bavarian forest and Garching campus

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Box 9. Caution with habitat provision data sources

The habitat provision ES is measured with two datasets: land cover and biodiversity intactness index data. For the landcover data, the assessment is unambiguous that a conversion results in a complete loss of the habitat. This holds true for all species which cannot find suitable habitat conditions within the new land type. To account for possibly persisting suitability conditions, the biodiversity intactness index aids in understanding current species occurrences within a location area and subsequently draw conclusions its habitat provision ability.

The magnitude in difference differs between the Indonesian and Bavarian context. While the city of Jakarta holds a biodiversity intactness index of 70%, the Garching campus retains only 30% of its original biodiversity and thus arguably of its habitat provision service.

For the valuation of these ES provision differences the two contexts have to be reviewed separately because the economic valuation data is region and biome specific.

For the Indonesian assessment, the largest monetary losses incurred by conversion are attributed to climate regulation (229-411 Int$/ha/a) and primary production services (15-235 Int$/ha/a) (Figure 54). The highest mean standardized value for the climate regulation service provided by the tropical rainforest is given specifically for the Indonesian biome scale with 635 Int$/ha/a. This is also the case for the food provisioning service with a valuation of 32 Int$/ha/a and contrasting gains in provision between 2-7 Int$/ha/a by conversion of forest to urban environment based on the used datasets.

Quantitative ESA - Indonesia Case Study		Supporting		Regulating	Provisioning	
	Ecosystem Service (ES)	Habitat Provision	Primary Production	Climate Regulation	Food	
Legend: Color scales apply for each row; red = loss, green = gain *Bold numbers are taken for valuation across all four ES*	UNBL Data Type	*Land cover type*	*Annual NPP*	*Above+Below biomass + soil carbon (d=1m)*	*Agricultural suitability (16 plants)*	*Step 1*
	UNBL Data Unit	*Qualitative land cover classification*	*gC/m2*	*tC/km2*	*scale 0-1*	
	UNBL Dataset	*ESA CGLS Land Cover 2019*	*2020 MODI Net Primary Production*	*WCMC Terrestrial Carbon 2010 Soil & Biomass Carbon*	*Crop Suitability 2011-2040*	
	ES Data Borneo	Closed Forest Evergreen Broad Leaf	15000	8.5	0.7	*Step 2*
	ES Data Jakarta	Urban/ Built Up	0	3	0.85	
	Difference Urban to Pristine	Loss of forest	15000	5.5	0.15	
Scales (Source)	Difference ESΔ in %	1.00	1.00	0.65	-0.21	
						Step 3
Monetary valuation global biome (literature; de Groot et al. 2021)	*Tropical forest mean standardised values in Int$/hectare/year; 2020 price levels*	6	235	577	10	
	*Monetary losses per hectare conversion per year; based on ES Δ*mean standardised value*	**6.00**	**235.00**	373.35	-2.14	
Monetary valuation global biome (ESVD; Brander et al. 2021)	*Tropical forest mean standardised values in Int$/hectare/year; 2020 price levels*	5.64	20	354	11	
	*Monetary losses per hectare conversion per year; based on ES Δ*mean standardised value*	5.64	20.00	229.06	-2.36	
Monetary valuation Indonesian biome (literature; de Groot et al. 2021)	*Tropical forest mean standardised values in Int$/hectare/year; 2020 price levels*	4	15	635	32	
	*Monetary losses per hectare conversion per year; based on ES Δ*mean standardised value*	4.00	15.00	**410.88**	**-6.86**	
Societal deficit incurred by conversion of tropical forest to urban environment in regard to four valued ecosystem services in Int$/hectare/year		***645.03***				

Figure 54. Coupled data with monetary valuation across different scales among valuation sources for the tropical rainforest biome

The order of magnitude greatly differs in the Bavarian context. The largest monetary losses incurred by conversion are attributed to habitat provision (9,495 Int$/ha/a) and climate regulation (231-4,463 Int$/ha/a) (Figure 55). The reduction in primary production service remain in a similar range to the Indonesian case (19-176 Int$/ha/a). The highest mean standardized values are by far for the habitat provision and climate regulation service for the temperate forest biome on a global scale with 9,495 Int$/ha/a and 8,925 Int$/ha/a respectively, compared to primary production and food provisioning with 351 Int$/ha/a and 5.74 Int$/ha/a respectively. This shows the deviations in regionally or nationally attributed values due their differing study and economic market backgrounds.

Box 10. Monetary value coupling for habitat provisioning

For the habitat provisioning service in both Indonesian and Bavarian context, economic valuation data has been tied to the land cover change data as most extreme case for consequential loss of habitat. This is to illustrate the worst case attributed losses incurred by land conversion.

As also indicated in the measured data trends before, there is no gain in the provisioning services and therefore also no financial benefit associated to the conversion of temperate forest to urban environment based on the selected ES and used datasets.

The approach effectively communicates the trends and differences in ES provision by conversion of natural ecosystems to urban environments. This simultaneously indicates the order of magnitude in accrued losses or gains in associated monetary benefit by conscious or unconscious consideration during development planning. Interestingly, the monetary significance of the climate regulation service stands out in the assessment of both of these contexts. Yet such ES provision potentials in or losses caused by the development of man-made environments are not addressed in building practice despite the main discourse on the decarbonization of the sector to achieve climate targets.

Despite its limitations, this is an easily operable approach for master planning which enables first high level indications on how the establishment of the BE, as existing to date, changes ES provision by showcasing quantitative estimates and potential impacts on the services society depends on.

Quantitative ESA - Garching Case Study		Supporting		Regulating	Provisioning	
	Ecosystem Service (ES)	Habitat Provision	Primary Production	Climate Regulation	Food	
Legend: Color scales apply for each row; red = loss, green = gain *Bold numbers are taken for valuation across all four ES*	UNBL Data Type	*Land cover type*	*Annual NPP*	*Above+Below biomass + soil carbon (d=1m)*	*Agricultural suitability (16 plants)*	*Step 1*
	UNBL Data Unit	*Qualitative land cover classification*	*gC/m2*	*tC/km2*	*scale 0-1*	
	UNBL Dataset	*ESA CGLS Land Cover 2019*	*2020 MODI Net Primary Production*	*WCMC Terrestrial Carbon 2010 Soil & Biomass Carbon*	*Crop Suitability 2011-2040*	
	ES Data Bavarian Forest	Forest	10000	4	0.6	*Step 2*
	ES Data Campus Garching	Settlements	5000	2	0.5	
	Difference Urban to Pristine	Loss of forest	5000	2	-0.1	
Scales (Source)	Difference ESΔ in %	1.00	0.50	0.50	0.17	
Monetary valuation Global biome (ESVD; Brander et al. 2021)	*Temperate forest mean standardised values in Int$/hectare/year; 2020 price levels*	9495	351	8925	5.74	*Step 3*
	*Monetary losses per hectare conversion per year; based on ES Δ*mean* standardised value	**9495.00**	**175.50**	**4462.50**	**0.96**	
Monetary valuation European biome (ESVD; Brander et al. 2021)	*Temperate forest mean standardised values in Int$/hectare/year; 2020 price levels*	-	37	462	5.74	
	*Monetary losses per hectare conversion per year; based on ES Δ*mean* standardised value	-	18.50	231.00	0.96	
Societal deficit incurred by conversion of temperate forest to urban environment in regard to four valued ecosystem services in Int$/hectare/year		***14133.96***				

Figure 55. Coupled data with monetary valuation across different scales among valuation sources for the temperate forest biome

Box 11. Possible applications of approach results

By utilizing the native natural ecosystem as a reference, similarly to ecosystem restoration practice (van Andel and Aronson 2012), measurable benchmarks for ES provision could be established upon which the definition of minimum requirements could be enforced to address and ultimately secure society's life support system. This could make the role of nature and society tangible in the development planning brief or increase high level targets as a start. On the other hand, connecting such requirements to constituents in the law on national climate change mitigation goals, counteractions against biodiversity loss or overall intergenerational protection of wellbeing , also enables the opportunity for societal intervention by law enforcement. For example, if a third party were to identify that a project development is evading responsibility to provide a bottom line of ES, subsequently jeopardizing the wellbeing of current and future generations, this could evoke public action and prosecution. Similarly, this is already possible in relation to the stop of major new infrastructure developments due to the exceedance of sectoral carbon budgets as derived from national targets tied to climate protection laws.

Cumulating the costs and benefits across the four quantifiable and monetary valued ES for both conversion contexts (habitat provision, primary production, climate regulation and food provisioning) enables the integration of a “partial minimum site value” to HWB. Only the highest valuations for each service are summed up. For the tropical forest conversion to urban environment this societal dept in ES provision due to development results in 645 Int$/ha/a. For the historical temperate forest conversion to the Garching campus this amounts to 14,134 Int$/ha/a (Figure 56).

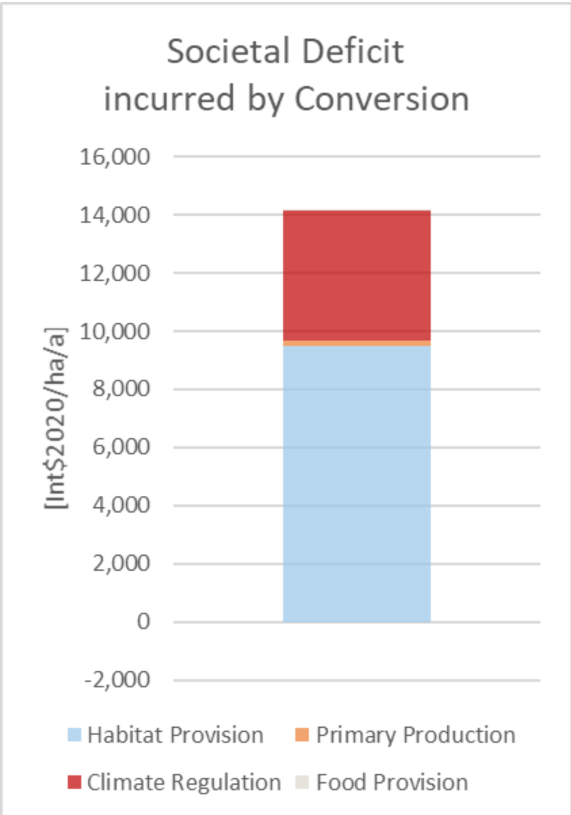

Figure 56. Societal deficit incurred by conversion of (historic) temperate forest to urban environment represented by Garching campus

To further illustrate the importance of assessing as many ES as possible to arrive at a more holistic value which accounts for the already known and quantifiable human benefit, (Groot et al. 2021) identified for their wider set of ES that tropical forests in South East Asia can be valued at 41,785 to 73,233 Int$/ha/a. This is roughly by a factor hundred larger than what has been found in this study for the provision of only four ES by tropical forests, which greatly extends development responsibilities and the societal value at risk (Figure 57).

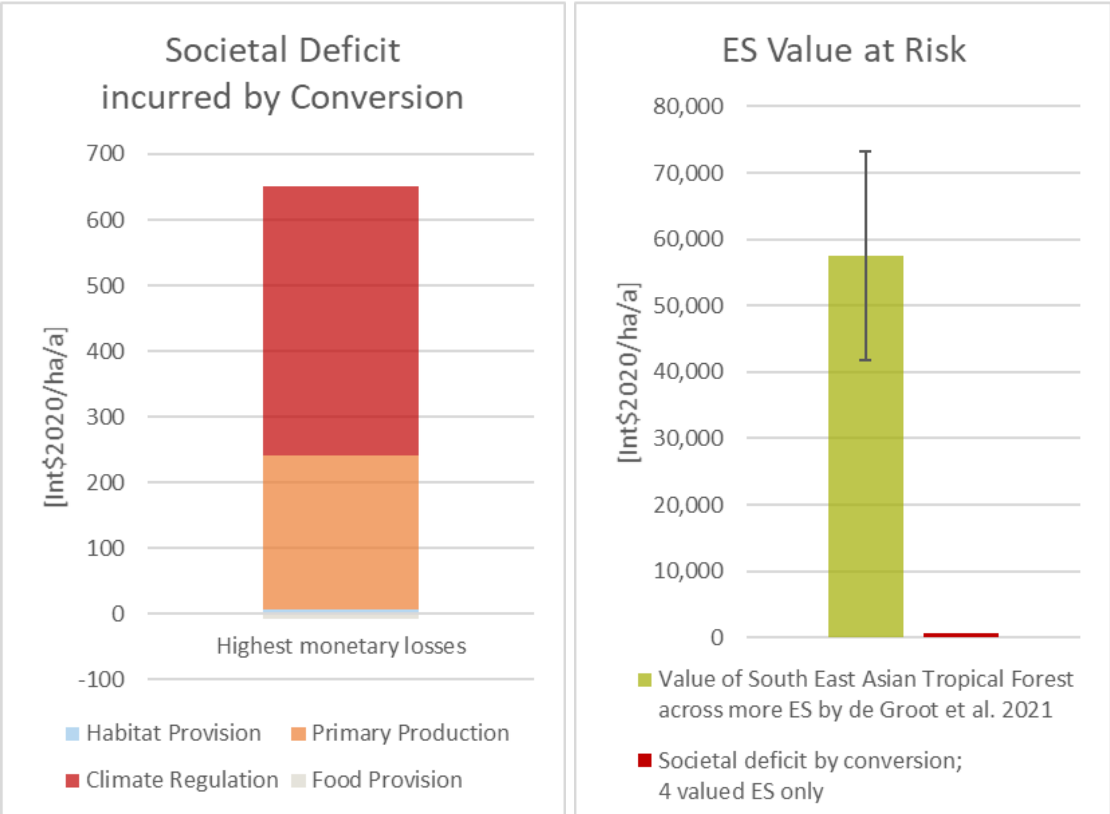

Figure 57. Societal deficit incurred by conversion of tropical rainforest to urban environment represented by the city of Jakarta and potentially larger value at risk

Accounting for these approximate values identifies a basic capital which any project has to prove to outperform for creating greater societal benefit than is already existent (as in the Bornean tropical forest case) or once has been traded off (as in the Garching campus case). This creates a fundamentally different view on what is to be replaced and generated and suggests a novel notion required for the building practice's transformation.

For many mentioned reasons (Chapter 2.4 Ecosystem service valuation) will the monetary valuation alone and derivation from ill structured market systems not suffice and adequately represent the true value of nature to people, however, it offers a first indication and possibility to integrate information in the economically driven reality of the BE.

From a mere natural capital and ES perspective, this analysis of both contexts does theoretically not offer any argumentation why the conversion of forest to an urban environment is to be preferred because even if there is a trade-off between the different services for the increase in food provisioning it comes at a comparably high price. In terms of a developments contributions to overall society, the case is rather made for nature conservation than for any “positive building” label.

This also suggests that in ES-poor man-made environments any green infrastructure addition in comparison to the previous urban condition will yield a great contribution while the actual trade-offs, potential and overall importance of the intervention remain blurred. Therefore, similarly, it becomes difficult to set environmentally friendly urban agendas from an urban perspective. For example, bee hives and insect hotels on buildings might well be a good shift towards wildlife inclusive design originating from within the construction practice compared to none but it does not compare to the overall societal responsibility and magnitude of halting biodiversity loss as overall goal when also viewing urbanization as a major cause for the rapid decline in the first place (see Chapter 1.1). Setting the right urban agendas for the fundamental transformation of cities is not possible from within the existing system and can only be realized by framing the bigger picture and deriving benchmarks thereof. If it is therefore the aspiration to decouple human development from nature degradation then it is necessary to set pristine environments as reference to assess impacts. Therefore, the focus of both approaches in this research deal with natural environments as a starting point for comparison to then operationalize the ES concept as bridge between natural capital and human benefit.

5.3. Qualitative assessment

Based on the research of the biome context and ecological understanding of the biophysical structure a few design considerations can be concluded that align with those suggested by Rovalo (2022). In general, the provision of ecosystem services is supported if a niche diversity along the vertical axis, similar to the one found in the natural BS is created, it is designed for the cycling of materials as part of the natural decomposition process, small scale openings are mimicked and connections between habitats are realized for natural successions and diversification.

5.3.1. Insights from the built environment impact assessment

Large cleared areas have the potential for becoming nutrient deficient because their recolonization cannot move in quick enough before the last nutrients are leached out of the soil while favorable natural succession to secondary forest would nevertheless still take twenty years (Mongabay 2012g). This successional forest is likely to not equate the previously existing one, also in terms of its services for human wellbeing (see Chapter 4.3.3). The alteration and fragmentation further creates sharp forest edges causing biophysically stressful environments because of 1) changes in environmental conditions (abiotic effects), 2) changes in abundance and distribution of species (direct biotic effects) and 3) changes in species interactions (indirect biotic effects). These are known to have consequences up to another 50meters depth (Osborne 2000). Improving on environmental performance of logging practice tied to a buildings lifecycle thus can mean for example to recreate natural gradients accounting for these influenced zones. Even selective logging of emergent trees as source for the most valuable timber is critical because the species specific habitat of predatory birds as home and nesting grounds is endangered (Mongabay 2012a) and would risk the extinction of a key ecosystem agent within the food web and biophysical structure. Decades ago, the German Forestry Association already reported that ecological destabilization, such as soil degradation and microclimate change caused even by small sized deforestations, negatively impacts the livelihoods of people living in the tropics (Deutscher Forstverein 1986).

This might also be linked to the likely and quick damage of the rainforest's shallow root-fungi system which sacrifices a valuable tool for tree's nutrient sourcing. The 'mycorrhiza' fungi of this mutualistic relation alone is worth as much as 20% of the plants photosynthetically generated carbon, only to increase nutrient capture efficiency for phosphorus and nitrogen especially in the rainforest's nutrient scarce soil (Ghazoul 2020). Also the importance of leaf litter increasing growth rates can be seen in accelerated growth in Hemiepiphytes (plants that "germinate on a host tree but later establish root contact with the soil" Zotz et al. 2021) rooting the ground (Mongabay 2012f). Compromising erosion control by root system extinction can increase manifold from i.e. 1t soil/a to more than 1,000 as it is the case for field crops (Mongabay 2012g).

In turn, harvesting rattan in too high numbers risks their benefits: "in many aspects of forest dynamics, including suppressing tree regeneration, increasing tree mortality, providing a valuable food source for animals and physically linking trees together, thereby providing canopy-to-canopy access for arboreal animals" (Schnitzer 2002) (supported for vines in general by Orians et al. 1996). A maximum sustainable yield was found to be at 1.13 harvesting actions per month per 7.07km² which could be used an indication and benchmark for their management and harvest (Hess 2013).

Epiphytes have been shown to evenly distribute water to the forest floor, which entails that their loss changes the spatial distribution of water resources. This subsequently means the same for nutrient availability because inorganic nitrogen is transported by droplets. Therefore, a removal of epiphytes is likely to equate water and nutrient deficits for dependent other organism, causing a shift in community composition and in biophysical structure, which affects ecosystem processes and services. Besides this correlation, Orians et al. (1996) further describes example linkages between plants and their role within the biophysical structure, as well as functional group effects on rain forest dynamics which enables further speculative predictions on the consequences of their disappearance (see Appendix Figure 67 and Figure 68) (note: robust and accurate predictions are often impossible to be made due to the ecosystems complexity, see Chapter 4.3.2 Ecological knowledge).

As also increasingly discussed in the European context, night time light pollution might have significant effects on reproduction interactions and population dynamics of specific plant species which depend on nocturnal pollination like moths or bats which are the most important mammal pollinators within the tropical rainforest (Mongabay 2012e, 2012c). Similarly, human sound disturbances could impact territorial behaviors and population dynamics through differing magnitudes in effects on individual species because sound signals are the main communication within dense canopy layer (Mongabay 2012b).

Disruptions in general might sacrifice stable conditions over time which are required for the occurrence of non-predictable, rare mast flowerings especially typical for dipterocarp trees (Mongabay 2012e; Osborne 2000) which risks their reproduction means and subsequently high value construction timber and the emergent cores of tropical rainforest and the occurrence of dependent primate species. If animals disappear, possibly also partially due to hunting or rodent pest control, canopy maintenance is compromised because 60-95% of woody species depend on birds and mammals for seed dispersal and reproduction (Mongabay 2012e; Ghazoul 2020). This represents the underlying regulating processes which are most often not accounted for.

More immediate construction impacts, such as too wide clearings for i.e. roads might even lead to fragmentation in pathways in trees or open new flight corridors so that there is a potential shift in the population dynamics (Mongabay 2012b). Adding to the insights for the transport phase is its varying degree in impacts on the habitat provisioning service. The coupled profiles show the necessary rethinking of activities which do not necessarily mean that human functions or activities cannot occur but that when ecological and ecosystem services (ES) knowledge is accounted for there is a clear benefit and use case for certain management practices which reduce the environmental impact significantly and thus protect natural capital and consequently human wellbeing. Whether it is a feasible alternative to choose walkways and footpaths over sealed large dimensioned roads is another question that is not supposed to be answered here but it enables an information basis which can tangibly allow for a discussion and informed conscious tradeoff.

As another example of the impact assessment, Lifecycle phase A5 (Construction) and its impacts on ES provision are described here. Through the clearance, preparations and access to the building site, the biophysical structure is severely altered and damaged. The canopy layer is erased by the clear cutting of the forest, while adjacent vegetation is possibly damaged by the handling and movement beyond the mere site boundaries. Setting the pile foundation, reduces but nevertheless still impacts deep soil layers while top soils and root mats are likely to be damaged by the intensive construction activities on the ground floor. Furthermore, the removal of the rainforest on the site changes the microclimate which has thus indirect disruption and change effects on the surrounding non directly impacted and undeveloped environment. These severe alterations and removals likely result in services losses due to the disappearance or heavily reduced process functionalities, as shown schematically for the habitat provision service in Figure 58 because natural shelter, space, food and water sources are lost.

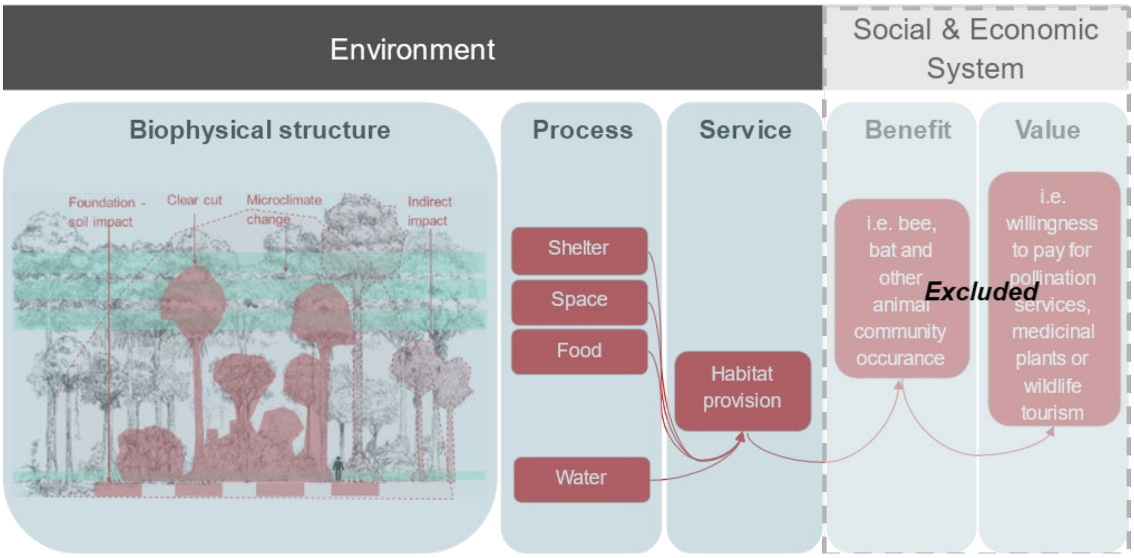

Figure 58. Exemplary visualization of lifecycle phase A5 Construction impacts on habitat provision

This establishes specific provision requirements to for example reduce construction impacts by limiting the damage, intensity and scale of interventions and that known sources of ecosystem processes should be preserved and incorporated in planning and design. Capitalizing on this information could entail the revision of a design with a smaller site area in height and width, smaller size and fewer pile foundations as well as designing with the preservation of large trees as opposed to without them. For the Indonesian design proposal this would mean especially the survival of the crucial canopy area for the biophysical structure which is also the most important layer in providing most processes and thus conditions for ES occurrence. This does not eradicate impacts but it does hamper their adverse effects and associated consequences in services provision which consequently yields a much higher likeliness of processes and thus services to occur, like the preservation of conditions for canopy habitats (Figure 59).

Hereby practice can even remain the same which is clearly not the necessary transformation but it is an easy start to make use of the generated understanding and enable an inclination for further uptake of improvements as outlined by the remaining more challenging requirements.

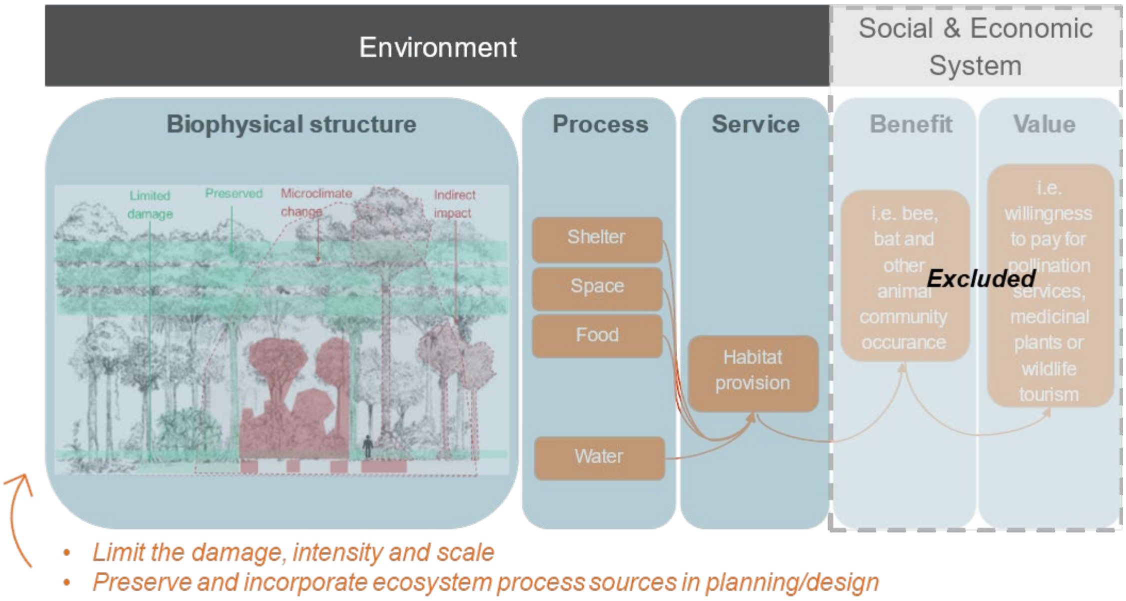

Figure 59. Exemplary visualization of lifecycle phase A5 Construction impacts on habitat provision after considering two ES provision requirements

5.3.2. Ecosystem service provision requirements and checklist

From this in depth analysis and resulting provision requirements for 45 combinations of lifecycle phases impacting the three selected ES, general requirements can be derived which in this research have been formulated to simple yes or no questions (Figure 60). The checklist format ensures a quick reviewability and can initiate more in depth discussions. While some questions are straightforward for practitioners in the built environment (BE) (such as “Are root mats and top soil kept intact?”), others might require some ecological knowledge beyond the common background (such as “Is there a niche diversity similar to the biome context?”). This research paper aids in that understanding and the previously described approach guides the process to obtain the necessary information to identify suitable actions.

Noticeably, no lifecycle distinctions are made anymore. This is because the provision of ES is not dependent on any lifecycle stage but on the presence of specific conditions in form of ecosystem processes derived by the biophysical structure (see Chapter 2.3 Ecosystem service cascade). The previous separation into lifecycle phases has merely been done to understand construction impacts in depth and per development step known to BE professionals. Yet, this checklist is still usable for any lifecycle phase analysis.

Checklist

Habitat provision

- ❑ Is there a niche diversity similar to the biome context?
- ❑ Are high quality food and water sources provided?
- ❑ Have previous habitats or shelter, space, food and water sources been preserved?
- ❑ Are habitats connected to allow for interdependence and space?
- ❑ Can disruptions be avoided, or frequency be prolonged?

Water Cycling

- ❑ Have previous evapotranspiration and soil water management sources been preserved?
- ❑ Are blue and green water rates comparable to predevelopment levels?

Nutrient Cycling

- ❑ Are rootmats and top soil kept intact?
- ❑ Have previous capture, retention, transfer and re-capture sources been preserved?
- ❑ Are nutrient cycling rates comparable to predevelopment levels?
- ❑ Are resources used decomposable and integrated into the natural cycle at the end of life?

General

- ❑ Is sealing avoided and the soil interface functioning and penetrable?
- ❑ Can clear cuts be avoided or extent and intensity be reduced?
- ❑ If impacts cannot be avoided, can natural disruptions be repaired and functional ecosystems be mimicked?

Figure 60. Ecosystem provision checklist by author

Going back to the previous example of the reduced impacts on habitat provision for lifecycle phase A5 (Construction) and reviewing the contents of the checklist clarifies that a lot more has to be changed in practice and specifically this phase which (currently) can hardly avoid impacts. Nevertheless, this only once more symbolizes and emphasizes the fundamental review of practice because development does not inherently entail degradation.

Without having to immediately go in depth and review lifecycle phase specific requirements, it becomes clear what is essential and that if a damage cannot be avoided, the lost functionality needs to be provided either in this lifecycle phase or the following. Critical to the habitat provision service are food and water sources, habitat condition varieties forming ecological niches for different species and habitat connectivity to invigorate (bio-)diversity. Thus if these conditions cannot be provided or mimicked in the construction phase, an operated building design in the following could reinstate shortcomings. If the BE is able to fulfill living conditions for people, why should it not be able to fulfill these conditions with a brief?

5.3.3. Nature-based solution review on ecosystem service provision

This checklist is scale unspecific, meaning that a whole building, complete site or an element such as an enveloped intervention can be reviewed according to the identified requirements.

Green roofs and facades are commonly seen and used as NbS to meet such requirements. However, despite their undoubtedly positive contributions, this can be challenged. The European Commission (2022a) requests that, based on its own NbS definition, “Nature-based solutions must therefore benefit biodiversity and support the delivery of a range of ecosystem services.” The review of the two interventions based on the defined requirements and checklist has identified that there are multiple shortcomings to the commonly implemented extent and quality of green roofs and facades in terms of ES provision (Figure 61) which limits the ability of the BE to address its responsibilities and transformation (see Appendix: LC phase specific ES Requirements - Review List for self-use).

In terms of habitat provision, green roofs and facades might have been connected and integrated to an overall planned network of sites to support biodiversity goals in urban environments but their individual diversity in providing ecological niches, let alone quality food and water sources for species to account for the full set of required conditions, is usually not considered in their design and implementation. Therefore, apart from perhaps being suitable for shelter and space to roam by mimicking forest floor and canopy environments, they do not usually provide the complete range of processes for the support and actual occurrence of the ecosystem service - habitat provision.

For the water and nutrient cycling services, the checklist suggests comparable rates to predevelopment levels. Such evaluation requires assessment steps to be taken, as for example in the presented methodologies, to identify ideally quantitative natural benchmarks but at least qualitatively responsible biophysical structures to be accounted for.

From the review of ecosystem processes, it becomes apparent that also here green roofs and facades usually do not utilize their full potential and only provide a part of the required conditions for the provision of these services.

Green roofs can theoretically replicate similar conditions to forest floor layers by establishing the same biophysical structure. The magnitude of processes however,is likely to differ due to the missing upper, tree and biomass dominant layers which are the driver for achieving natural benchmark rates. For example, nutrient processes (capture, retention, recycling and transfer) can be performed by intensive green roofs but at least in regards to their capture-, retention and transfer-ability will have much lower rates compared to forests with their extensive canopy layers which contribute the majority to this functionality overall.

In contrast to this, green facades can hypothetically mimic these canopy layers and processes, even though with limited depth, but in turn usually do not target floor resemblance due to their vertical setup. Therefore, they are also only partially suitable for services occurrence.

Figure 61. Review of ES provision by common green roofs and facades through the use of the checklist

From this review, it has also become clear that these interventions merely target the provision of ES during the operation phase of a buildings lifecycle but do not influence any of the adverse effects during previous or later lifecycle stages (Figure 62). Possibly the only other benefits to other lifecycle phases could be seen in the reuse of them (lifecycle phase D) if appropriately deconstructed and kept intact or specifically for the nutrient cycling service in their decomposition during lifecycle phase C4 (Disposal). The latter thus also ties back to the checklist question: “Are resources used decomposable and integrated into the natural cycle at the end of life?” However also in this regard, usually only the biomass but not the waterproofing, supporting structure or drainage system is considered for this.

Yet, if green roofs and facades are designed and implemented appropriately by considering all the process conditions, there are positive ES contribution opportunities to be expected, which could, based on the theoretical cascade model, also generate hypothetical monetary benefits for society.

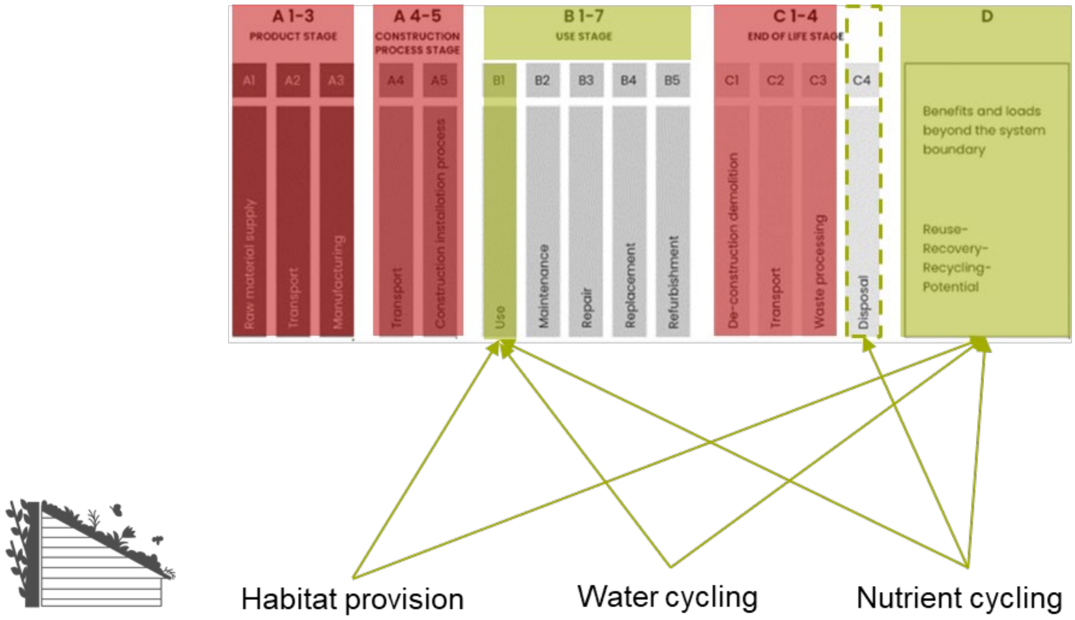

Figure 62. Limited ecosystem service provision by green roofs and facades across the complete building lifecycle

5.3.4. Applicability to European context

Another advantage of the checklist, even though derived from this biome context specific assessment is that it is translatable and applicable to other biomes as well, as long as the identified EP's match. This is possible if biophysical structures are similar. Biome structures can be alike despite containing different sets of animal and plant species (Tryse 2017).

This can be shown with temperate forests, which makes the insights and conclusions largely applicable to the European building practice. Temperate forests compare to tropical forests because they have a similar though simpler and less biodiverse biophysical structure (WWF 2022c; EEA 2016a) (Figure 63). ES provision also depends on the fundamental functioning and health by energy-, water- and nutrient exchanges supported by biodiversity driven complexity connected to supporting services (EEA 2016a). Therefore, qualitatively, the concepts of ES category hierarchies and the ES service cascade apply as much as for the tropical pendant. This enables the theoretical basis of transferring qualitative results and requirements even though that specifically responsible species realizing the EP's for ES provision and quantities differ.

This re-emphasizes the relevance of this research also for the European context because temperate forests are the dominant biome and cover most of mainland Europe (Rigo et al. 2016; Tryse 2017) (Figure 64).

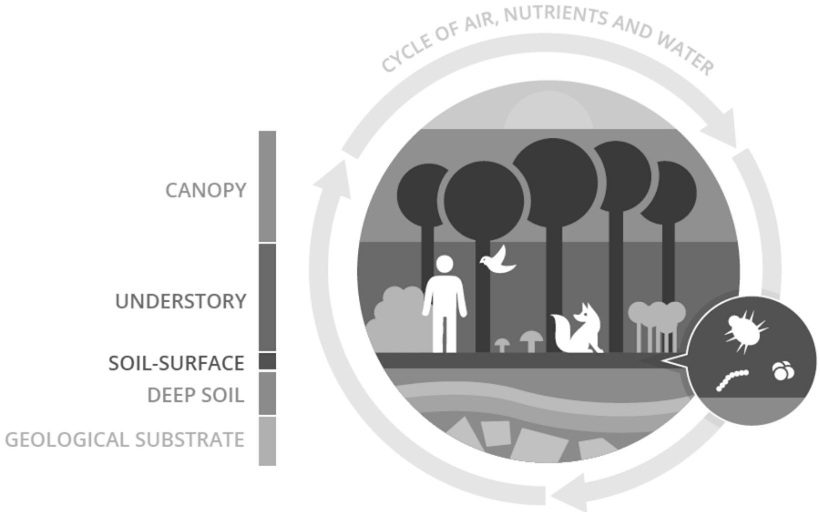

Figure 63. Temperate forest structure and supporting services as defined by (EEA 2016a)

Figure 64. Temperate forests covering most of mainland Europe (Tryse 2017)

Therefore, the impact assessment, shortcomings, requirements and checklist apply to European practice in (historic pre-development) temperate forest environments. This makes it clear that not only in the Indonesian but also the German context more of the qualitative design-level assessments should be conducted for Designs and Masterplans.

From the quantitative assessment it becomes apparent that the conversion to urban environments results in overall losses in ES provision and subsequent nature's benefits to people upon which human wellbeing and development depends. Therefore, the built environment must make use of its responsibility of constantly surrounding most of the human population and regenerate and actually support overall societal human wellbeing by building actions instead of directly or indirectly degrading functioning ecosystems which supply ES. The quantitative assessment approach can aid in the definition of minimum requirements and benchmarks, while the ES provision requirements and checklist should be applied to NbS design and implementation to realize their full potential.

These fundamental changes in approaching practice and set of goals consequently entail a redefinition of urban agendas and understanding of "positive building". Nevertheless, the presented approaches align with aspirations and complement other BE agenda's such as climate neutrality or circularity (see Chapter 5.4).

5.3.5. Ecosystem service assessment in comparison to LCA

Beneficially this is also the case for increasingly used lifecycle assessments (LCA) as main tool for analyzing environmental impacts, even though not being mandatorily instated (yet). Nonetheless, the proposed ecosystem services assessment (ESA) greatly differs from the lifecycle assessment (LCA) practice (Figure 65). The main difference is its usability of results. While the LCA is designed for the detailed optimization of industrial processes based on numerical values, this is not (yet) achievable with ESA. However, its quantitative and qualitative results are able to tangibly communicate the direct effects on environment and human wellbeing, while even post processed LCA results to human- and ecosystem health remain intangible and different studies difficult to compare.

ESA	LCA
Local + national + global results significance	National + global results significance
Tangible direct effects on environment and human wellbeing	Intangible effects, requires postprocessing by experts for any statement towards human or ecosystem health
Designed for overall optimization of societal wellbeing	Designed for detail optimization of industrial processes
Data background in infancy	Data background increasing
Can be coupled to monetary values	Theoretically possible to couple to monetary values after expert assessment i.e. Costs associated to DALY
Different categorization by different frameworks but comparable	Different boundary conditions by same method but difficult comparability
in BE utilized on landscape level	in BE utilized on building and product level

Figure 65. Comparison ecosystem services assessment (ESA) to lifecycle assessment (LCA)

This might be attributable to shorter linkage from the units investigated to the ‘endpoint’ and final interest. While the ESA approach directly works with ecosystem services as measured entities which are thus only one connection away from the tangible understanding of how an improvement contributes to the constituents of human wellbeing (for example climate regulation from human health) (Figure 66), an LCA has to have at least two connections (Figure 67). Depending on the background knowledge of a stakeholder, however this is likely to be many more.

For example, an ‘inventory result’ of a building product measures the global warming potential (GWP) in one or more lifecycle phases. This elementary flow of CO^2 equivalent emitted thus contributes to climate change as a ‘midpoint’. Overall this climate change impact is attributable to human health as an ‘endpoint’ impact which is quantitively presentable and provided in ‘*disability-adjusted life years*’ (DALY). However, for non-experts it is much less tangible why specifically the GWP at the initial stage is to be reduced if there is many more ‘midpoint’ impacts which likewise contribute to the deterioration of human health. Thus it also becomes clear that in BE practice the focus lies much more on ‘midpoint’ optimization and transparency, as for example climate change contributions are relevant for the prevailing decarbonization discourse of the sector. This in turn also shows that the LCA framework already offers many more assessment and optimization possibilities but is much reduced to single ‘midpoint’ concerns in the BE. A targeted optimization for more broad ‘endpoint’ optimizations such as for human health are much more intangible and difficult to conduct because it is unclear what to prioritize or how different importance should be assigned or weighted. Its strength is possibly therefore also a key barrier to realizing its full potential for BE practice because a designer might have improved the building product by a fraction of a DALY, yet does that exact but global number communicate and better convince the client of its worth?

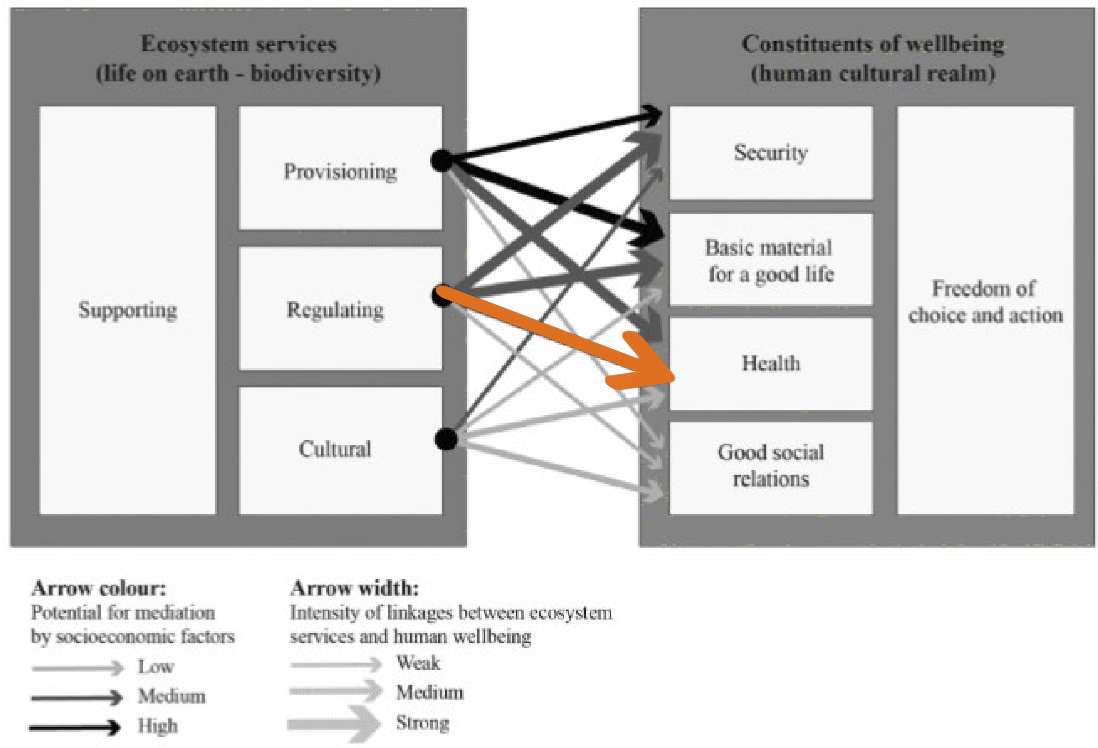

Figure 66. Direct linkage of Nature's health and ecosystem services to human wellbeing. Adapted from Pedersen Zari (2018) based on MEA (2005)

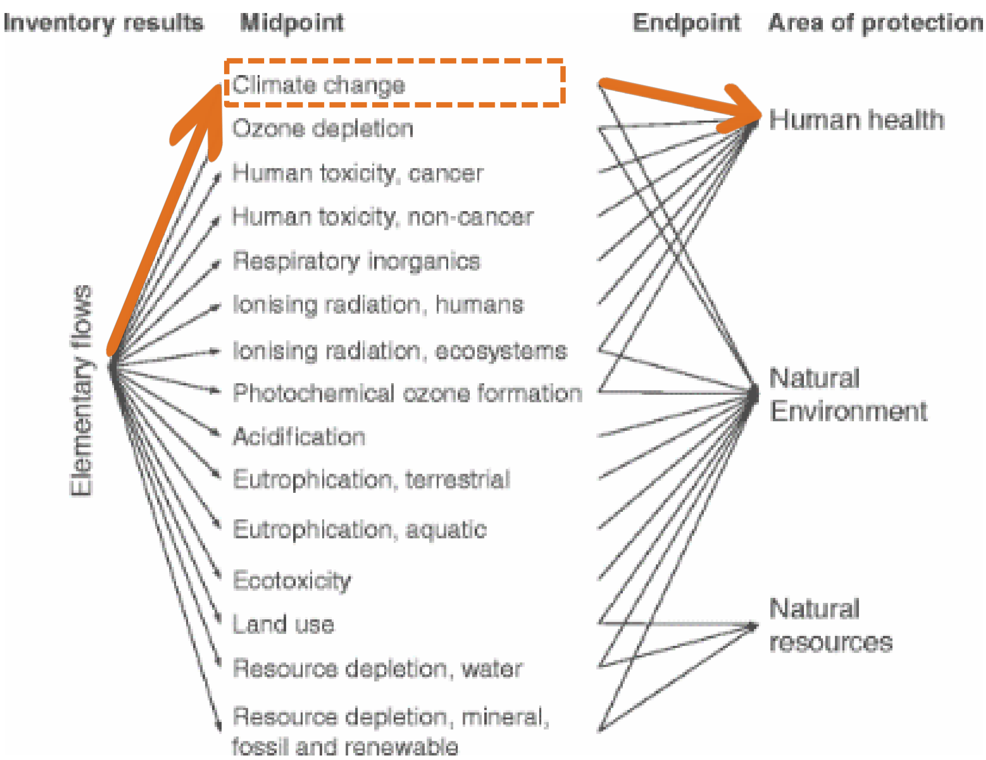

Figure 67. LCA transfer of pollution and emission inventory data to human and ecosystem health endpoints resulting in numerical values adapted from Hauschild et al. (2013)

Nonetheless, facing the urgency of adequately monitoring and addressing humanity's environmental impacts should thus necessitate the use of different available and complementary tools and approaches for the variety of scales in which the complex societal challenges occur.

"The EU is the main importer of deforestation- related commodities" (EEA 2016a) and Irwin et al. (2022) found that the construction sector has the third largest global species extinction risk footprint behind the food and beverage and agriculture sector. They also found that especially European and North American countries are net importers of such extinction risk through national consumption (Figure 68). Häyhä et al. (2018) support this for the European context and found that in 2007, European construction, wood- and manufactured products have together consumed 30 Mha land, of which 23 Mha originate from outside Europe. This shows the effects of globalization and the geographical detachment of consumption and environmental impacts, possibly also tied to increasing wealth. Germany is one of the largest net importers of extinction risk and thus a significant driver of impacts abroad (Irwin et al. 2022). Hence, the question needs to be asked whether first world countries obtain a certain prosperity by the exploitation of other nations and ecosystems and even if not, how can they address their much broader responsibility if it is known to impact others along the supply chains?

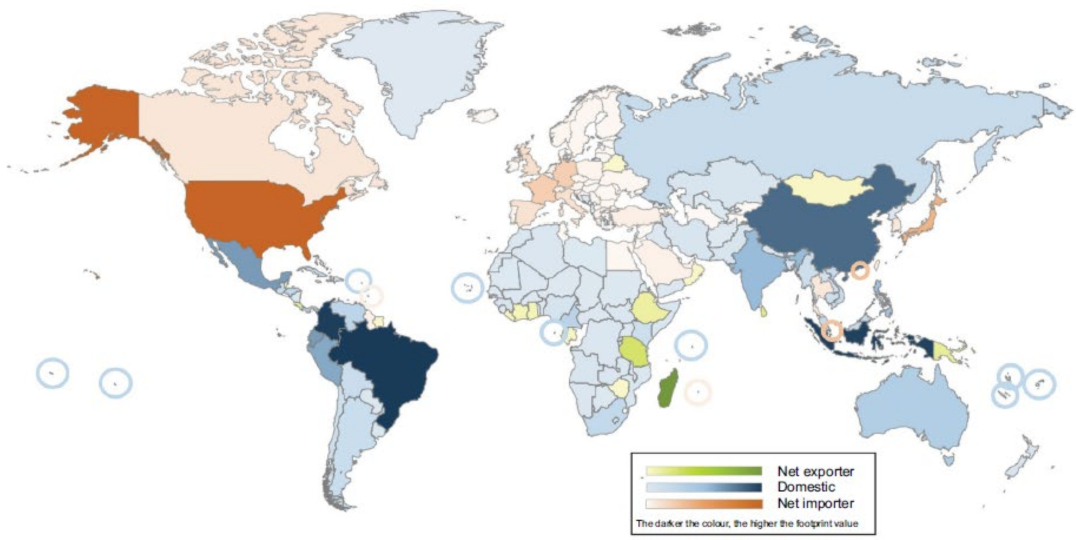

Figure 68. Species extinction risk profiles by country (Irwin et al. 2022)

These effects are somewhat already known to LCA's of building products. Dissecting an imported photovoltaic panel into its raw materials for example quickly demonstrates the global origins and subsequent impacts on several ecosystems abroad, before its operation is usually positively perceived for a transition to a renewable energy system (Figure 69). However, at what actual cost and damage to society's life support system on national and global scale?

Figure 69. Material import and its global supply chain. Graphic by (Bacheva, Pepin 2022)

Looking back at Europe's wood product consumption which induces deforestation in tropical forests of supplying countries such as Indonesia, a clear contribution to Indonesia's transgression of the planetary land boundary (53% of original forest cover left vs. 85% identified as planetary boundary) and thus conscious sacrifice of foreign livelihoods can be identified (Häyhä et al. 2018).

An LCA might be able to numerically value such environmental effects of products and their industrial supply chains on a global scale but the previously discussed tangibility is lacking. Taking for example DALY again to account for the human health at stake by cumulating midpoint impacts such as human toxicity or climate change impacts of a product or a building, there is only the information conveyed of having to reduce these values in midpoint impacts (Figure 67). However, there is no tangible '*how*' to achieve such, other than changing the initial inventory assessed by replacing components with alternatives which might score a little different in for example GWP which influences climate change impacts at the midpoint level. Still, even professionals warn that environmental product declarations (EPDs), upon which these environmental impact values for components are based, are rarely or hardly comparable because of possibly differing assumptions on the analysis boundary conditions despite European standardization of the general methodology.

This is where an equivalent land requirement of impacts can aid in this understanding for the BE because it more tangibly communicates how much area of a certain land type is theoretically degraded by a certain performance in GWP, acidification potential (in literature abbreviated as AP) and eutrophication potential (in literature abbreviated as EP). Thus, presenting specific amounts of area which could be gradually reduced as indicator for performance or would have to be offset for a net zero footprint of a project. Vollmer (2022) has developed and presents such LCA-based approach. Results show that the land demand is much larger (in the range of double digits) than the German case study building's plot.

The ESA approach can clearly complement these results by tying ES provision changes to these specific amounts of land. Thus, further detailing and communicating the impacts of a product or building throughout their lifecycle to more tangible direct effects on human wellbeing. Raising awareness for this fundamental degradation of people's life support system, also and especially, elsewhere is possibly addressing otherwise forgotten responsibilities and stewardship.

But even within the EU, land use change and deforestation as main drivers of biodiversity loss are largely attributed to urban expansions, infrastructure and foremost intensification of agriculture which is induced by the more than three quarters of Europeans living in urban environments (EEA 2016a; European Forest Institute 2021). Thus, there is a clear incentive for the BE to act, change and realize new ways to long-term sustainability.

5.4. Relevance for the realization of sustainable buildings

A change in perspective and approach is necessary because the current built environment (BE) discourses and focuses on climate neutrality, material circularity or change of mobility patterns do not suffice in tackling the complete spectrum of planetary boundary exceedances, although the BE and especially cities are the main driver and cause for the deterioration of human's life support system (see Chapter 1 Introduction). As a matter of fact, they will continue to do so because of the continued global population growth. Thus, the path to a sustainable, resilient and prosperous future is decided in the cities of the world and in the built environment that the profession creates.

People strive for equal wealth which, from an ethical perspective, they are entitled to. However, it would have devastating consequences for the foundations of global livelihoods, if the recently and continuously emerging urban communities around the world (Figure 70) were to develop and exhaust resources and natural capital similarly to Europeans (see Box 12).

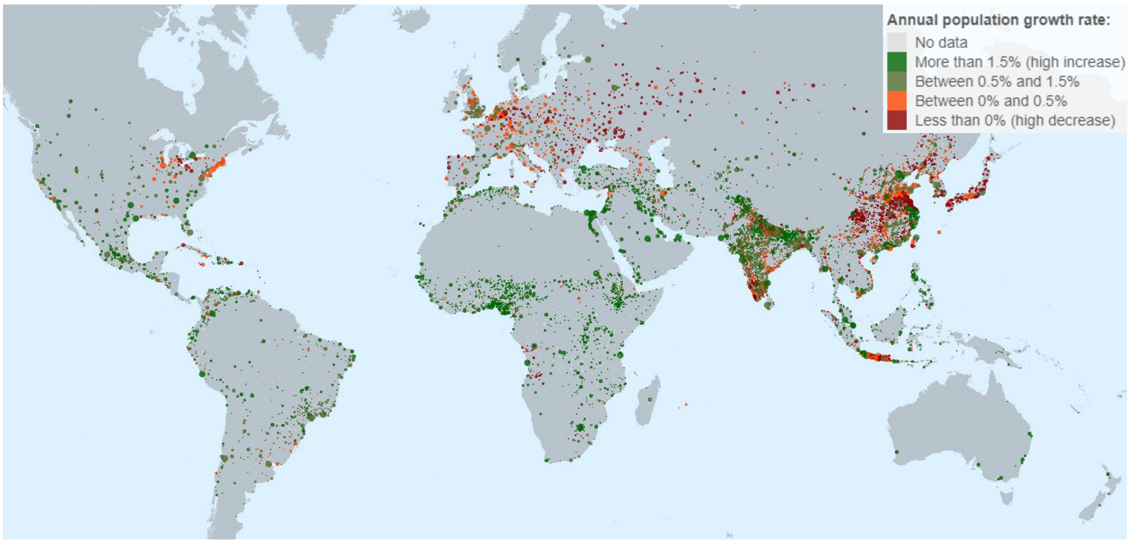

Figure 70. Population growth rate between 2000-2015 for metropolitan around cities worldwide. Adapted from OECD and European Commission (2022)

Box 12. Earth overshoot day

"Earth Overshoot Day marks the date when humanity has used all the biological resources that Earth generates during the entire year" (Global Footprint Network 2022c). This means the earlier the date falls within a year, the earlier the annual resources are exhausted. Together with 2018, the day in 2022 falls on the 28th of July (Global Footprint Network 2022a), as earliest days ever calculated which is 156 days earlier than the end of the year. The global population is currently requiring the biocapacity of 1.75 Earths and has generated 19-years of ecological debt over the last 50 years. (Global Footprint Network 2022d)

If all countries were to live like Germany for example, Earth Overshoot Day would land on the 4/5th of May (Global Footprint Network 2022b) (Figure 71). Countries which do not consume more than the earth can generate within a year do not have an Overshoot Day. However, almost three quarters of the world's population live in a nation which do and yet generate less income than the world average.

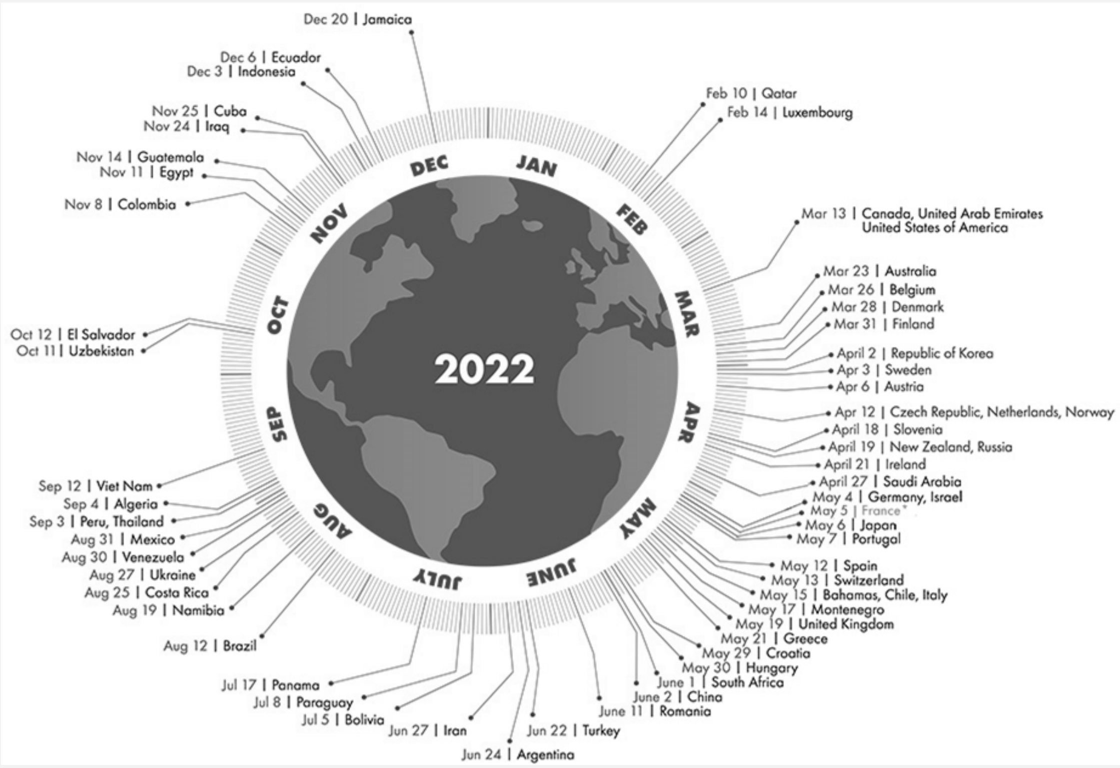

Figure 71. Country overshoot days in 2022 from Global Footprint Network (2022b)

Furthermore, Elliot et al. (2022) support that "Urban expansion encroaches on local habitats, while urban land teleconnections simultaneously degrade distant ecosystems." The authors further state that "These processes decrease the supply of and increase the demand for ecosystem services inside and outside urban areas [and that] Most cities are in a state of ecosystem services deficit, whereby demand exceeds local supply", which ties to the imported extinction risks by consumption for European and North American countries identified by Irwin et al. (2022). Thus cities as a landcover type in their current form are actually undesirable to sustain its inhabitants. Yet, there is a tremendously growing demand, also for ecosystem services. Elliot et al. (2022) expect that climate regulation and global habitat maintenance service deficits will increase respectively from 8%-214% and 11%-431% until 2050, which was representatively analyzed for eight European cities. The root causes have been identified to be dietary patterns and electricity mixes. Thus, even for business as usual (BAU), the BE profession needs to respond to these demands.

Nonetheless, having understood the dependence of humanity on nature’s services and the degrading characteristics of current supply systems to urban environments, it becomes clear that the BAU scenario is a shortsighted endeavor. Therefore, the development of European cities and growing built environments worldwide must not proceed as in the past but evolve towards net zero losses of natural capital and its regeneration for the sake of a stable and generationally just future. Alternatives need to educate and display another way forward, if only for the long-term benefit for the people for whom it is built.

Answers need to be found to the questions: “How can nations that still have expanses of largely unmodified or pristine habitats [/natural capital] achieve higher living standards without despoiling the environment and destroying these habitats in the pursuit of economic advancement? How can we link sustainable development with environmental conservation?” (Osborne 2000)

On the 28th of July 2022, which coincided with Earth Overshoot Day (see Box 12), access to clean and healthy environments has been declared a universal human right (UN News 2022). How can the BE justly fulfill this right, if it evidently violates the resolution?

Answers to these questions imply a critical review of traditional practice, addressing deficiencies and taking position against all far reaching adverse consequences of construction known to date. This process starts first with ***transparency on all the impacts*** and losses generated by practice and its building actions. It is the key which enables the desired structured and targeted ***optimization on all fronts*** to ideally accomplish a reversal of adverse effects and ultimately bring about positive contributions and a regeneration ability through an ‘ecosystem approach’ (see Glossary).

The presented novel ecosystem service assessment (ESA) achieves exactly that.

I. ESA measures ecosystem services (ES) as societal foundations of human wellbeing. This allows the recognition of and spatial planning with these services (Považan et al. 2021). This ability to work with societal foundations and the subsequent direct tangible relation to the human benefit is especially relevant for masterplanning and is not, or only isolated, possible with currently existing tools and skill sets. See for example the working with '*disability-adjusted life years'* (DALY) in lifecycle assessment (LCA) as described in the previous chapter or a microclimate analysis identifying the temperature regulation abilities by trees through simulation. The ESA approach not only measures one but the total range of benefits to people from nature which is also desirable from a valuation perspective (see Chapter 2.5 Ecosystem service valuation).

   "a detailed and thorough understanding of the spatial and temporal dimensions of multiple ES […] could support urban planners in decision making about the location, purpose, and management of greenspace; the potential augmentation or replacement of grey infrastructure with [green infrastructure] GI; or support trade-off analysis when making difficult choices about competing potential land uses. In addition, ongoing monitoring of ES flows would give planners valuable feedback about the environmental impacts of planning interventions to inform future planning and management." (Thompson et al. 2021)

   Ultimately, "planners must understand the spatial distribution of the impacts [both positive and negative] of urban infrastructure, beyond [a project's immediate vicinity or] municipal boundaries [and account for transnational impacts]." This is to identify the optimal mix of solutions to meet growing local and global service demands (UNEP 2022).

II. ESA evaluates negative but also positive impacts on the societal foundations for human wellbeing by assessing the changes and causes in ES provision. This permits also the improvement and re-design of projects based on services provision performance by its integration in the design process, as it is similarly conducted for daylighting or energy performance.

LCA is the only known tool to the BE which is theoretically capable of similarly assessing the total range of environmental impacts for human health and, subsequently, able to optimize design accordingly. Yet again, it cannot tangibly communicate the direct gains or losses to human wellbeing within a design process or strongly leverage the endpoint interest for meaningful and widely understood optimization (see Chapter 5.3.5). This is also because it is not practiced, nor designed, to reverse its usual assessment order and meticulously analyse from endpoint impacts like DALY for human health back to the various individual sources in the inventory, such as global warming potential (GWP). Even if so, for such use the question for the designer would remain '*how can the specifically assessed design improve its performance in contributing to human wellbeing (for which there is the economic incentive) based on this very global information?*'

III. ESA provides the means to set quantitative benchmarks on ES provision and uptake in socio-economic decision making by indicating societal monetary gains and losses associated to a service provision change, based on scientific studies (see Chapter 5.2). Moreover, this also enables investors in and developers of ES provision projects to concretely discuss their (planned) societal contributions if certain costs limit their further implementation and if financing mechanisms need to be found.

Additionally, "While urban natural capital [and ES provision, as promoted by blue and green infrastructure,] is largely recognised as a positive element, its benefits are difficult to measure both in space and time, making its inclusion in urban (re)development difficult to justify" (O'Keeffe et al. 2022), especially if considered to only be 'a nice to have' because of its valuable space, which seemingly would otherwise yield more (monetary) returns on investment considered from a traditional point of view.

This aligns with the challenges for nature-based solutions (NbS) which "can play a major role in achieving the 'triple wins' of increased environmental, social and economic sustainability" (UNEP 2022), but require a quality assessment. NetworkNature (2022) outlined climate change mitigation and adaptation, tackling of biodiversity loss, the generation of societal benefits and their equal distribution as well as local applicability as main quality criteria. ESA provides the performance information for these criteria for successful implementation and scaling.

IV. ESA engages societal participation as main stakeholder and beneficiary of human wellbeing contributions (Považan et al. 2021). This can lead to increased acceptance, support and success of ES provision projects. Reporting on ES provision performance can also become an important driver and positive feedback loop for the BE sector to continuously increase contributions to the foundation of human wellbeing. This is the case because especially local people are empowered to exert public pressure on those projects which prioritize their own private short-term interests instead of suitably accounting for the communal good.

V. ESA also permits the delivery of argumentative results to the seldomly asked, though primary, question: '*Should be built and developed at all if an overall value contribution to human wellbeing cannot be demonstrated?*' How the BE builds does not really matter, if the initial fundamental question is not thoroughly analyzed and overlooked in decision making.

This sheds also a different light on the rightful discussion to prioritize existing buildings over new builds but, as discussed (see Chapter 5.3.5), also the nevertheless used, mostly new, building materials have an origin and foreign human wellbeing impact through extensive ecosystem degradation before a building's construction lifecycle phase. This equally holds true for increasingly using timber over non-renewable materials in regards to human lifetime. The cyclical deforestation for wood products from ESA perspective becomes questionable because (pre-) existing ecosystems and subsequent services provision are likely to not be obtained.

It is a paradox that humans deforest and convert natural forest ecosystems because "natural ecosystems have properties that humans desire […] [but] farmers [must] labor to restore or maintain these same soil properties." (Bermingham et al. 2005)

These ES provision impacts need to and can be transparently identified and communicated to examine the same bottom line to make informed and mindful decisions on how is built, if it is decided to build.

VI. ESA does not only account for biodiversity loss but through the ES concept brings different aspirations and expertise together. Examples of these are restoration, wildlife inclusive design or nature conservation as a whole. This results in significant synergy and convergence effects through acting on the naturally coupled three domains biodiversity, climate and human wellbeing.

In order to achieve nature-positive cities, indices such as the IUCN Urban Nature Index (UNI) are developed. The UNI for example is based on the Singapore Index on Cities' Biodiversity (CBI), which was endorsed by the Convention on Biological Diversity (CBD) (Catalano et al. 2021; CBD 2022), and they are tools to monitor biodiversity conservation progress (WEF 2022). Despite being certainly helpful and necessary, these do not resonate with the majority of BE stakeholders which would ideally be concerned with its implementation, unless they specifically get a brief which demands a biodiversity performance. Since this is often not the case yet, a pathway over ESA opens a greater opportunity in tying ecological optimization, as a necessary background, to targeted current interests and briefs of decarbonization, urban heat island mitigation, ambient cooling, stormwater management or air purification as nature's benefit to people. Another barrier which the ESA approach bridges, contrary to the index tools, is supporting the process of finding and implementing the right solutions to achieve set targets.

VII. ESA evaluates construction interventions and strategies on their expected ES provision performance and therefore aids in their targeted optimization and implementation. This has been described before and shown for nature-based solutions (NbS) (see Chapter 5.3.3) but it also applies to guidelines such as the sustainable infrastructure principles by UNEP (2022).

Definition: Sustainable infrastructure

"Sustainable infrastructure [SI] systems are those that are planned, designed, constructed, operated and decommissioned in a manner that ensures economic and financial, social, environmental (including climate resilience), and institutional sustainability over the entire infrastructure life cycle. [SI] can include built infrastructure, natural infrastructure [such as actively managed GI like forested urban parks] or hybrid infrastructure that contains elements of both [like green roofs] […] NbS are not limited to infrastructure but are highly relevant." (UNEP 2022)

The ten guiding principles on SI, of which seven are clear outcomes of the ESA approach, target the before described strategic planning with resilient service provision, understanding and avoiding environmental impacts, evidence based and participatory decision making, but also comprehensive life cycle assessment and promoting local equity by ES provision.

Thus, ultimately, solutions are created for already current 'sustainability' oriented brief requirements, while simultaneously establishing transformational projects, which already target the core challenges and source problem within the built environment by concurrently addressing different strategies and goals of local, national or global importance.

Practically using and learning from the ESA has multiple outcomes for building practice.

A. It is understood that "plants provide a complex living framework of habitats for a phenomenal variety of animals" (Osborne 2000) which together create an ecosystem's structure. This structure and its biodiversity are responsible for the functioning and resilience of the system which provide the ecosystem processes (EP) for ES delivery.

B. "The best way to conserve species [and thus services as foundations to human livelihoods] is to ensure that ecosystems continue to have the same structure and function" (Osborne 2000) which should thus be a clear goal for the creation of urban environments and ecosystems. This could be termed '*ecological sustainability*' which "seeks to preserve the normal ecological processes and functions that occur within ecosystems" (Osborne 2000). This displays once again that this ES perspective gives urban agendas an entirely different focus. While positive that there are biodiversity strategies for cities (see for example Landeshauptstadt München 2019) and biodiversity targets in sustainable building certification schemes (see for example DGNB 2022), there is no respective benchmarks of what is, or has been historically, and should be provided at a minimum from an ES perspective. This displays the disregard of a societally important reference at the cost of adequate performance and contribution to human wellbeing.

C. Thus, "Adverse environmental impacts from infrastructure [and the BE] should be minimized, and […] Construction should be avoided in areas important for the persistence of biodiversity or having high ecosystem service value." (UNEP

2022). This ties to the argument of requiring and being able to achieve an initial transparency, to be capable of identifying capitals or reduction measures. The UNEP (2022) supports targeting zero net losses of biodiversity as a minimum requirement in the project design phase and encourages a biodiversity net gain as goal.

D. “The threat [,] a change [/disruption or impact] poses to [bio-] diversity depends crucially on whether or not the ecosystem has frequently experienced that change in the past – in other words, on whether or not the ecosystem is ‘designed’ to cope with that change.” Thus as also suggested by Bermingham et al. (2005) a cutting or non-reducible impact should make the effort to mimic natural disturbances (see succession and forest recovery cycles in Chapter 4.3.3). The average tree composition and mortality rate of 1-2% (Pfadenhauer and Klötzli 2020) can be of guidance. However, this is far from current primary forest loss rates of 10,6% in Indonesia for example in 2021 (GFW 2022), which can be mainly attributed to other human demands such as large-scale oil palm and timber plantations, conversion to grasslands and small-scale agriculture and plantations (Austin et al. 2019).

E. Mimicking entire ecosystems with a building and construction practice should enable a pathway towards net zero impacts. This might never be attainable in relation to its pristine reference, but it progresses towards a co-development with nature and a BE ability to provide functions and services for human wellbeing as well as for nature. For example, there is a clear case for corridor connections to diminish adverse effects on population decreases and biodiversity loss caused by habitat fragmentation. Osborne (2000) reports on a study for bird populations of tropical forests for which 100-300m wide forest corridors where identified as a suitable size. Even though the BE might not be able to replace these forest corridor environments, practice can move closer to attaining similar suitability by addressing for example only the habitat provision service requirements outlined in this work and qualitatively contribute and expand these corridor networks as also suggested by many biodiversity strategies.

F. Moreover, this means aligning with identified natural cycles. Besides disruption patterns as in treefall, this concerns resource flows such as natural nutrient rates (see Chapter 4.3.4) or reproduction through for example mast flowering events (see Chapter 5.3.1). However, especially interesting is the aspect of regeneration which is supposed to be an important element of the circular economy (CE) for its conscious use of materials (Casiano Flores et al. 2018). Stahel (2019) states that a CE “seeks to rebuild capital, whether this is financial, manufactured, human, social or natural”. Biodiversity shall be structurally supported and enhanced as outlined in pillars for the CE (Metabolic 2019). Yet, a pursuit of circular strategies, that are currently available to the BE, does not achieve an ecological regeneration of natural capital nor does it protect biodiversity. It can rather only replace new demand and strain on natural resources by (re-) using materials which are kept in a circular material system instead of being discarded.

For example, as to be seen in simplification (Figure 72), a tree undergoes a natural cycle in which it fulfills multiple ecosystem functions. However, the derived human construction product timber has distinctive different functions throughout its product lifecycle and is solely purposed for the human need. At the end of the product lifecycle of timber, it is mostly incinerated or unusable for a natural decay, while this is a precondition for regrowth and closing of the natural cycle for a tree. Thus there is no merging between the two lifecycles, which means that none is able to, at least, partially replace the other. This, nonetheless, would be necessary in order to accomplish a regeneration of resources or co-development.

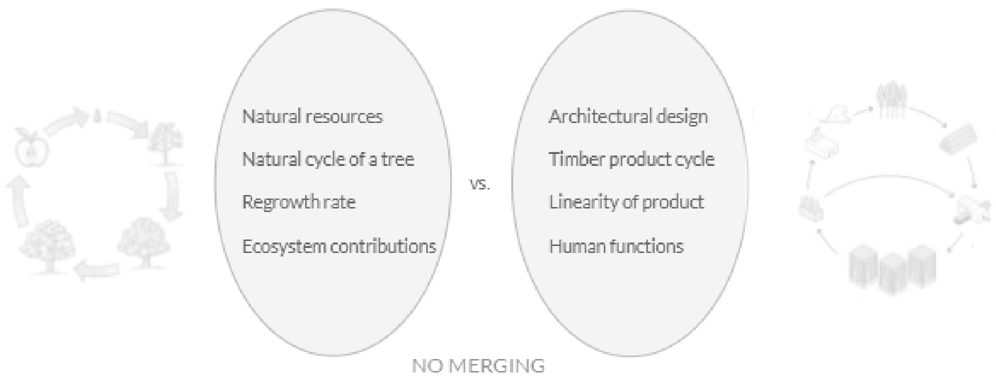

Figure 72. Exemplary natural resource cycle and human product cycle in comparison. Images on left and right adapted from Brock 2008 and Brasington 2018

This is also not the case when reviewing currently emerging, though not common, circular economy strategies within the BE context (Figure 73). These are solutions to prolong the industrial product lifecycle, aid in the formation of innovative business models and more efficient handling of used resources, but do not deal with the root problem of a separation between human resource use and natural cycles.

BE CE strategy	Description	Focus & Result
Design for deconstruction	Dismantlability of construction products, i.e. no glued or welded connections	Reduction of demolition waste, prolonging product lifespan
Renting schemes	i.e. lighting as a service with monthly payments per unit lux instead of purchasing complete lighting systems with self-maintenance	Improving product efficiency and quality
Buildings as material banks	Building products or elements retain some of their value by being reusable and purchasable at a later stage of their lifecycle	New business model, shifting costs

Figure 73. Circularity strategies within the built environment

G. Nonetheless claiming to build with a positive footprint and for the health of people is in light of ESA clearly unachieved, a distortion of reality and deception of the public because accomplishing a net zero balance footprint is still of theoretical nature. The BE can only begin to understand how to fundamentally change building processes and outcomes for the health of nature and thus actual contribution to human wellbeing.

It is time for humanity and especially the BE to reorganize and act upon the knowledge of its impacts and to justly fulfill the role of building for human wellbeing and for a truly sustainable future for the generations to come.

“Natural capital [should be] enhanced to the greatest degree possible […] [and] The development of physical infrastructure should seek to complement or strengthen, rather than replace, nature’s ability to provide services such as water supply and purification, flood control and carbon sequestration […] [and] Investment in preserving and enhancing natural capital and ecosystem services should also be considered even when there are no immediate and direct social or economic benefits” (UNEP 2022)

This is because the ES perspective will stand the test of time, since it represents the immediate needs which the inhabitants and stakeholders to the BE depend on. With progressing climate change and increasing global populations, natural resources will only become more scarce, also due to socio-economic insecurities caused by crisis such as pandemics or international conflicts. ES deficits are likely to be a similarly concerning topic as the national energy security is for Germany (Bundesregierung 2022) or the reduced supply of basic food provision globally due to the war between Russia and Ukraine (Statistisches Bundesamt 2022) in 2022. However, the significant difference being that an ES provision scarcity cannot be solved by imports if it has become a global issue. Thus locally investing in self-sufficiency and resilience in ecosystem services supply to match ES demand, equates assurances and stability for future uncertainties.

6. Discussion

This chapter elaborates the limitations of the two presented approaches. This mainly applies to the limited datasets available for measuring mostly only one of the many suggested indicators for an ES and the coupling of representative monetary data. Nonetheless, a framework has been provided with many possibilities for new research and interdisciplinary extensions as detailed in the outlook of this chapter.

6.1. Approach One

In the Indonesian case study, the ES food provisioning is interestingly higher in the urban environment compared to the reference tropical rainforest location on Borneo. This is likely due to the chosen dataset ‘Crop Suitability’ of the UNBL platform and its setup. It considers the sixteen most important food and energy crops based on climatic, soil and topographic conditions paired with currently irrigated areas (Zabel et al. 2014). Most significant for the deviation in both environments however,is likely the topography. Whereas Jakarta lies in the flat lowland watershed of higher elevations to the south, the Bornean location directly borders such higher elevations and drastic topographic changes to the northwest (Yamazaki et al. 2017). The dataset by Zabel et al. (2014) ties an increasing slope to decreasing suitability which is probably the main cause for the identified difference. However, this identifies an important shortcoming in the match of the dataset and ES analyzed because the dataset does not take the actual built-environment into consideration. This means that the sealing of urban areas is not accounted for and this dataset rather enables a hypothetical suitability comparison of locations in disregard of their actual development state as long as climatic, soil or topographic conditions are not affected. Thus, the use of this dataset for the intended purpose for investigating this specific ES is inadequate. This limitation therefore also applies to the German Campus Garching case study for food provision service. This emphasizes the importance of validating and matching the right data sources with the ecosystem services that are quantitatively assessed to achieve meaningful and correct results. Nevertheless, the quantification has been further used to generate results because monetary data is available for this service which extends the exemplary display of the practicability of the presented framework and approach as main goal. This is especially due to the fact that only the quantitative trend analysis is noticeably affected to become aware and discuss this shortcoming and proceeding with caution in initial setup of the assessment. However, the monetary coupling and results are not significantly affected by the ES due to its minor economically valued role in both case study contexts in comparison to the other three ecosystem services that have been measured and monetary valued.

The currently chosen UNBL platform is moreover limited in providing data for a comprehensive range of ES, as to be overserved in Table 3 (p.71). Furthermore, it lacks the variation of data which is often required to establish a more representative condition for the provision of one ES by a variety of indicators (see Table 2. Primary and secondary indicators for three supporting ecosystem services, p.53).

Nonetheless, the suggested assessment approaches can be further detailed and informed by other datasets from ES modelling and assessment techniques such as TESSA, ARIES, InVEST or MIMES. (Peh et al. 2013) and (Neugarten and Langhammer 2018) describe and compare the different tools while the latter authors also provide decisions trees for their selection based on mapping, valuation or output intents. The use of these tools and generation of own location specific data has been out of the scope of this research.

Connecting the evaluation data to the ES introduces other inaccuracies by matching related valued ES to increase the assessable basis of investigated services. For example, valuations for habitat provision, nutrient cycling and primary production are retrieved from values for maintenance of genetic diversity, maintenance of soil fertility and provision of raw materials respectively which are strictly speaking not the same ES investigated. Nevertheless, they are associated to each other by the ES categories hierarchy (see Chapter 2.2). Habitat provision, nutrient cycling and primary production are supporting services to the services that have been valued by the ESVD. This subsequently means that the monetary data on maintenance of genetic diversity, maintenance of soil fertility and provision of raw materials is a secondary indicator for and a partial valuation of the supporting services assessed, validating their use for indicative means.

This once again points out, that as mentioned, the valuation should not be taken too precisely and is at most an indication of the lowest known value attributed to a service.

Also due to the fact, that this database has only a few data records upon which the mean standardised values are based, especially the more specific filters are applied. Therefore, during the conduction of steps the different values for different regional scales are showcased which identify large deviations despite valuing the same biome. Naturally, complete biome specific valuation data on national is the most preferred but as in the assessed Garching campus case, this is not always possible yet. However, as also previously mentioned this procedure is meant to rather illustrate and inform about the implications and trajectory of practice at large. Furthermore, the more sophisticated and extensive the database develops due to progressing research, the more founded and complete valuations will become, even for specific continents and regions or nations.

Besides, if there were monetary valuation data on ES provided by urban environments this could and would have to be subtracted from the monetary difference. The ESVD does not provide such data, merely but also limited on urban green and blue infrastructure. This valuation is seen as irrelevant to this approach due to the previous geographical data measurement step which should identify, display and account for such infrastructure benefits in the consequently measured and used data.

Even though the selected databases do not cover the full extent of diverse data demands, this is acceptable because the goal of the quantification and valuation is of indicative nature and nevertheless adequately displays current abilities in translating concepts and research into usable information for practice. More so because there is no other readily available and more broad data platforms such as the UNBL and ESVD to the authors knowledge. Thus the only alternative to the incomplete ES data would be to not use any, which does not aid in the development of such quantification methodologies nor does it offer partial answers to the immediate demand for improving the environmental performance of the BE.

The approach enables a temporal analysis of development through history if actual data is available (i.e. short-term, few years back, already measured) or previous conditions are known (i.e. biome type, extent and quality) to which similar current sites can be identified for comparison. The latter case has to document this similarity for validating consequent results. For the Garching campus case, this similarity of historic and current Bavarian temperate forest has only been assumed through written historic records but could not be validated.

After all, the UNBL platform opens a theoretical opportunity to quantify and monitor the disturbances and reductions in ES provision caused by human activity with the monitoring data available. A correlation to the inverse effect of for example night-time light, deforestation and terrestrial anthropogenic pressure would have to be shown but could be detected by the VIIRS Nightlights, Global Forest Change and Human footprint datasets respectively.

6.2. Approach Two

The investigated design does not resemble the usual urban design and is thus only partially representative because most of the associated activities match the standard definition but are likely to vary in their extent for city developments. On the other hand the analyzed design already includes desirable local material based construction and illustrates already smaller scale project impacts as origins of faulty construction practice.

Furthermore, in the ecosystem service profile definition the priority lies on understanding and simplifying the general workings of an ecosystem. Due to its complexity and ongoing research to close large knowledge gaps, this is of course only possible to a limited degree. For example it is still uncertain what the relative significance of top down or bottom up processes in tropical ecosystem and synergistic effects of interactions, composition and pressure drivers is (Fayle et al. 2015). Nevertheless, as previously mentioned, it was tried to recognize overall patterns to enable an operability of the currently available and agreed upon knowledge for use in the BE.

Due to the scope of this research, the shown approach is limited to one specific biome, the tropical rainforest and its primary EP resulting of the specific BS. Thus, if EP's do not match, it is not possible to transfer insights, even if the same construction activities are assumed. This becomes clear when viewing for example a mangrove or reef, which are in the immediate proximity of and interlinked with tropical rainforest's on island. It would be ideal to also identify the impacts on these ecosystems as transient parts of the supply chain to building. However, these might have different EPs and certainly fundamentally different BS characteristics and species which are responsible for the provision of the same ES. In the case of a reef, the habitat provisioning service might still anchor on the same identified EP's (shelter, space, food and water) but their functioning is derived from an entirely other BS centering around coral layers. Similarities might be drawn if similar construction activity impacts can be identified but a direct transfer is not possible. Therefore, to understand the impacts of a design proposal on another ecosystem or biome requires specific research and validation by interdisciplinary exchange with biologists or ecologists again.

Lastly, the approach misses the social & economic system dimension which would extend insights on the qualitative ES changes by valued consequences tied to a proposal's design. Therefore, another body of research could focus on measuring the qualitatively identified impacts with the scientifically established ES indicators (see Chapter 2.4) and couple this information with i.e. the available monetary data as in approach one.

Hence, despite these current limitations, this research provides the framework for further development over time and ability to comprehensively analyze environmental impacts and stewardship from an ES perspective.

6.3. Outlook on further research

New research based on the presented two methodologies (Figure 74) could include the quantitative assessment of other case studies by looking at different cities, urban scenarios, settlements but also different biome contexts because for this high-level analysis no further ecological knowledge is necessarily required.

For the qualitative assessment different design proposals could be chosen and another set of ecosystem services, perhaps also from the other categories, be investigated. Further research into improving green roof or façade interventions for ES provision and the review of other NbS or ecosystem based adaptations, especially throughout lifecycle stages before and after operation, is undoubtedly still outstanding.

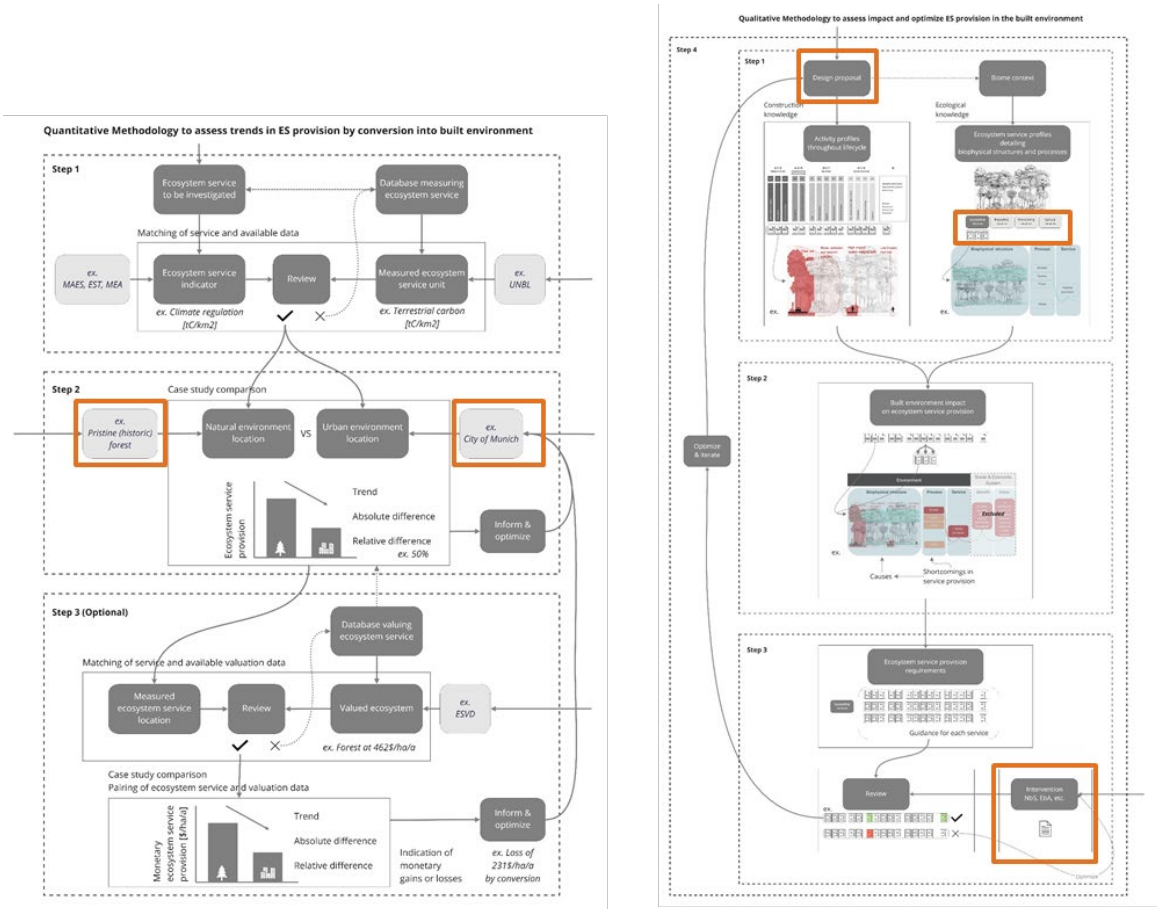

Figure 74. New research based on the presented two methodologies

In terms of improvements and extensions to the presented methodologies (Figure 75), firstly, the generated (societal) real estate value of development could be compared to the monetary indications resulting from the quantitative assessment. Current construction briefs focus on useable floor area for retail, offices or housing which unmistakably are the economic drivers for most building projects. These expected revenues by development, even though accruing to only a few stakeholders, do not materialize in ESA but are the primary incentive for converting sites. Thus, comparing them aside each other might also identify potential synergies where an increase of an ES yields also positive returns in real estate value. One of the examples based on Evans et al. (2020) findings would be the provision of recreational green spaces as cultural service which increases property and rental values by 9.5% and 7% respectively.

Other, previously discussed detailing of ES profiles and valuation extensions to the design impacts on ES provision and potentials of NbS would help deepen insights for the qualitative assessment.

Useful and easily integrate-able would also be a review of city, regional or national strategies and goals with the insights generated by both methodologies. This could also help identifying convergences of efforts and ideals and aid in the process of matching tangible projects by the BE to achieve funded targets which in turn could beneficially create funding mechanisms across different departments with focuses on climate change, biodiversity or innovation for instance. Knowing of such opportunities might enable an increased implementation and willingness to optimize for ES provision when reviewing city masterplans or design proposals.

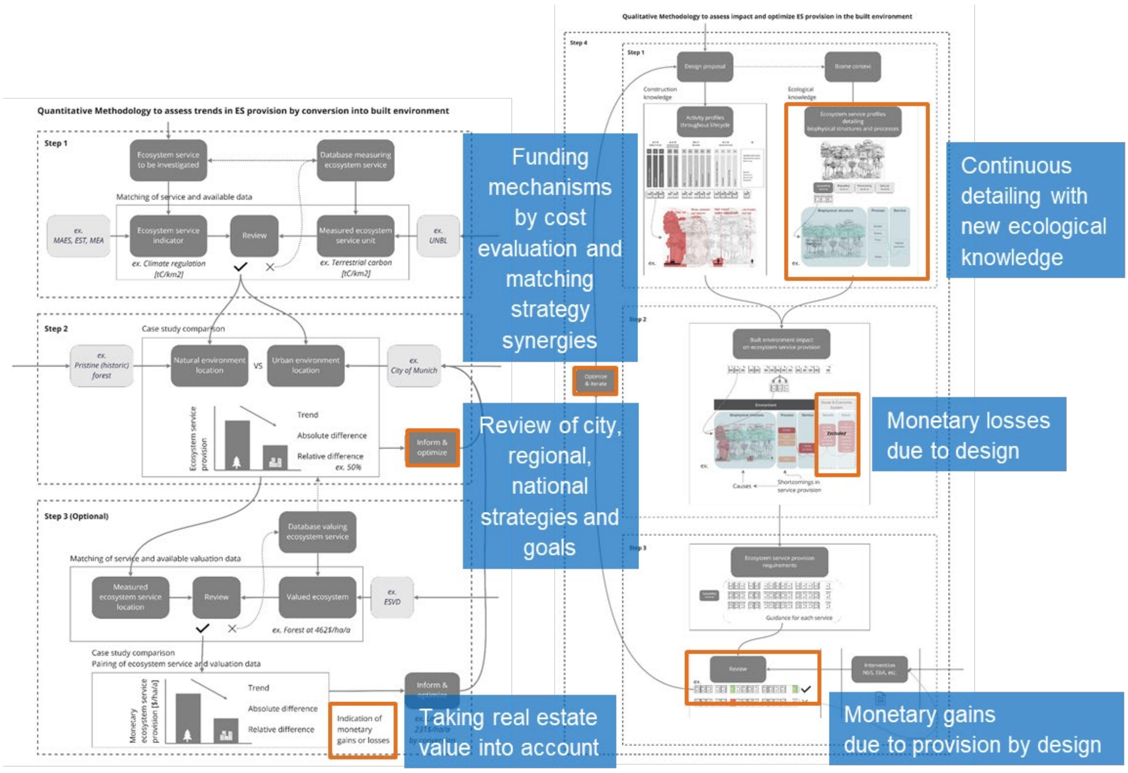

Figure 75. Improvements and extensions to the presented methodologies

7. Conclusion

This thesis aids in the understanding and novel working with ecological knowledge through the development and exemplary execution of two ecosystem service assessment (ESA) approaches. The described qualitative approach guides the process to obtain the necessary information to identify suitable actions to act upon ecosystem service (ES) impacts and provision requirements. As an important result of this research, independently of being lifecycle specific or generalized in a checklist, these requirements clearly communicate the shortcomings but also abundance of opportunities to improve construction activities and design.

Simultaneously, it enables the review of specific interventions and their expectable quality of ES provision. Nature-based solutions, such as the green roof and façade discussed here, carry high expectations on their contributions to biodiversity and ecosystem services supply. Nevertheless, they do not realize their full potential in becoming key ecologically regenerative elements of practice yet.

The exemplary ESA over the entire building lifecycle identifies the detailed construction impacts on the structure of investigated forest ecosystems and solidifies that the built environment (BE) practice currently lacks the necessary ecological understanding to safeguard the living conditions for mankind in the face of the multitude of planetary challenges. These are the unaddressed sources which subsequently cause the adverse consequences on human wellbeing and produce societal deficits. Moreover, these already begin with the outset of human settlement development and not purely because it is built but remarkably how is being built.

The results of the presented quantitative ESA further underline that the built environment deteriorates the biosphere and changes the provision of ES upon which societal livelihoods and prosperous futures depend. In contrast to a 'positive building' paradigm for human wellbeing, the conversion of natural to urban environments significantly decreases overall ES provision and incurs also monetary-measurable societal deficits. This shows that the construction of man-made environments has other drivers which do not account for people's life support system. Particularly the losses accrued in decreasing the climate regulation service contradict pledges to decarbonize the BE sector and actively address climate change. Reducing and offsetting operational and embodied carbon are absurd if carbon sinks are lost in the first place which manifests the need to fundamentally transform practice targets and the adjustment of urban agendas with an ES perspective.

In spite of its limitations, the developed work stream of the quantitative approach offers a basis for easily accessible ES data interpretation and benchmark setting with global coverage which – with further progress of each component and contributing domain – will only become more complete, accurate and representative for high-level spatial analysis and planning.

Complexity and knowledge gaps are unavoidable in this interdisciplinary knowledge transfer. However, this attempt of making available scientific understanding accessible and actionable displays its suitability and manifold benefits for the BE practice. Especially because, active stewardship of nature and its ecosystems is indispensable, the BE has the urgent responsibility to rebuild a resilient biosphere and reconnect it as foundation to anthropogenic development.

In conclusion, this thesis presents the blueprint for the transformation process to holistically address multiple societal challenges and goals by utilizing the built environment nexus to tangibly plan and construct for ecosystem services provision, consequently increasing resilience and benefits to human wellbeing.

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Appendix

	Valuation method families				Considerations for valuation by IPLCs
	Nature-based valuation	Statement-based valuation	Behaviour-based valuation	Integrated valuation	
What is assessed? What is the source of information	Nature, physical or ecological components of nature and nature's contributions to people	What people say or express when asked about the importance of nature and nature's contributions to people	What people do in nature, for nature, with nature, to nature or nature's contributions to people	Different outputs from one or more methods to support decision-making	Indigenous peoples and local communities gauge nature and its interdependencies with people by also gathering information from ancestors, future generations, non-human beings, the cosmos and the spiritual world. Information gathering through territory patrols, natural resources monitoring or communal assemblies can entail rituals and ceremonies undertaken by specialized traditional experts. Valuation is often a collective process that considers all members of a community (including children or those who are not visibly present), as legitimate generators of information. Understanding the richness and depth of indigenous peoples' and local communities' valuation approaches implies deconstructing disciplinary definitions of methods and concepts such as 'evidence' and recognizing that integration of knowledge systems is not always possible, desirable or necessary.
Examples of methods and approaches	Biodiversity inventory, ecosystem services mapping, Delphi method, participatory mapping of ecological values	Group discussions, Q-methodology, contingent valuation, choice experiments, deliberative methods	Participant observation, travel cost method, cost-based methods, hedonic pricing,livelihood dependence, photo-series analysis	Ecosystem service valuation, cost-benefit analysis, multi-criteria decision analysis, integrated modelling, scenario building, deliberative decision methods	
How is information about values generated?	Directly measuring nature, remote sensing, consulting experts Consulting users/ experts/local communities as knowledge holders	Asking questions to people (interviews, surveys), undertaking activities with people (e.g., discussions, games, art), analyzing narratives (e.g., twitter posts)	Observing people, assessing records of people's behaviors (e.g., park visits, house purchases), assessing records of policy choices, assessing (non-) market exchanges	Synthesising, comparing, contrasting, deliberating, consolidating or aggregating multiple values for decision making or decision support	
'Specific values' elicited and examples of value indicators	Mainly intrinsic and instrumental values Species counts, carbon stored, ecological health indicators	Instrumental, intrinsic and relational values Subjective well-being indicators, narratives of human-nature relationships, willingness to accept compensation for setting aside land, willingness to pay for access to nature	Mostly instrumental values Time spent, share of household income, prevalence of disease, price on a hectare of land, use of indigenous plants	Instrumental, intrinsic and relational values Strength of support or objections to policy options, welfare gains or losses from projects of indigenous plants	
Type of stakeholder inclusion	Inclusive methods exist (e.g., community monitoring of biodiversity) but most methods do not include stakeholders	All methods include stakeholders to some extent (e.g., surveys) and inclusion is often integral to the methodology (e.g., deliberative valuation)	Most methods have limited or no stakeholder inclusion (e.g., analysis of market accounts), but encompass observations of diverse stakeholders	Some methods can be non-inclusive (e.g., desktop multi-criteria decision analysis) but often, inclusion is key to the decision support aspect (e.g., participatory scenario building)	
Examples of typical valuation 'products'	Biodiversity indices, maps of pri-ority areas for policy/ management action Improved understanding of the importance of components of nature	Ranked importance of nature's contributions to people Monetary value for protection of areas of biodiversity significance Explanations for why people value nature	Ranked importance of nature and nature's contributions to people Additional costs due to degradation (e.g., changes in time to collect fuelwood) Explanations for how people value nature	Ranked policy options Evaluation of socio-economic and environmental impacts of policy options Improved understanding of conflicts/shared values of nature	
Limitations	Impact on people assumed but not assessed Dependence of nature is not assessed by those directly living from, living as and living with nature	Potential large variability in the reliability of statements (i.e., do people respond truthfully?) Power disparity can reduce the validity of group-based (e.g., deliberative) methods Representativeness in selection of respondents biases results	Requires conceptual and empirical understanding of the relationships between behavior, nature and its contribution to well-being Cannot reveal in-depth understanding of motivations behind behaviour	Aggregation of values across groups of people can reduce representation of values, combining multiple value types creates incommensurability concerns	

Figure 76. Overview of the four main valuation method families from IPBES (2022)

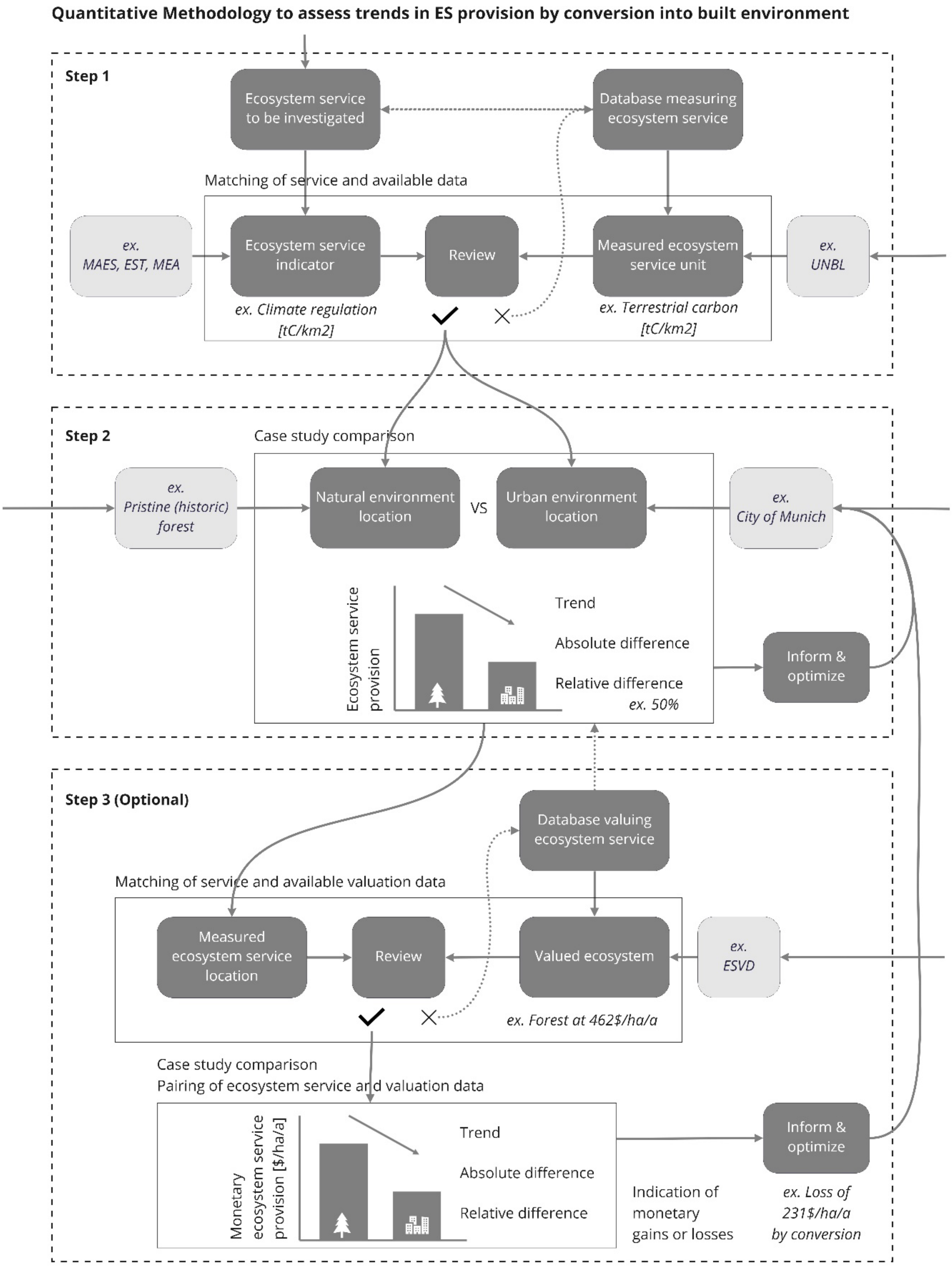

Figure 77. Extensive process diagram for quantitative ecosystem service assessment on high level with example steps.

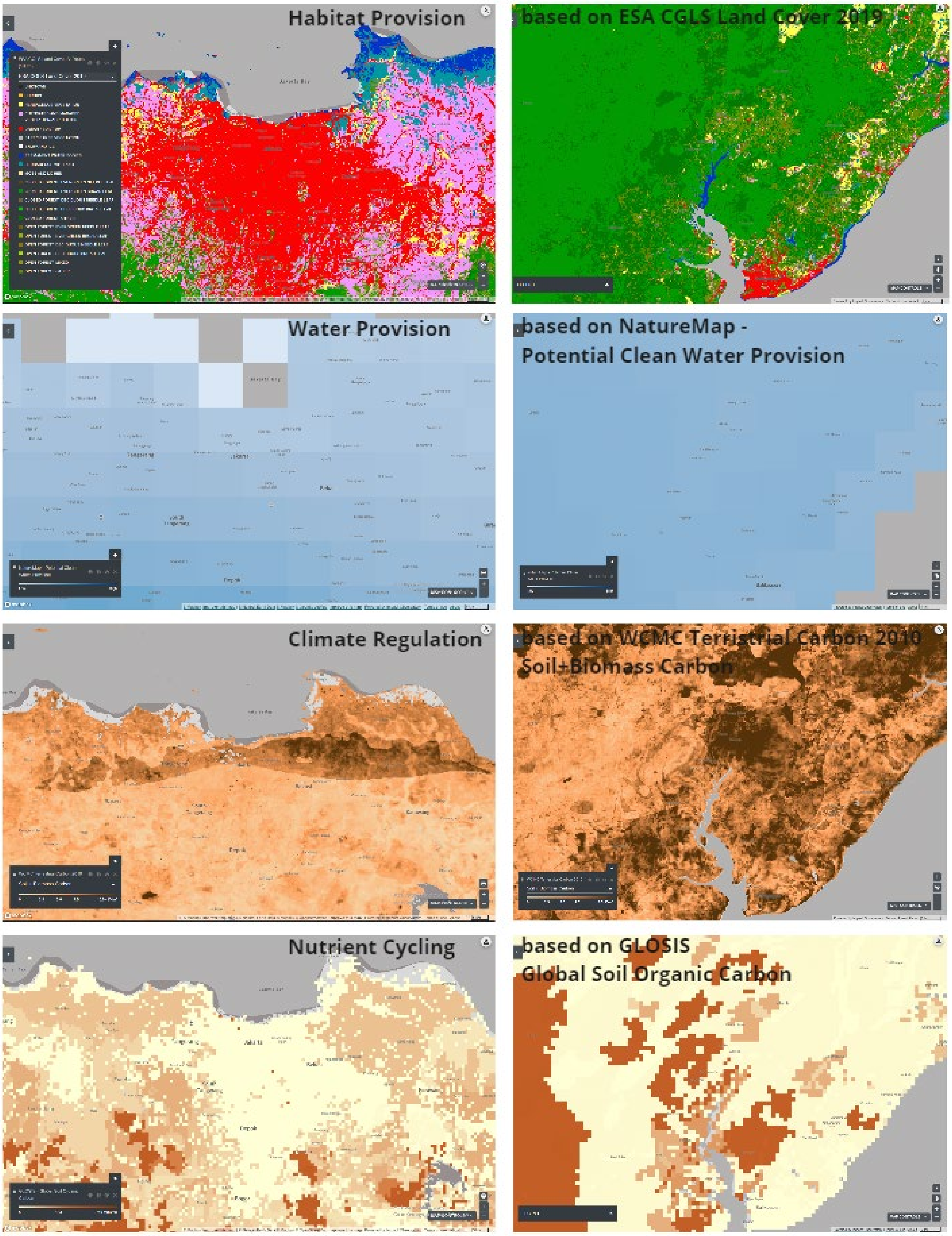

Figure 78. Remaining data maps used to measure ecosystem services for the Indonesian case study. Compiled and adapted from UN Biodiversity Lab 2022

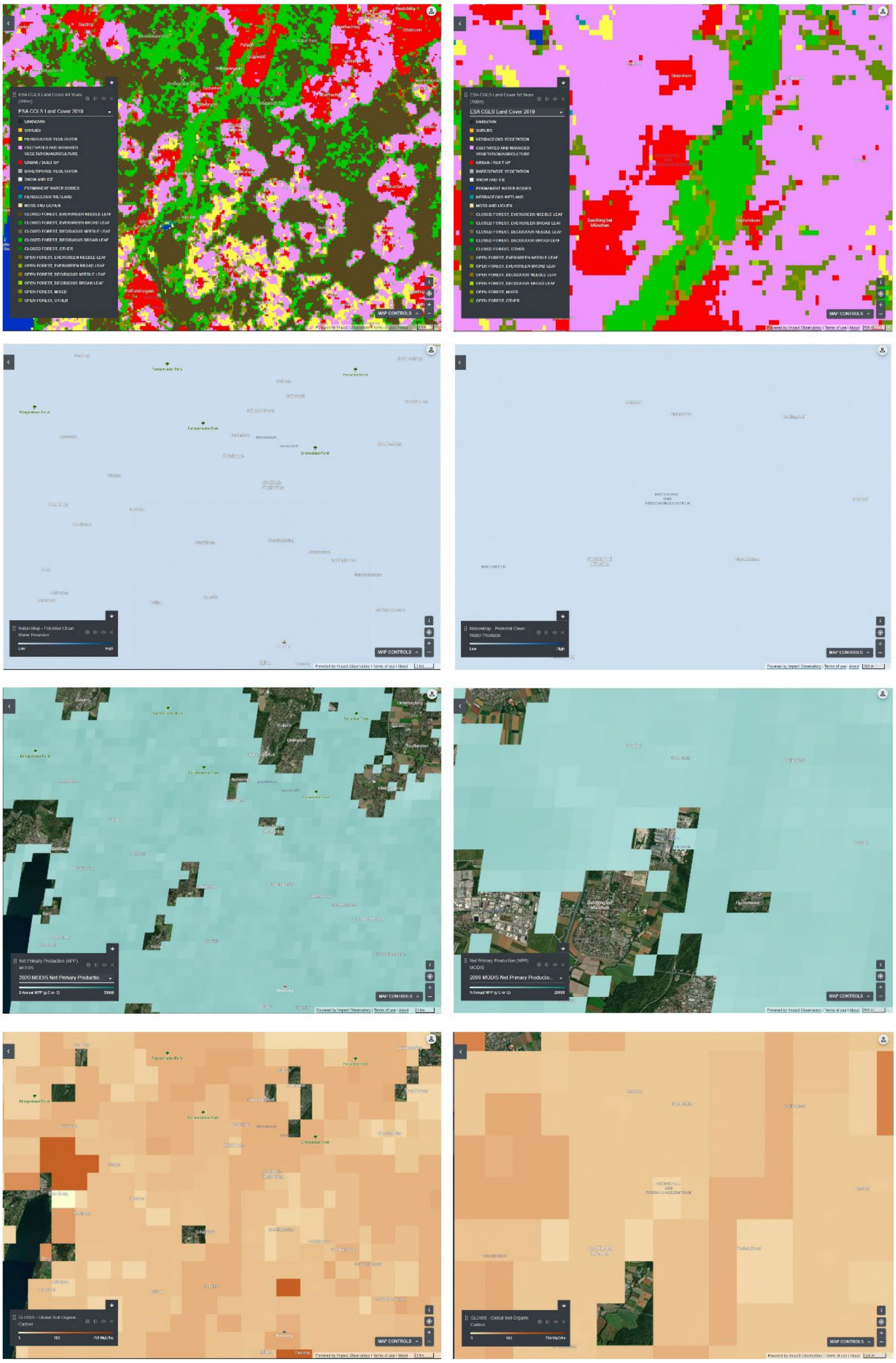

Figure 79. Remaining data maps used to measure ecosystem services for the Munich case study. Compiled and adapted from UN Biodiversity Lab 2022

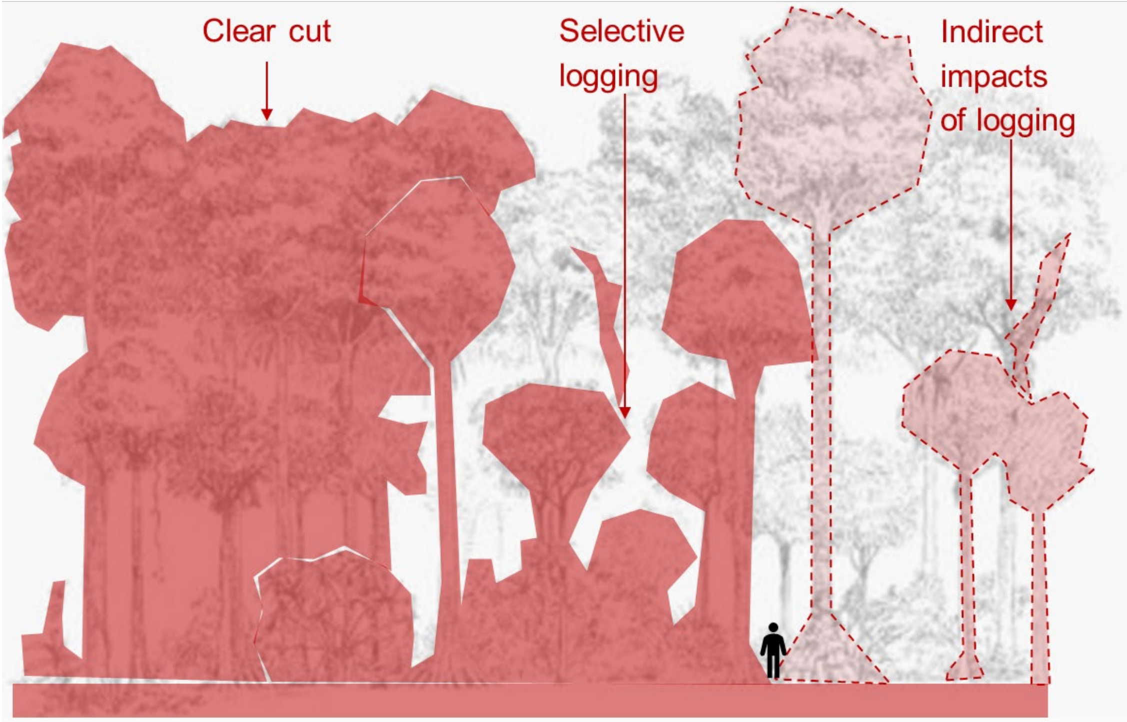

Figure 80. Summary graphic of impacts in lifecycle stage A1 Raw material supply. Rainforest image adapted from Brandon (2014)

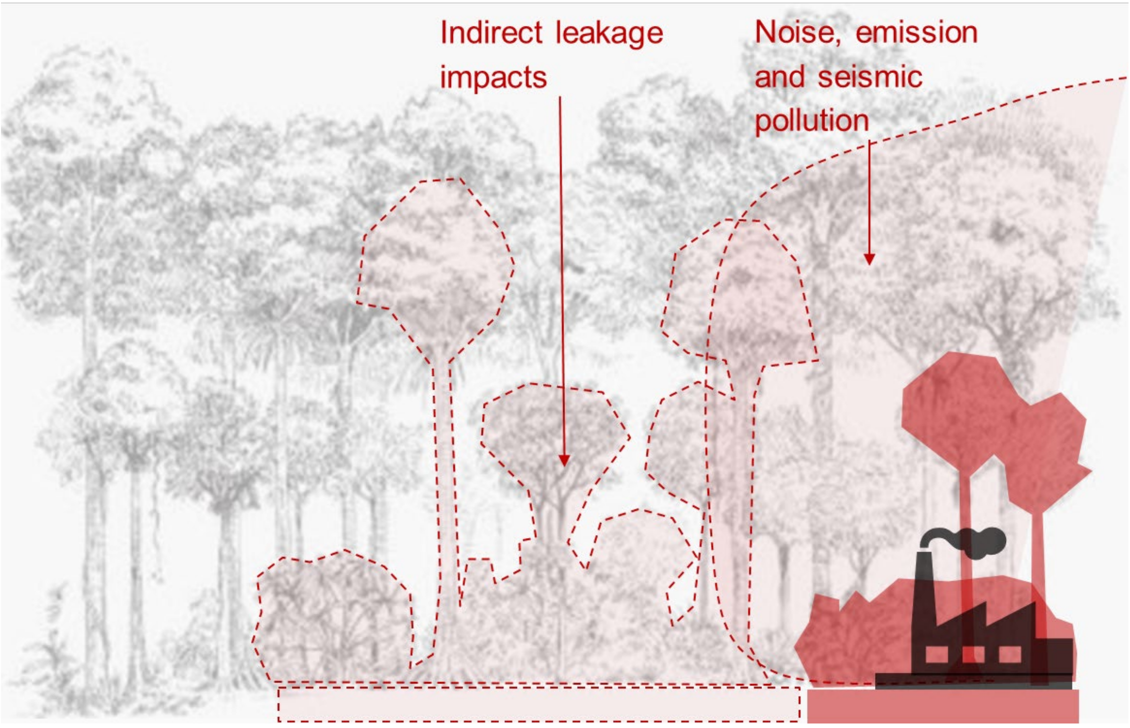

Figure 81. Summary graphic of impacts in lifecycle stage A3 Manufacturing. Rainforest image adapted from Brandon (2014)

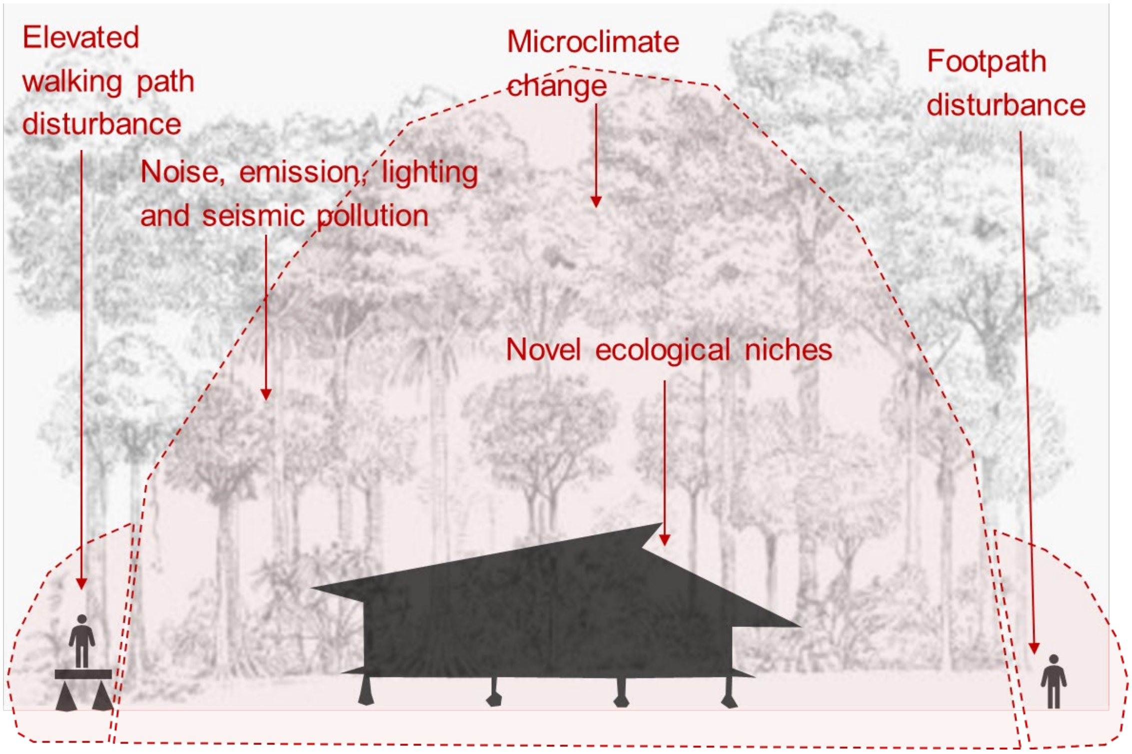

Figure 82. Summary graphic of impacts in lifecycle stage B1 Use. Rainforest image adapted from Brandon (2014)

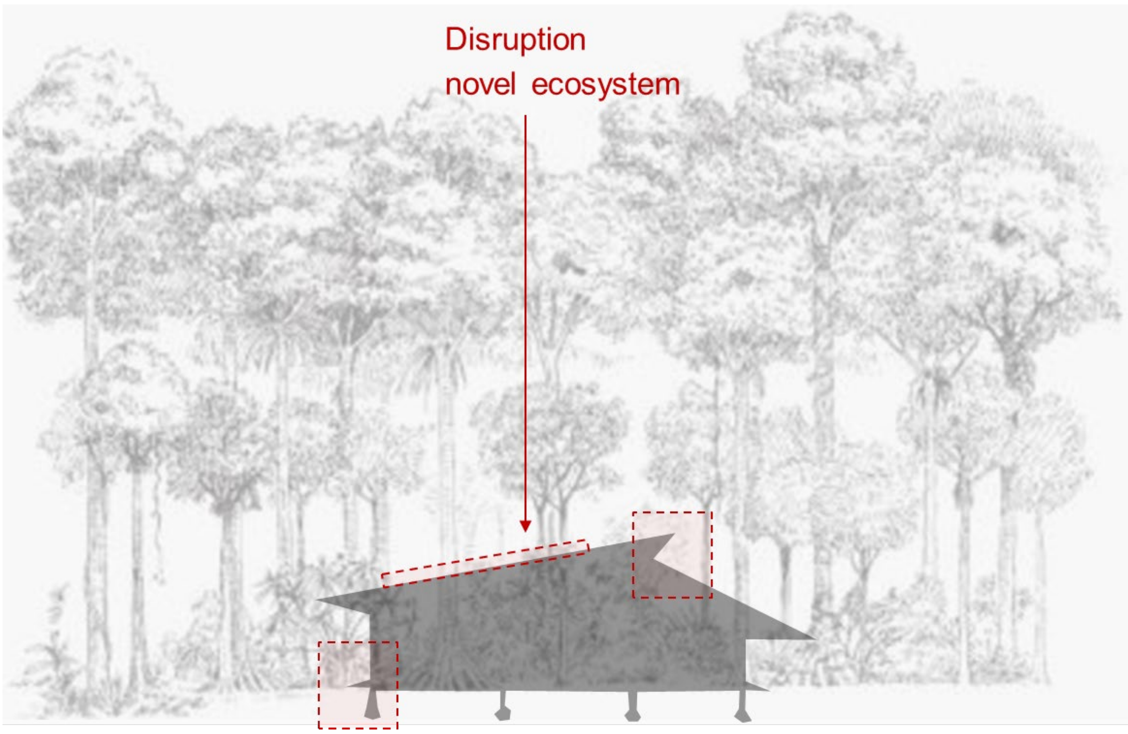

Figure 83. Summary graphic of impacts in lifecycle stage B2 Maintenance or B3 Repair. Rainforest image adapted from Brandon (2014)

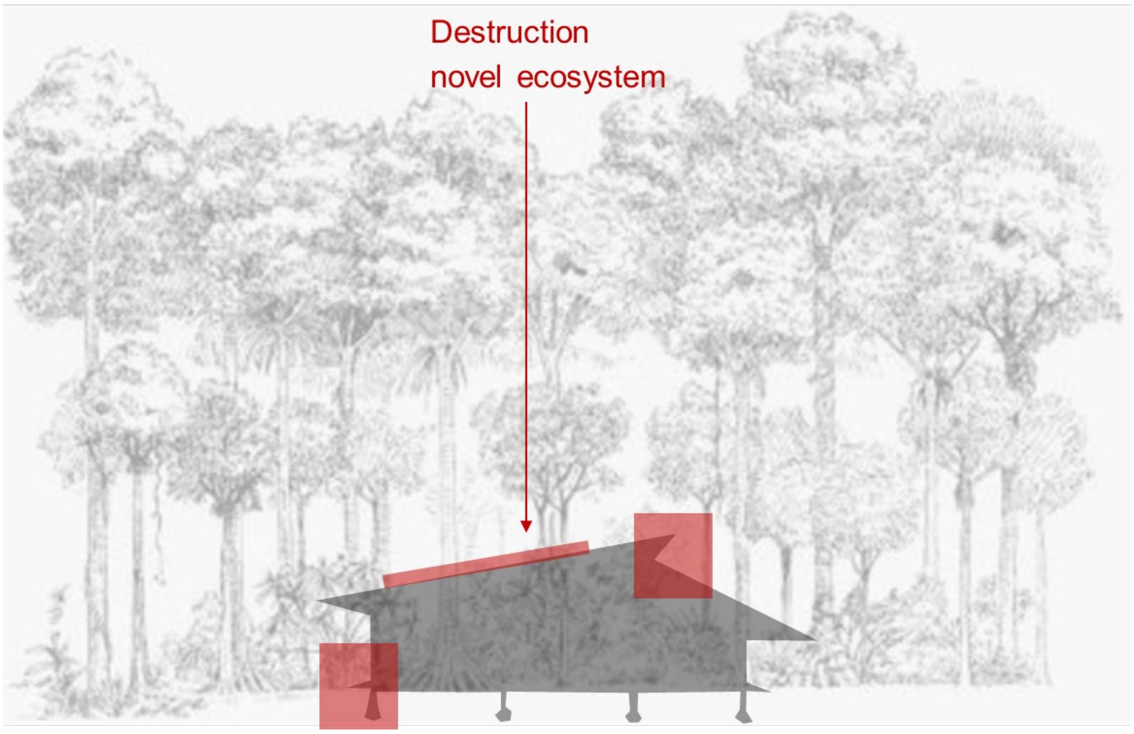

Figure 84. Summary graphic of impacts in lifecycle stage B4 Replacement. Rainforest image adapted from Brandon (2014)

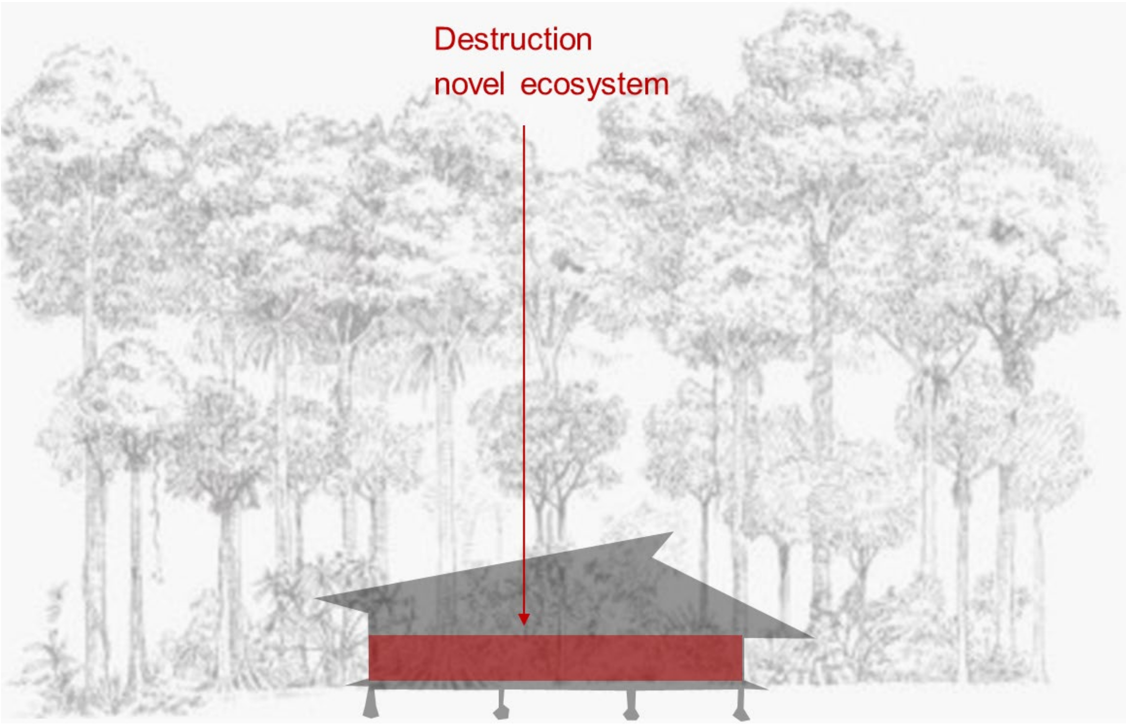

Figure 85. Summary graphic of impacts in lifecycle stage B5 Refurbishment. Rainforest image adapted from Brandon (2014)

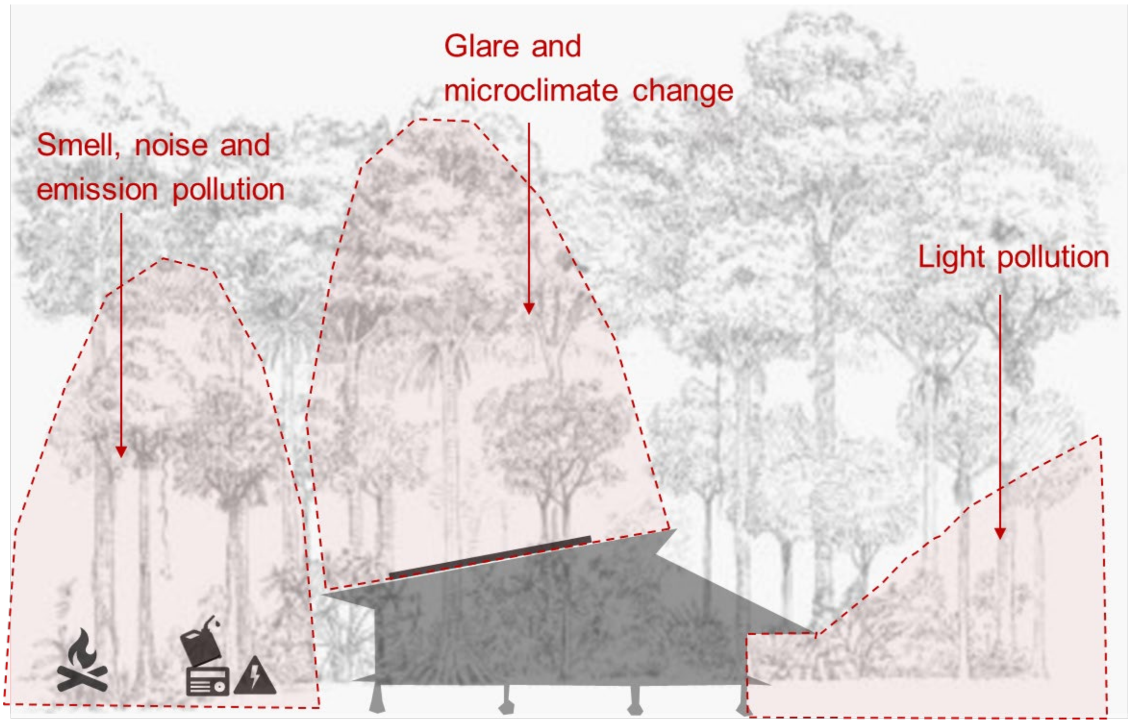

Figure 86. Summary graphic of impacts in lifecycle stage B6 Operational Energy Use. Rainforest image adapted from Brandon (2014)

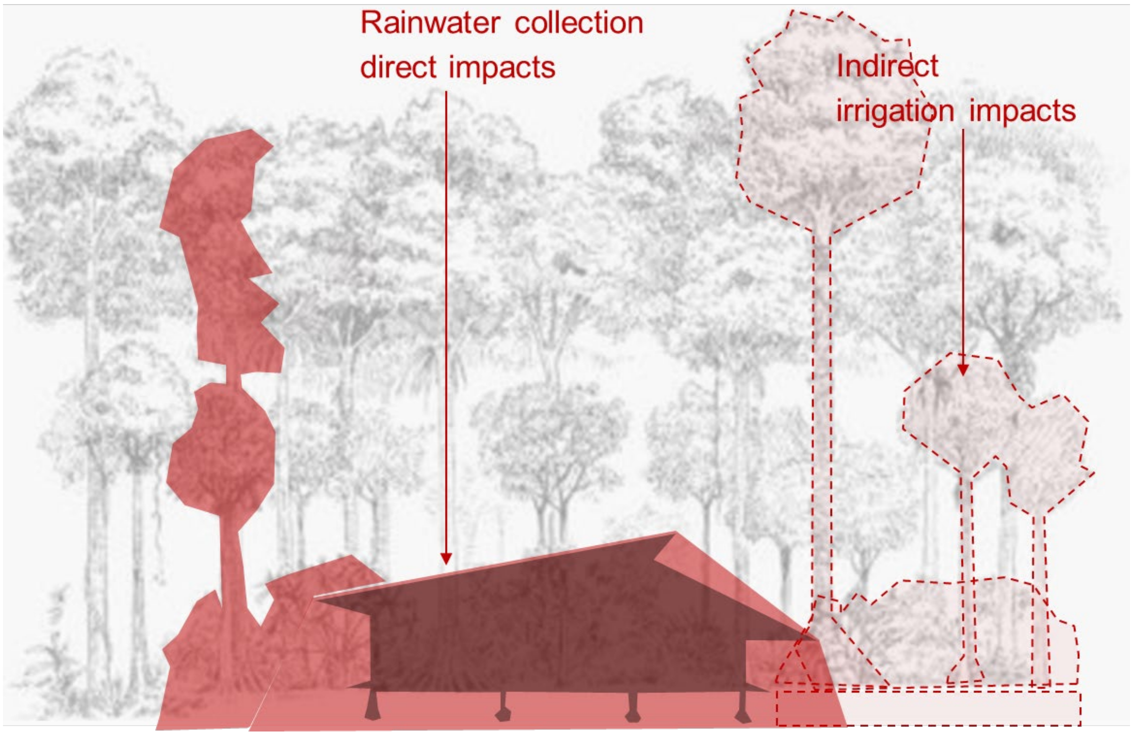

Figure 87. Summary graphic of impacts in lifecycle stage B7 Operational Water Use. Rainforest image adapted from Brandon (2014)

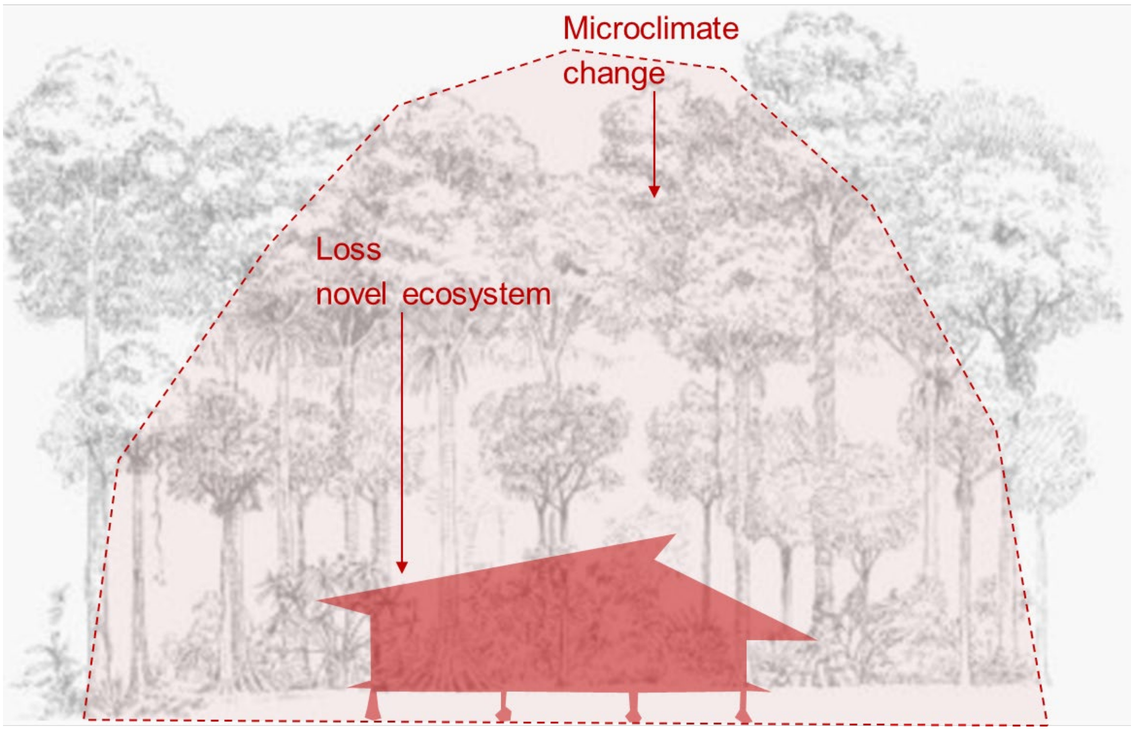

Figure 88. Summary graphic of impacts in lifecycle stage C1 Deconstruction/Demolition. Rainforest image adapted from Brandon (2014)

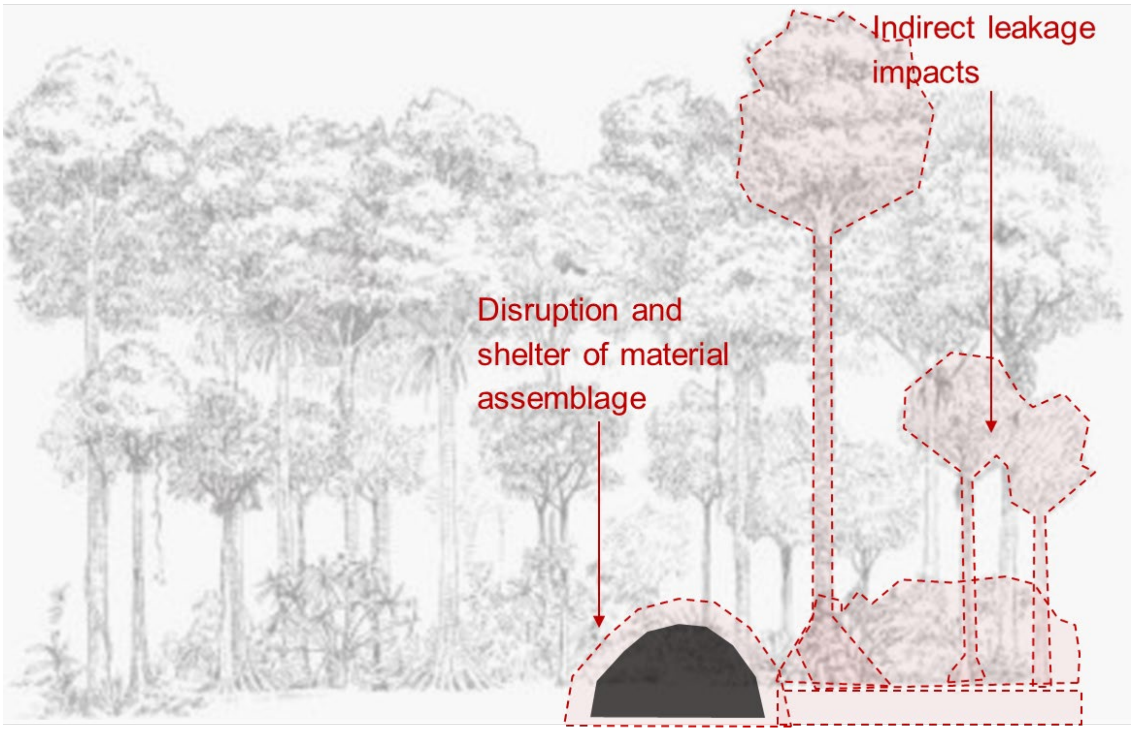

Figure 89. Summary graphic of impacts in lifecycle stage C3 Waste processing. Rainforest image adapted from Brandon (2014)

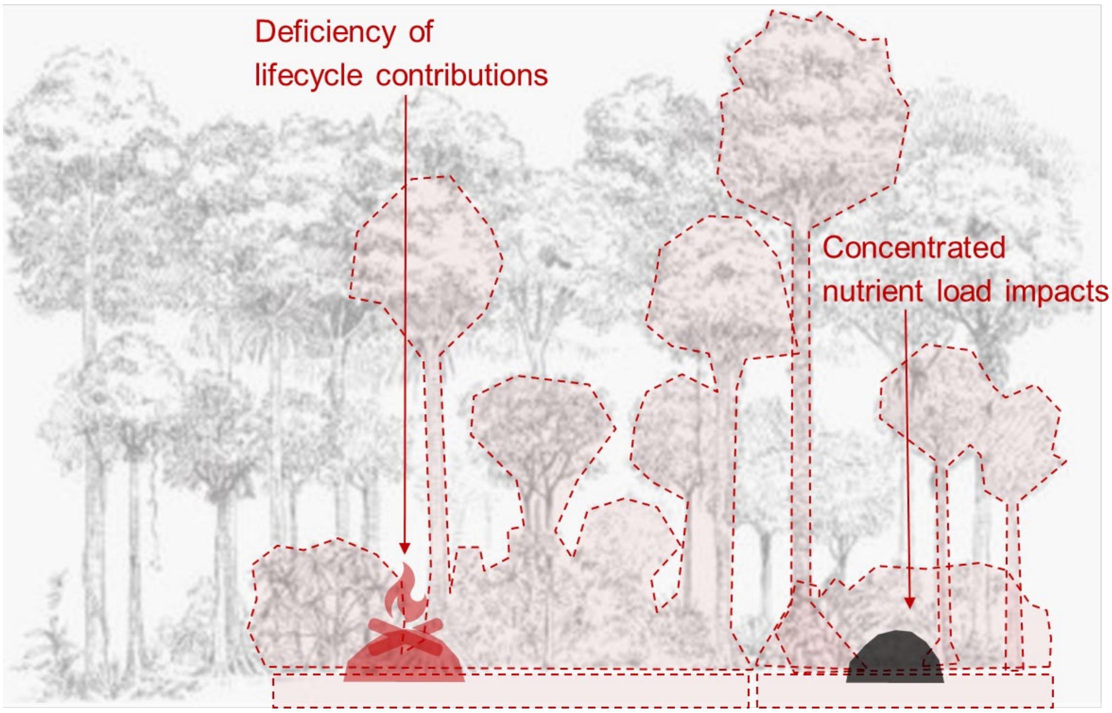

Figure 90. Summary graphic of impacts in lifecycle stage C4 Disposal. Rainforest image adapted from Brandon (2014)

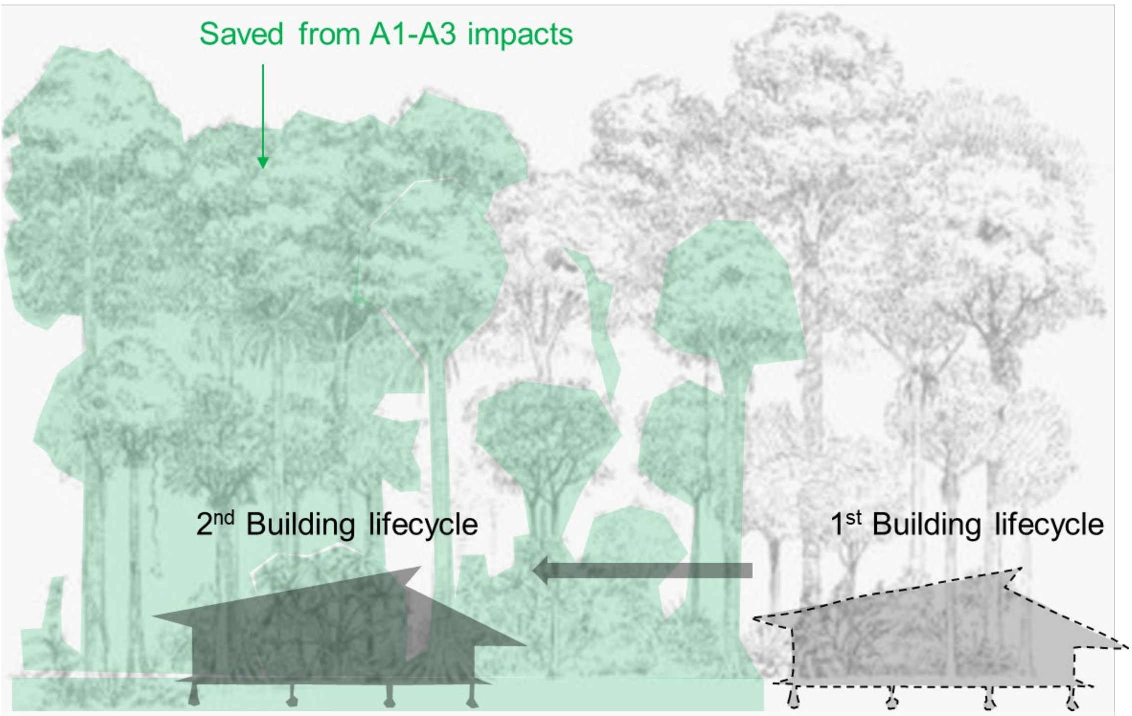

Figure 91. Summary graphic of impacts in lifecycle stage D Reuse, Recovery, Recycling potential. Rainforest image adapted from Brandon (2014)

Table 5.1 Ecosystem services from forest ecosystems and examples

	Examples of ecosystem services from forests in Europe	Links to human well-being
Provisioning services		
Crop, livestock and fisheries	Non-wood forest products for commercial and local use (e.g. honey, berries, fungi, cork, resin and medicinal plants) and meat (e.g. from reindeer and Iberian pigs). Products from agroforestry (e.g. cork ecosystems and silvopastoralism (*))	Food, medicine and health
Trees for timber	Raw timber materials for roundwood and further processing and manufacturing of wood (e.g. chips for paper board and pulp for paper); alternative construction material substituting steel and concrete to reduce the use of fossil fuels and enhance building standards	Shelter, materials, furniture and nappies
Trees for wood fuel	Wood of all kinds from residues after harvest, stumps, roots, recycled for local firewood and heat as well as power plants	Heating
Water supply	Upland forested catchments providing water downstream for, for instance, urban areas	Drinking water
Regulating services		
Climate	Regulation of climatic stress, lowering extreme temperature, heavy rainfall, water retention, and protecting soils, humans and animals; carbon stock and carbon sequestration by forests and soils; stock of carbon in wood products	Access to clean air and water
Water	Water conservation, run-off regulation, and water retention and storage	
Hazards	Soil erosion control; reduced chemical and pesticide exposure; flood regulation; air pollution reduction	Security from disasters
Disease and pests	Regulation of incidence and spread of insects, pathogens and diseases	Safety
Detoxification and purification	Water, soil, air quality and noise reduction	Clean air, water and soils, and tranquillity and health
Pollination	Habitat for wild pollinators	
Cultural services		
Wild species diversity	Habitat for flora, fauna and microorganisms; genetic reserves	
Environmental settings	Education and research, recreation and health, social activities, and spiritual and cultural values	Well-being, health, strength and social cohesion
Supporting services		
Soil formation, and nutrient and water cycles	Forests support soil formation and other biogeochemical processes essential to life	
Biodiversity	Protection of unique and native species, genetic biodiversity and ancient forests	

Note: (*) Silvopastoralism refers to the use of extensive livestock (for grazing) in management practices to maintain a balance between the forest and grasslands.

Source: Adapted from CICES, 2016, and EC, 2014.

Figure 92. Ecosystem services from forest ecosystems and examples from (EEA 2016a)

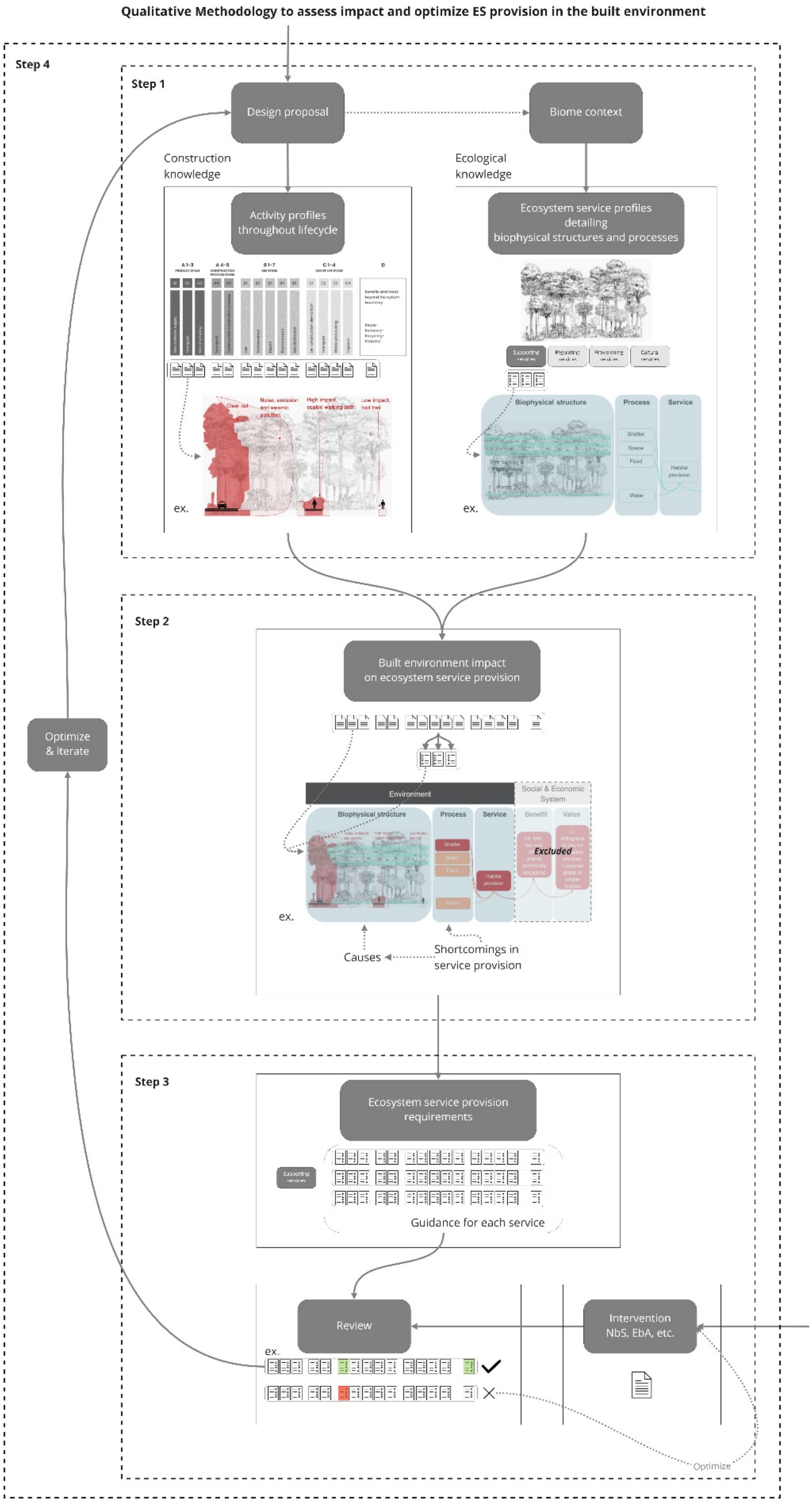

Figure 93. Extensive process diagram for qualitative ecosystem service assessment on design level with example visualizations of steps.

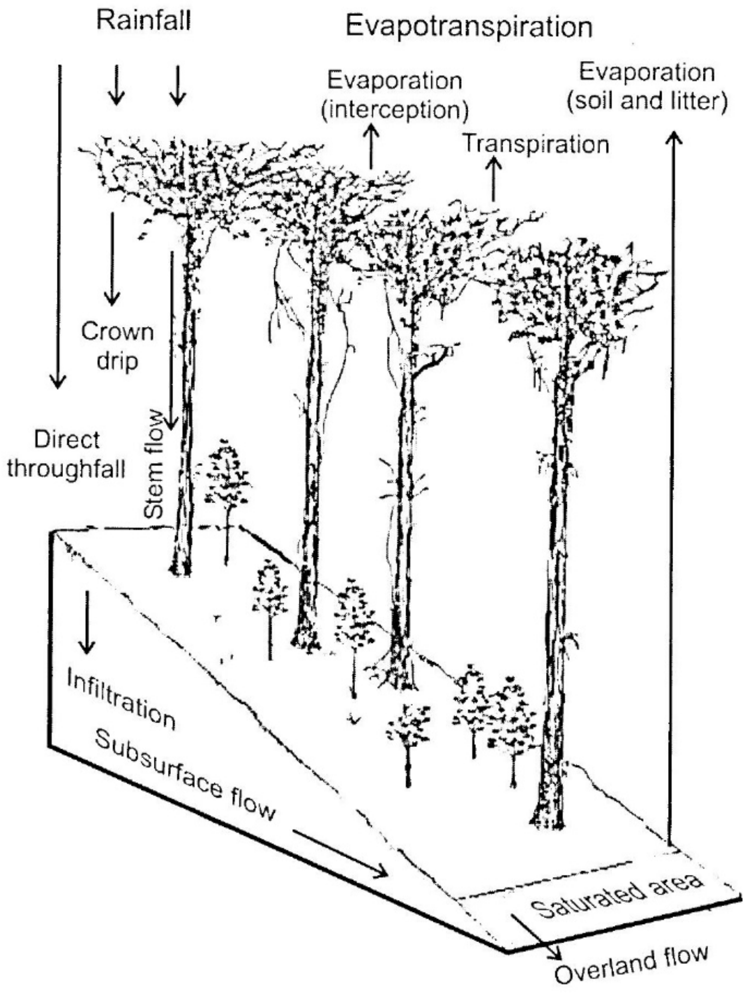

Figure 94. Water flow within a tropical rainforest from Ghazoul and Sheil (2010)

Life-form	Role
Dicotyledonous trees, long-lived	1. Provide skeletal structure of entire forest 2. Dominate primary productivity and material flows 3. Influence off-site climate and hydrology 4. Provide shelter and roosts in hollow trunks
Dicotyledonous trees, short-lived	1. Reduce nutrient loss in early succession 2. Reduce likelihood of site takeover by vines and shrubs
Rosette trees (e.g., palms)	1. Channel rainwater toward stem 2. Capture and aggregate litter 3. Concentrate calcium 4. Roots bore through soil pans, creating channels that can be exploited by other plants 5. Root foraging emphasizes scale (rather than precision, sensu Campbell et al. 1991)
Understory trees	1. Scavenge sparse radiation of understory (and have low nitrogen demand) 2. Provide platforms (in humid microenvironment) for nitrogen-fixing epiphylls
Shrubs	1. Drive productivity of scansorial rodents and birds that feed on fleshy fruits 2. Retard nutrient loss in early succession
Giant-leaved herbs	1. Constitute large, homogeneous patches in otherwise heterogeneous understory 2. Foster secondary productivity through nectar and fruit production 3. Provide roosting sites for bats and building sites for carton nests of social insects
Vines	1. Provide trellises for movement of arboreal animals 2. Act as webbing that ties trees together 3. Buffer microclimatic changes by sealing forest edges
Graminoids	1. Constitute readily combustible dry-season fuel 2. Provide forage for grazers and food for seed-eating birds, rodents, ants, and fungi
Hemiepiphytes	1. Increase tree mortality rates 2. Provide slender vine trellises (aerial roots) in understory of closed canopy forest
Epiphytes	1. Augment leaf area (by colonizing opaque surfaces) 2. Slow nitrogen through-flow 3. Divert water from soil to atmosphere 4. Redistribute through-fall and stem flow 5. Provide unique habitats essential for reproduction of other species

Figure 95. Examples of linkages between plants and processes in tropical forests from Orians et al. (1996)

I. Plants

Group	Characteristics	Effects on forest dynamics
A. Herbs and Shrubs		
1. Pioneer	Incl. grasses and ferns; high light requirements, low nutrient tolerance	Colonization of large gaps, landslides, skid tracks, old fields, pastures; can suppress tree seedlings
2. Understory		
a. Large-leaved	Shade-tolerant herbs and shrubs; often palm-like	Heavy shade suppresses seedlings in understory
b. Small-leaved	Shade-tolerant, multi-stemmed herbs, shrubs	Competition with seedling, and saplings
B. Treelets	Small trees; generally not long-lived	
1. Pioneer	High light-demanding, short lived, copious small seeds	Rapid growth in large canopy openings and clearings Suppress growth of pioneer herbs and shrubs; affect micro-environment of early succession
2. Understory	Shade tolerants, sub-canopy trees; resprouters	Compete with saplings of canopy trees
C. Canopy and emergent trees	Big trees, long-lived, shade-tolerant or light-demanding	
1. Legumes	Often dominant plant family, high N litter	Increase decomposition rate and availability of nutrients
2. Palms	Voluminous, high-fiber litter; dense shade	Decrease litter decomposition rates; colonize landslides
3. Emergents	Very large trees with crowns projecting above canopy; long-lived but may be fast-growing	Create large treefall gaps and patches of high light
D. Lianas and vines		
1. Lianas	Large woody vines; long-lived, high-light response; often connect many tree crowns	May increase treefall gaps; high litter production; rapid growth in large gaps; compete with saplings
2. Vines	Herbaceous, high-light- or shade-tolerant	Grow rapidly in gaps, landslides, skid tracks
E. Epiphytes and hemiepiphytes		
1.Nonparasitic herbs	Herbaceous, canopy habitat	Sequester nutrients; weight may increase branch falls
2.Parasitic and hemi-epiphytic trees and shrubs	Woody; sometimes stranglers or vascular parasites	May contribute to death of canopy trees

II. Fungi, microbes, and animals

Group	Taxonomic composition	Effects on forest dynamics
A. Seed dispersers	Fruit-eating birds and mammals	Disperse seeds within forests and across landscapes
B. Pathogens and herbivores	Parasitic fungi, herbivorous insects, and some vertebrates (e.g., peccaries pacas, possums)	Affect vigor and mortality of plants of all sizes, but especially establishing seedlings in the understory
C. Soil processers		
1.Decomposers	Fungi, microbes, soil mesofauna	Increase nutrient supply rates; affect soil structure, incl. nutrients, moisture, and oxygen availability
2.Mycorrhizal fungi	Symbiotic associations with plants; endotrophic or ectotrophic	Increase availability of P and perhaps other nutrients; decompose organic matter (ectotrophic); increase seedling survival.
3.Soil churners	Animals foraging in litter and top soil (incl. ground-feeding birds, peccaries, leaf-cutter ants)	Remove litter, aerate soils, may create establishment sites for small seeded species; also kill seedlings

Figure 96. Functional groups influencing rainforest dynamics from Orians et al. (1996)

BE impacts and ES provision requirements per lifecycle phase

For details and background research see Fricke, M. M. – Ecosystem Services Guiding Built Environment Design (2023)

Built environment (BE) impact on three supporting ecosystem services (ES) over a complete building's lifecycle, with a requirements list for ES provision

Legend
Red=loss
Green=contribution
Orange=disruption/Decrease
White=neutral or only slight potential for disruption/decrease

Phase	No.	Stage	Overall impact on Biophysical Structure (BS) of [Tropical Rainforest] Ecosystem	Activity I	Impact on Ecosystem I	Activity II	Impact on Ecosystem II	Activity III	Impact on Ecosystem III	Summary & Simplification of ES provision based on Cascade model / Underlying Ecosystem Process (EP)	Habitat Provision: Shelter	Space	Food	Water	Overall impact on ES	Habitat provision by the BE: How could this impact be improved/positive, in terms of EP?	Nutrient Cycling: Capture	Retention	Transfer	Re-capture	Overall impact on ES	Nutrient cycling by the BE: How could this impact be improved/positive, in terms of EP?	Water Cycling: Interception	Transpiration	Evaporation	Surface runoff	Groundwater drainage	Change in soil water content	Overall impact on ES	Water cycling by the BE: How could this impact be improved/positive, in terms of EP?
Product	A1	Raw material supply		Logging of Trees -by hand with a saw or ax -chainsaw -harvester -Clear cutting: for access and most timber dimensions -Selective logging for emergent trees for large structural dimension timber	Consequences -Surface damage to vegetation cover on ground by movement, access with machinery and falling trees -Partial total vegetation clearance -Creation of clearances, leaving ground more exposed to sun and rain and increase of forest edges to wind -Extent of damage and disruption increases with frequency and intensity of activity -Especially disruption of top soil also greater in wet conditions -Noise pollution by machinery -Fossil fuel emissions by power supply for machinery -Unintentional damage or increased branching to surrounding trees by falling trees or machinery	Harvesting of Rattan -by hand with a machete -vines within reach; pulling from the canopy Wild or cultivated in forest; selectively cut trees as carrier are unharmed	Consequences -Disruption and disconnection of vertical connections between vegetation layers			BE Impact on EP & ES	Lost individual to large scale	Lost (only on ground or soil possibly left in a functioning state)	Lost individual to large scale	Lost most sources for supply	Lost; severity dependent on activity intensity and fragmentation of initial habitat	Limit the damage, intensity and scale; replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; resource provision is more difficult and requires more (regeneration) time; consider mimicking natural destruction events in characteristics, severity and extent if losses cannot be avoided	Lost individual to large scale (only rootmats of ground/soil possibly left in a functioning state)		Lost individual to large scale (only rootmats and Mycorrhizae of ground/soil possibly left in a functioning state)	Lost individual to large scale (only rootmats and decomposers of ground/soil possibly left in a functioning state)	Lost; severity dependent on activity intensity and complete loss dependent on ground/rootmat impact	Limit the damage, intensity and scale; replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent if losses cannot be avoided	Lost individual to large scale		Lost individual to large scale for vegetation surfaces; (only ground/soil possibly left in a functioning state)	Heavily altered by ground impacts on the topography	Lost or severely damaged root network (which retains proper drainage); above ground deforestation causes starvation death underground		Lost and severely damaged	Limit the damage, intensity and scale; replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent if losses cannot be avoided
Product	A2	Transport		by Road Use classification -Access roads for raw material supply activity -Distribution network roads to manufacturing Material classification -Unpaved informal dirt roads for access -Unpaved Compacted dirt roads for more frequent use and better drainage to last longer	Consequences -Total surface damage to vegetation cover on ground and top soil by truck and caterpillar movement -Creation of clearances, leaving ground more exposed to sun and rain and increase of forest edges to wind -Frequent noise pollution due to traffic -Frequent seismic activity due to traffic -Fossil fuel emissions by exhaust -Roadkills of animalia kingdom -Potential unintentional transport of invasive species -potentially human induced alteration of topography/ flattening and compacting of soil additionally affects water uptake and flow	by Foot Intensity and frequency deviations -occasional trail for access -permanent walking path for distribution	Consequences -low: vegetation cover on ground is pressed down, can bounce back or is not even interfered with by placing steps beside stems and crowns -medium: vegetation cover on ground stays down, dies by impact and is succeeded -high: vegetation cover on ground and soil is destructed by walking and becomes dirt path			BE Impact on EP & ES	Lost for road and frequently disrupted	Possible danger due to motorized traffic; frequent disruptions; connectivity might still be given	Quality compromised by pollution of road		Partially lost on individual level and larger affected areas by disruption and degradation/loss of resources	Limit the damage, intensity and scale of direct road impact; enable shelter and space characteristics at least around direct ground losses; minimize usage disruption, frequency and danger; avoid pollution	Lost for cleared and sealed area; rootmats in any case degraded (possibly to some degree still functioning if not sealed)		Lost for cleared and sealed area and process exchange greatly reduced even if rootmats are still to some degree functional		Lost; if not sealed severity dependent on activity intensity and degree of functioning of rootmats	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider non rootmat impacting approaches	Lost for cleared area		Lost for vegetation surfaces; ground/soil surfaces replaced and possibly enhanced evaporation by (sealed/compacted) roads or further decreased process due to increased runoff and drainage	Significantly increased depending on impenatrability of surface areas	Lost or severely damaged for cleared area; possibly handling more water from road runoffs on adjacent soil and rootmats		Lost and severely damaged; possibly also increasing management load	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider redistributions of runoff and redesign of road ways according to natural processes tied to the ground level
Product	A3	Manufacturing		Processing Timber -sorting -storage -debarking -sawing -drying	Consequences -Fossil fuel emissions by power supply for machinery -noise pollution -fine dust and smell from sawmill -cleared space requirement for sorting, storage and drying	Processing Rattan -dried in the sun (oil bath for curing to increase durability and quality) -peeling -steaming -bending -sanding	Consequences -(potential toxic emissions and leakages for bathing, fumes and smells) -cleared space requirement for sorting, storage and drying			BE Impact on EP & ES	Lost for cleared area		Potentially quality compromised by pollution through fine dust or toxic fumes	Potentially quality compromised by pollution through fine dust or toxic leakages	Lost on cleared area and larger area disrupted by degradation of resources	Limit the damage, intensity and scale of cleared area; replicate/mimic EP characteristics with site to equal or outweigh previous conditions; avoid pollution and minimize disruption on surroundings during operation	Lost for cleared and sealed area; rootmats in any case degraded (possibly to some degree still functioning if not sealed)		Lost for cleared and sealed area and process exchange greatly reduced even if rootmats are still to some degree functional		Lost; if not sealed severity dependent on activity intensity and degree of functioning of rootmats	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider non rootmat impacting approaches; replicate/mimic EP characteristics with site to equal or outweigh previous conditions	Lost for cleared area		Lost for vegetation surfaces; ground/soil surfaces replaced and possibly enhanced evaporation by (sealed/compacted) ground or further decreased process due to increased runoff and drainage	Significantly increased depending on impenatrability of surface areas	Lost or severely damaged for cleared area; possibly handling more/concentrated water from area/roof runoffs on adjacent soil and rootmats		Lost and damaged; possibly also increasing management load	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider redistributions of runoff and redesign of sealed area according to natural processes tied to the ground level; replicate/mimic EP characteristics with site to equal or outweigh previous conditions
Construction	A4	Transport		by Road	Consequences	by Foot	Consequences			BE Impact on EP & ES	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Construction	A5	Construction installation process		Site Preparation	Consequences	Setting base structure and floor	Consequences	Installation of green roofs, PV, HVAC, plumbing and electricity	Consequences	BE Impact on EP & ES	[illegible]	[illegible]	[illegible]	[illegible]	Lost	[illegible]	[illegible]				[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Use	B1	Use		Circulation and movement by people	Consequences	Building Services Systems	Consequences	Building envelope	Consequences	BE Impact on EP & ES	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Use	B2	Maintenance		Maintaining usually undisrupted areas of the envelope or landscape	[illegible]					BE Impact on EP & ES	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]	[illegible]			[illegible]	Unknown	[illegible]	[illegible]	[illegible]
Use	B3	Repair		Repairing usually undisrupted areas of the envelope or landscape	[illegible]					BE Impact on EP & ES	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]				Unknown			Unknown	Unknown
Use	B4	Replacement		Replacing usually undisrupted areas of the envelope or landscape	[illegible]					BE Impact on EP & ES	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]				Unknown			Unknown	Unknown
Use	B5	Refurbishment		Replacing usually undisrupted areas of the envelope or landscape	[illegible]					BE Impact on EP & ES	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]				Unknown			Unknown	Unknown
Use	B6	Operational Energy Use		Energy Use	Consequences					BE Impact on EP & ES	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]	Unknown		[illegible]		Unknown		[illegible]	[illegible]
Use	B7	Operational Water Use		Water Use	Consequences					BE Impact on EP & ES	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]	Unknown		[illegible]	Unknown	[illegible]	[illegible]	[illegible]	[illegible]
End of Life	C1	Deconstruction/ Demolition		Removal of envelope	Consequences					BE Impact on EP & ES	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]	Unknown		[illegible]		[illegible]		[illegible]	[illegible]
End of Life	C2	Transport		by Road	Consequences	by Foot	Consequences			BE Impact on EP & ES	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
End of Life	C3	Waste processing		Grouping of materials on ground	Consequences					BE Impact on EP & ES	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]				[illegible]	[illegible]	[illegible]			[illegible]	[illegible]		[illegible]	[illegible]
End of Life	C4	Disposal		Burning	Consequences	Decomposition	Consequences			BE Impact on EP & ES	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]				Unknown			Unknown	Unknown
Benefit	D	Reuse-, Recovery-, Recycling Potential		Reuse	Consequences					BE Impact on EP & ES	Unknown				[illegible]	[illegible]	Unknown		[illegible]		[illegible]	[illegible]				Unknown			[illegible]	[illegible]

LC phase specific ES requirements - Review list for self-use

For details and background research see Fricke, M.M. - Ecosystem Services Guiding Built Environment Design (2022)	Legend: Red=loss; Green=contribution (degree by gradient); Orange=disruption/decrease White=neutral or not applicable		Product			Construction		Use							End of Life				Benefit
			A1 Raw material supply	A2 Transport	A3 Manufacturing	A4 Transport	A5 Construction installation process	B1 Use	B2 Maintenance	B3 Repair	B4 Replacement	B5 Refurbishment	B6 Operational Energy Use	B7 Operational Water Use	C1 Deconstruction/ Demolition	C2 Transport	C3 Waste processing	C4 Disposal	D Reuse -, Recovery -, Recycling Potential
	Review List ES provision requirements		Habitat Provision																
Strategies/ NbS	Description	Source	Limit the damage, intensity and scale; replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; resource provision is more difficult and requires more (regeneration) time; consider mimicking natural destruction events in characteristics, severity and extent if losses cannot be avoided	Limit the damage, intensity and scale of direct road impact; enable shelter and space characteristics at least around direct ground losses; minimize usage disruption, frequency and danger; avoid pollution	Limit the damage, intensity and scale of cleared area; replicate/mimic EP characteristics with site to equal or outweigh previous conditions; avoid pollution and minimize disruption on surroundings during operation	Limit the damage, intensity and scale of direct road impact; enable shelter and space characteristics at least around direct ground losses; minimize usage disruption, frequency and danger; avoid pollution	Limit the damage, intensity and scale; preserve and incorporate key EP sources in planning/design; replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; resource provision more difficult and requires more (regeneration) time; consider mimicking natural destruction events in characteristics, severity and extent if losses cannot be avoided	avoid pollution and minimize disruption on surroundings during operation; mimic/ replicate/ integrate the diversity of naturally occuring niches that are defined by the EP's as much as possible with the design; make water and shelter accessible, consider natural space requirements and food sources (by this order possibly the latter the most difficult for current practice)	limit disruption/damage intensity and frequency; consider mimicking natural events in characteristics, severity and extent to interfere and adapt activity accordingly (i.e. conceptually: rain-flush/cleaning or irrigation, wind pollination/coating or nutrient transfer/paint runoff)	limit disruption/damage intensity and frequency; consider mimicking natural events in characteristics, severity and extent to interfere and adapt activity accordingly (i.e. conceptually: rain-flush/cleaning or irrigation, wind pollination/coating or nutrient transfer/paint runoff)	Limit the damage, intensity and scale; preserve and incorporate newly established EP sources in planning/design (further evolution) on original or new location (reuse of EP/ES); replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent (i.e. conceptually as canopy is trimmed by storms, so can a similar roof ecosystem with its EP be interfered by replacement)	Limit the damage, intensity and scale; preserve and incorporate newly established EP sources in planning/design (further evolution) on original or new location (reuse of EP/ES); replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent (i.e. conceptually as canopy is trimmed by storms, so can a similar roof ecosystem with its EP be interfered by replacement)	limit disruption intensity and frequency; avoid pollution; consider mimicking natural events in characteristics, severity and extent to interfere and adapt activity accordingly (i.e. conceptually: similarity to moonlight, specific spectrum or glow or similarity to natural microclimate differences inferred by sun radiation and absorption/relectance/radiation of materials)	make water accessible to natural cycle, consider mimicking natural rain events and flows and adapt activity accordingly (i.e. certain amounts, cascades and storages for irrigation actions; non closed technical loop for solely building's water use)	Limit the damage, intensity and scale; preserve and incorporate newly established EP sources in planning/design (further evolution) on original or new location (reuse of EP/ES); replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent (i.e. rare stormevent or fire)	Limit the damage, intensity and scale of direct road impact; enable shelter and space characteristics at least around direct ground losses; minimize usage disruption, frequency and danger; avoid pollution	avoid pollution, mismanagement and minimize disruption on surroundings and resources during operation; consider mimicking/replicating natural temporary shelter and space occurances	avoid pollution and burning; consider natural nutrient/material cascades adding to EP's; relocate if necessary and naturally degrade to dispose	a direct transfer/relocation of ES/habitat is seldomly feasible for the same individual species, however the provision of the sources/EP's increases the likelihood for a new establishment of ES/habitat for the same or another species
Green Façade	Climbing plants; partial or complete coverage of wall; direct or indirect growing systems; ground or container based	Katharina NbS Design Strategies Review			not applicable			For specific species contribution to shelter and space (similar to dense vegetation in canopy or undergrowth); food usually not produced/aimed at; sufficient water might be supplied through artificial irrigation but not similar to natural occurances in epiphyte catchments for example						not applicable					a possible relocation for new establishement is more feasible with indirect, container based systems since the attachment system is possibly demountable from the façade, making a transport as a whole a possibility
Intensive Green Roof	vegetation growing on layer of soil substrate, root barrier, drainage system and waterproof membrane on top of insulation and roof structure; substrate thickness (~15cm), size of vegetation dependent on substrate depth and roof load bearing strength; however trees are not common due to weight restrictions; suitable for human use	Katharina NbS Design Strategies Review; https://urbinat.eu/nbs/green-roof-2/			not applicable			can resemble lower BS layers depending on selection and setup; canopy layers usually not possible due to sizes and weight constraints; could thus only contribute to species which inhabit the ground and undergrowth without being too much dependent on the canopy layer and its waste/resources						not applicable					a relocation is most feasible in parts which however disrupts integrity and dissects established root/soil network
Insert the to be investigated strategy below	*Describe the selected strategy below*	*Describe your potential source of reference*											*Review the above requirements for the selected strategy and document below*						

For details and background research see Fricke, M.M. - Ecosystem Services Guiding Built Environment Design (2022)	Legend: Red=loss; Green=contribution (degree by gradient); Orange=disruption/decrease White=neutral or not applicable		Product			Construction		Use							End of Life				Benefit
			A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
			Raw material supply	Transport	Manufacturing	Transport	Construction installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction/ Demolition	Transport	Waste processing	Disposal	Reuse -, Recovery -, Recycling Potential
	Review List ES provision requirements		Nutrient Cycling																
Strategies/ NbS	Description	Source	Limit the damage, intensity and scale; replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent if losses cannot be avoided	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider non rootmat impacting approaches	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider non rootmat impacting approaches; replicate/mimic EP characteristics with site to equal or outweigh previous conditions	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider non rootmat impacting approaches	Limit the damage, intensity and scale; preserve and incorporate key EP sources in planning/design; replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent if losses cannot be avoided	limit the damage and avoid over-concentration; mimic/ replicate/ integrate naturally occuring agents for EP's as much as possible with the design; enable capture, retention, transfer and recycling processes (by this order possibly the latter the most time and energy intense to establish)	limit disruption/damage intensity and frequency; avoid overconcentration; consider mimicking natural events in characteristics, severity and extent to interfere and adapt activity accordingly	limit disruption/damage intensity and frequency; avoid overconcentration; consider mimicking natural events in characteristics, severity and extent to interfere and adapt activity accordingly	Limit the damage, intensity and scale; preserve and incorporate newly established BS/EP's in planning/design (further evolution) on original or new location (reuse of EP/ES); replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent (i.e. conceptually as canopy is trimmed by storms, so can a similar roof ecosystem with its BS/EP's be interfered by replacement)	Limit the damage, intensity and scale; preserve and incorporate newly established BS/EP's in planning/design (further evolution) on original or new location (reuse of EP/ES); replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent (i.e. conceptually as canopy is trimmed by storms, so can a similar roof ecosystem with its BS/EP's be interfered by replacement)	limit disruption on BS and avoid pollution	limit disruption and damage; consider mimicking natural rain events and flows and adapt activity accordingly; avoid overconcentrations	Limit the damage, intensity and scale; preserve and incorporate newly established EP sources in planning/design (further evolution) on original or new location (reuse of EP/ES); replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent (i.e. rare stormevent or fire)	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider non rootmat impacting approaches	limit the disruption and damage; keep BS intact	limit and avoid direct disposals; consider and target natural decompositions and cascades; control and manage nutrient loads instead of compiling and concentrating action	if BS actors for EP can be provided, there are contributions in form of the ES
Green Façade	Climbing plants; partial or complete coverage of wall; direct or indirect growing systems; ground or container based	Katharina NbS Design Strategies Review	not applicable					nutrient capture depending on selected vegetation is possible; retention due to verticality and usually selected plants limited; transfer and recycling is with current practice not possible due to seperation of patches, limited root networks and limited exposure of these due to verticality	not applicable									natural decomposition can contribute to the transfer and recycling of the captured nutrients in the newly established biomass; concentration loads usually probably higher than natural litterfall densities	a relocation of intact vegetation should be able to keep capture ability as much as in the use phase, while other EP's are limited due to setup
Intensive Green Roof	vegetation growing on layer of soil substrate, root barrier, drainage system and waterproof membrane on top of insulation and roof structure; substrate thickness (~15cm), size of vegetation dependent on substrate depth and roof load bearing strength; however trees are not common due to weight restrictions; suitable for human use	Katharina NbS Design Strategies Review; https://urbinat.eu/nbs/green-roof-2/	not applicable					except for the higher BS layers, natural processes can theoretically if targeted with the same agents/plants be replicated and provided; thus only extent of processes is likely to differ in magnitude due to missing of dominant tree infrastructure in analysed rainforest ecosystem	not applicable									natural decomposition can contribute to the transfer and recycling of the captured nutrients in the newly established biomass; concentration loads usually probably higher than natural litterfall densities	a relocation is most feasible in parts which however disrupts integrity and dissects established root/soil network
Insert the to be investigated strategy below	*Describe the selected strategy below*	*Describe your potential source of reference*	*Review the above requirements for the selected strategy and document below*																

For details and background research see Fricke, M.M. - Ecosystem Services Guiding Built Environment Design (2022)	*Legend: Red=loss; Green=contribution (degree by gradient); Orange=disruption/decrease White=neutral or not applicable*		Product			Construction		Use							End of Life				Benefit
			A1	*A2*	*A3*	*A4*	*A5*	*B1*	*B2*	*B3*	*B4*	*B5*	*B6*	*B7*	*C1*	*C2*	*C3*	*C4*	*D*
			Raw material supply	Transport	Manufacturing	Transport	Construction installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction/ Demolition	Transport	Waste processing	Disposal	Reuse -, Recovery -, Recycling Potential
	Review List ES provision requirements		Water Cycling																
Strategies/ NbS	Description	Source	Limit the damage, intensity and scale; replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent if losses cannot be avoided	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider redistributions of runoff and redesign of road ways according to natural processes tied to the ground level	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider redistributions of runoff and redesign of sealed area according to natural processes tied to the ground level; replicate/mimic EP characteristics with site to equal or outweigh previous conditions	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider redistributions of runoff and redesign of road ways according to natural processes tied to the ground level	Limit the damage, intensity and scale; preserve and incorporate present BS in planning/design; replicate/mimic EP characteristics with actions to equal or outweigh previous conditions; consider mimicking natural destruction events in characteristics, severity and extent if losses cannot be avoided	limit the reduction in evapotranspiration processes; mimic/ replicate/ integrate naturally occuring agents for EP's as much as possible with the design; enable evapotranspiration and incorporate the natural water cycle in the operational water use setup	limit disruption/damage intensity and frequency; avoid excessively reducing vegetation/BS; consider mimicking natural events in characteristics, severity and extent to interfere and adapt activity accordingly	Unknown	Unknown	Unknown	Unknown	incorporate the natural water cycle in the operational water use setup; enable evapotranspiration	support natural regeneration of BS structure to accelerate EP/ES provision and extent	Limit the damage, intensity and scale of clearance and sealing area; enable EP's with BS structure at least around direct ground losses; consider redistributions of runoff and redesign of road ways according to natural processes tied to the ground level	limit the disruption and damage; keep BS intact	Unknown	if BS actors for EP can be provided, there are contributions in form of the ES
Green Façade	Climbing plants; partial or complete coverage of wall; direct or indirect growing systems; ground or container based	Katharina NbS Design Strategies Review	not applicable					can contribute to evapotranspiration and runoff processes and achieve similarity to natural rates, however other EP's related to groundwater drainage and regulation of soil water content are not targeted/limited due to vertical setup	not applicable										a relocation of intact vegetation should be able to keep evapotranspiration ability as much as in the use phase, while other EP's are limited due to setup
Intensive Green Roof	vegetation growing on layer of soil substrate, root barrier, drainage system and waterproof membrane on top of insulation and roof structure; substrate thickness (~15cm), size of vegetation dependent on substrate depth and roof load bearing strength; however trees are not common due to weight restrictions; suitable for human use	Katharina NbS Design Strategies Review; https://urbinat.eu/nbs/green-roof-2/	not applicable					except for the higher BS layers, natural processes can theoretically be replicated and provided by vegetation; thus only extent of processes is likely to differ in magnitude due to missing of dominant tree infrastructure in analysed rainforest ecosystem (much reduced biomass and transpiration)	not applicable										a relocation of intact vegetation should be able to keep EP provision ability as much as in the use phase; however a relocation is most feasible in parts which however disrupts integrity and dissects established root/soil network
Insert the to be investigated strategy below	*Describe the selected strategy below*	*Describe your potential source of reference*	*Review the above requirements for the selected strategy and document below*																