Scoping study on the ability of circular economy to enhance biodiversity

Identifying knowledge gaps and research questions

H. Chouchane, A. Jellema, N.B.P. Polman, P.C. Roebeling

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Abstract

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Through an in-depth analysis of EU and Dutch governmental policy documents and scientific papers, this study identifies three main knowledge gaps for halving the ecological footprint of Dutch consumption by 2050: (1) national and EU policies do mention, though not explicitly, the relationship between circular economy (CE) and biodiversity – indicating a potential lack of knowledge and action perspective; (2) that the entire set of footprint indicators (footprint family) is essential for measuring the effects of CE on biodiversity; and (3) research on CE footprints and biodiversity is currently mainly focused on the energy and food sectors while sectors, such as mining, manufacturing and construction are the focus of many CE policies.

Keywords: Biodiversity, circular economy, circular policy, footprint family, knowledge gaps, scoping study

Referaat

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In deze studie worden kennishiaten verkend voor het halveren van de ecologische voetafdruk van de Nederlandse consumptie in 2050. Op basis van een analyse van beleidsdocumenten en wetenschappelijke literatuur zijn de volgende hiaten onderscheiden: (1) in nationaal en EU-beleid wordt de relatie tussen circulaire economie (CE) en biodiversiteit wel genoemd, zij het niet expliciet - wat duidt op een mogelijk gebrek aan kennis en handelingsperspectief; (2) dat de gehele set voetafdrukindicatoren (footprint family) essentieel is voor het meten van de effecten van CE op biodiversiteit; en (3) onderzoek naar CE-voetafdrukken en biodiversiteit momenteel vooral gericht is op de energie- en voedselsector, terwijl sectoren als mijnbouw, industrie en bouw de focus zijn van veel CE-beleid.

Trefwoorden: Biodiversiteit, circulaire economie, circulair beleid, footprint family, kennishiaten, scoping onderzoek

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Preface

This report is the result of a scoping study undertaken to map which knowledge is available and which is still required to analyze the potential of measures that would enable a circular economy to contribute to halving the ecological footprint of the Netherlands. The results were used in the preparation of the WOT Working Plan 2022 on Knowledge Development and Application for Nature & Environment, commissioned by PBL.

We especially want to thank Mark van Oorschot (Netherlands Environmental Assessment Agency) and Joep Dirkx (WOT Nature and the Environment) for providing feedback, and the participants in the workshops and everyone else we spoke to for their stimulating discussions and critical assessment of our findings.

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Summary

Global biodiversity and the ecosystems that it provides are declining at unprecedented rates, threatening nature and human well-being. According to the Intergovernmental Panel on Biodiversity and Ecosystems (IPBES), increased efforts are needed to halt the decline of biodiversity, including radical changes in the way we consume and produce. The Dutch government has the ambition to halve its ecological footprint by 2050. A transition to a circular economy (CE) is considered to be a means to achieve this objective. However, without further research, the potential of CE to halve the Dutch ecological footprint and enhance biodiversity remains insufficiently substantiated. This study identifies knowledge gaps surrounding the relationship between circular economy, biodiversity, and the footprint family. It aims to map which knowledge is available and which knowledge is still required to enable statements to be made about the potential of CE measures to halve the Dutch ecological footprint.

This study shows that:
1. Circular economy was initially considered as a contributor to the preservation and restoration of biodiversity. Although explicit connections to measures are lacking, it has now become a goal for Dutch policy.
2. EU policies mention the relationship between CE and biodiversity, but this is not explained in detail.
3. Policies need to be (further) developed to stimulate structural changes in the Dutch agricultural sector that should lead to circular agriculture aimed at enhanced biodiversity.
4. The entire set of footprint indicators – referred to as ‘the footprint family’ is essential for measuring the effects of CE on biodiversity. They capture both synergies and trade-offs of changes in resource use. There is also a specific footprint indicator for biodiversity that has emerged (internationally) in recent years.
5. Research on CE, footprints and biodiversity is currently mainly focused on the energy and food sectors, while sectors, such as manufacturing and construction are the focus in many circular economy policies.
6. Although literature that focuses on the link between CE, footprint and biodiversity in support of policy is still limited in scope, it has increased in quantity from 2015 onwards.
7. The LCA methodology has dominated literature in the last two decades.
8. Five main research questions resulted from the in-depth literature research and policy analysis: including what is necessary to improve the applicability of biodiversity indicators in the context of circular economy? How to deal with upscaling/out-scaling of solutions? What are the effects of Dutch circular policies? What are the impacts on construction? And finally, what is necessary for holistic policy evaluation?

Methods
The study was carried out in two steps: (a) an initial explorative scoping study on research gaps and knowledge questions surrounding the three research fields through analysis of EU and governmental policy documents and scientific papers, and (b) an in-depth systematic literature research, performed using the Elsevier Scopus database. Combinations of search terms were used to perform searches in the selected database. Additionally, synonyms and wildcard search terms were used, to ensure comprehensive coverage of articles.

Samenvatting

De wereldwijde biodiversiteit en de ecosysteemdiensten die het levert nemen in ongekend tempo af. Dit is een bedreiging voor de natuur en het welzijn van de mens. Volgens het Intergovernmental Panel on Biodiversity and Ecosystems (IPBES) zijn meer inspanningen nodig om de achteruitgang van biodiversiteit te stoppen, waaronder radicale veranderingen in de manier waarop we consumeren en produceren. De Nederlandse overheid heeft de ambitie om haar ecologische voetafdruk in 2050 te halveren. Een transitie naar een circulaire economie (CE) wordt gezien als een middel om deze doelstelling te bereiken. Echter, zonder verder onderzoek blijft de potentie van CE om de Nederlandse ecologische voetafdruk te halveren en de biodiversiteit te vergroten onvoldoende onderbouwd. Dit onderzoek identificeert kennislacunes rondom de relatie tussen circulaire economie, biodiversiteit, en de voetafdrukfamilie. Het beoogt in kaart te brengen welke kennis beschikbaar is en welke kennis nog nodig is om uitspraken te kunnen doen over de potentie van CE-maatregelen om de Nederlandse ecologische voetafdruk te halveren.

Uit deze studie blijkt dat:
1. Van een circulaire economie werd aanvankelijk verwacht dat het automatisch zou bijdragen aan het behoud en herstel van biodiversiteit. Inmiddels is dit een opzichzelfstaand doel geworden
2. Het EU-beleid noemt de relatie tussen CE en biodiversiteit, maar maakt deze niet expliciet.
3. Beleid gericht op structurele veranderingen in de Nederlandse landbouwsector die moeten leiden tot kringlooplandbouw en tot vergroting van biodiversiteit moeten (verder) worden ontwikkeld.
4. De gehele set van voetafdrukindicatoren - aangeduid als de voetafdrukfamilie - is essentieel voor het meten van de effecten van CE op biodiversiteit, waarbij zowel synergiën als trade-offs van veranderingen in hulpbronnengebruik in beeld worden gebracht. Er is ook een specifieke voetafdrukindicator voor biodiversiteit, die de laatste jaren (internationaal) in opkomst is.
5. Onderzoek naar CE, voetafdrukken en biodiversiteit is momenteel vooral gericht op de energie- en voedselsector, terwijl sectoren als de verwerkende industrie en de bouw in veel circulaire economie-beleid centraal staan.
6. Hoewel literatuur gericht op de relatie tussen CE, footprints en biodiversiteit ter ondersteuning van beleid nog beperkt van omvang is, neemt deze vanaf 2015 wel in omvang toe.
7. De LCA-methodologie domineerde de literatuur in de laatste twee decennia.
8. Uit het verdiepende literatuuronderzoek en de beleidsanalyse volgen 5 hoofdonderzoeksvragen over de noodzaak van het verbeteren van de toepasbaarheid van biodiversiteitsindicatoren in de context van de circulaire economie, hoe om te gaan met opschalen/uitschalen van oplossingen, effecten van Nederlands circulair beleid, effecten op de bouw, en tot slot de noodzaak van holistische beleidsevaluatie.

Methoden
Het onderzoek is uitgevoerd in twee stappen: (a) een eerste verkennende scopingstudie naar leemtes in onderzoek en kennisvragen rond de drie onderzoeksgebieden doormiddel van een analyse van beleidsdocumenten van de EU en de Rijksoverheid en wetenschappelijke papers, en (b) een diepgaand systematisch literatuuronderzoek, uitgevoerd met behulp van de Elsevier Scopus database. Combinaties van zoektermen werden gebruikt om zoekopdrachten uit te voeren in de geselecteerde databank. Daarnaast werden synoniemen en wildcard-zoektermen gebruikt, zodat een uitgebreide dekking van artikelen werd gegarandeerd.

1 The decline in biodiversity

Biodiversity is indispensable to human existence on Earth. It provides us with food, filters our drinking water, supplies the air that we breathe, and is essential for our mental- and physical well-being. Biodiversity is also the foundation of our economy. For example, sectors, such as agriculture, renewable energy and construction, are highly dependent on biodiversity.

Despite the economic and environmental necessity, biodiversity is declining rapidly worldwide. Biodiversity decline stems mainly from changes in land use (e.g. deforestation, urbanization), climate change, direct exploitation of organisms, pollution and the spread of invasive alien species (IPBES, 2019).

Global discussion on biodiversity loss is not new; a multilateral biodiversity treaty to combat biodiversity decline was drawn-up in 1992: the UN Convention on Biological Diversity (CBD). However, global efforts are insufficient to achieve the targets defined in the UN Convention and, therefore, this effort has largely failed. In 2010, the third edition of the Global Biodiversity Outlook revealed that none of the 21 sub-targets set for 2002-2010 had been achieved globally (although some local targets have been achieved) (Secretariat of the Convention on Biological Diversity, 2010). In response to this failure, a new strategic plan was adopted in 2010 for the period 2011-2020 (Aichi Biodiversity Targets). However, in 2020 it turned out that none of the 20 targets set in the plan had been fully accomplished (Secretariat of the Convention on Biological Diversity, 2020).

As a result, the fifth edition of the Global Biodiversity Diversity Outlook emphasized that current policies jeopardize the achievement of the Sustainable Development Goals and undermine climate change mitigation efforts. Alongside this, it is stressed that significant change must occur in a wide range of human activities to restore biodiversity (Secretariat of the Convention on Biological Diversity, 2020).

2 Circular economy: Policy context to deal with biodiversity decline

Why a circular economy?
The need for a transition to a circular economy (as defined in Box 1) stems from a number of developments. One of the main factors is that the demand for raw materials has risen sharply over the past century (SER, 2016). In the 20th century, the extraction of construction materials, minerals and ores, and fossil fuels grew by, factors of 34, 27 and 12 (respectively) (UNEP, 2011). Due to the growing demand for raw materials, pressure on climate and the environment continues to increase. This is reflected in climate change, biodiversity loss, soil erosion and air pollution (UNEP, 2016). In addition, the Netherlands and Europe are highly dependent upon the import of raw materials. The Netherlands obtains 68% of its raw materials from outside its borders. Of the 54 critical materials required in Europe, 90% is imported, mainly from China (SER, 2016).

The demand for raw materials is anticipated to increase further as a result of global population growth (expected to reach 9-10 billion by 2050), the fast-growing middle class in emerging economies and the application of new technologies that require specific raw materials (for example, rare metals for electric motors) (SER, 2016). If no action is taken, pressure on the natural environment will increase sharply in the coming decades, with several consequences, such as climate change and biodiversity loss. In this context, efforts are being made at both international- and national levels to initiate a transition from the current linear economy to a circular economy (see Figure 1).

A renewed EU Circular Economy Action Plan under the Green Deal
The current European Union (EU) circular economy policy has emerged along two tracks: The EU's Environmental Policy and the EU's Raw Materials Policy. The EU Environmental Policy stems from the 2012 Treaty on the European Union's Functioning (TFEU, Article 191). Amongst others, the policy aims to preserve, protect and improve the environment and the use of natural resources. The EU Raw Materials Policy is mainly anchored in the EU's Economic Policy (TFEU article 173). With the Raw Materials Policy, the EU aims to ensure the supply security of raw materials for the EU economy (Hanemaaijer et al., 2021).

In 2015, the European Commission (EC) presented a circular economy action plan: Closing the loop – An EU action plan for the Circular Economy. The EC aimed to promote the transition to a circular economy in the EU. In this plan, the EU Environmental- and Raw Materials Policies have been brought together in an integrated policy framework. It includes a wide range of measures to preserve the value of products, materials and resources for as long as possible, and minimize waste production (EC, 2015).

Box 1 What is a circular economy?

The circular economy proposes an alternative economic model that replaces the traditional linear economy end-of-life concept by reducing, alternatively reusing, recycling and recovering raw materials in production/distribution and consumption processes. It operates at micro-level (products, companies, consumers), meso level (eco-industrial parks) and macro-level (city, region, nation and beyond), intending to achieve sustainable development and simultaneously benefiting environmental quality, economic prosperity and social justice of current and future generations (Kirchherr et al., 2017).

More efficient use of raw materials can be achieved with several circularity strategies, known as R-strategies. Forgoing certain products or using them more intensively by sharing them with others or through multifunctionality (Refuse and Rethink), more efficient manufacturing of products or making them more efficient to use (Reduce), reuse (Reuse) and repair products so that they last longer (Repair and Refurbish), the reuse of materials so that less waste is generated (Recycle) and, finally, fewer new raw materials are needed, and recovering energy from certain materials (Recover).

In 2019, the European Green Deal was presented. It contains a package of measures through which the EC intends to modernize the European economy by, amongst others, reducing net greenhouse gas emissions in the EU to zero by 2050. With the Green Deal, the EC wants to support the transition to a circular economy (Hanemaaijer et al., 2021). In 2020, the EC presented a new action plan for the circular economy, published under the Green Deal: A new Circular Economic Action plan for a cleaner and more competitive Europe. The plan includes measures aimed at promoting sustainable consumption (EC, 2020).

The plan aims to further anchor circular principles in existing EU policy instruments. The EC has also expressed the ambition to extend current 'hard' instruments, such as legislation and regulations to the circular economy. This includes legislative initiatives to ensure that products contain as many recycled materials as possible, last longer, and are easier to repair and reuse. With this, the EU is taking a different course than previously. Except for waste policy and energy use policy, legislation, regulations and challenging targets are still largely lacking in the circular economy policy of the EU. They mainly relate to the design and consumption phase of products (Hanemaaijer et al., 2021).

The circular economy is gaining ground in Dutch policy
The transition to a circular economy in the Netherlands stems from the Dutch waste policy. The first contours of circular policy can be found in 2014 from the Waste to Resources program (Van Afval Naar Grondstoffen: VANG). The program focused on managing waste flows and aimed to halve the amount of waste being incinerated or deposited by 2023 (PBL, 2020).

In 2016, the Dutch government presented its Circular Economy program, with which the government expressed its ambition to establish a circular economy in the Netherlands before 2050. The government's ambition is to achieve an intermediate target of halving the use of primary abiotic raw materials, such as minerals, fossil fuels and metals, by 2030 (Rijksoverheid, 2016). The Raw Materials Agreement (Grondstoffenakkoord) has been created as a follow-up to the government-wide Circular Economy program. In this agreement, the government has made arrangements with other parties in society to accelerate the transition to a circular economy. The Raw Materials Agreement has been signed by more than 400 organizations, including NGOs, financial institutions, governments and companies. On behalf of these organizations, five transition agendas were drawn-up for the following themes: (1) Biomass and food; (2) Plastics; (3) Manufacturing industry; (4) Construction; and (5) Consumer goods (Rijksoverheid, 2019).

For the period 2019-2023, the five transition agendas were translated into concrete actions and projects in the context of the Circular Economy Implementation Program. This program was created to identify and remove obstacles in current legislation and regulations that hinder the development of a circular economy, alongside others (Rijksoverheid, 2019).

The Dutch Environmental Assessment Agency (PBL) has emphasized that the chosen approach forms the basis for initiating the transition to a circular economy. However, most policy instruments used in the context of circular economy are mainly supportive. Few legal and economic instruments have been applied. In cases, in which these instruments have been used, they often have to be further elaborated and adopted by Parliament. In order to promote the transition towards a circular economy, it is necessary to apply legal and economic instruments, in particular, because the voluntary and non-committal nature of the current policy is not in-line with the ambitions of the government, as described in the program circular economy (Hanemaaijer et al., 2021).

EU roadmap to stop biodiversity decline under the Green Deal
The EC considers circular economy as a means to restore biodiversity, which is made clear by the following quotation taken from the EC Communication on the New Circular Economy Action plan:

> "*The circular economy can significantly reduce the negative impacts of resource extraction and use on the environment and contribute to restoring biodiversity and natural capital in Europe*."
> (EC, 2020, p.12).

However, the relation between circular economy and biodiversity is not further discussed in-depth and elaborated upon with a specific approach. The Action Plan mainly announces initiatives aimed to ensure that resources are kept in the EU economy for as long as possible.

In addition to the Circular Economy Action Plan, the EU Green Deal also consists of the Biodiversity Strategy and the Farm to Fork Strategy.

By introducing the Biodiversity Strategy, the EU acknowledges the threats imposed by the decline in biodiversity. The strategy aims to stop biodiversity loss by 2030, and to convert it into biodiversity restoration. In addition, the strategy includes new ways to implement existing legislation more effectively. For example, existing Nature 2000 areas will be expanded, with protection for areas with high biodiversity and climate value. A far-reaching EU plan for the restoration of nature is also presented, including developing a proposal for a new legal framework for nature restoration, with binding targets to restore damaged ecosystems (European Commission, 2020b).

Through the Farm-to-Fork Strategy, the EC aims to create a fair, healthy and environmental-friendly food system by minimizing the climate and environmental impact of food production, distribution and consumption. Alongside others, the Farm to Fork Strategy sets out to reduce the overall use and risk of chemical pesticides by 50%, reduce nutrient losses by 50% and stimulate organic farming (EC, 2020c).

Both the Biodiversity Strategy and the Farm-to-Fork Strategy were presented at the same time. This is not without reason. The EC emphasizes that the two strategies are mutually reinforcing (EC, 2020d). For example, the use of pesticides in agriculture is damaging to biodiversity. The Farm to Fork Strategy sets out to reduce the number of hazardous pesticides in agriculture.

The relationship between the New Circular Economy Action Plan and the Biodiversity Strategy is less clear. Nevertheless, it is mentioned in the Biodiversity Strategy that:

> *"the pressure from plastics is notably addressed through the implementation of the European Strategy for Plastics and the new Circular Economy Action Plan."* (EC, 2020, p.14).

Concrete policy measures to support Dutch ambition to reverse biodiversity decline through a circular agriculture need to be (further) developed
As mentioned earlier, many environmental problems, such as loss of biodiversity, are caused by the increasing use of raw materials worldwide. If nothing is done about the ever-increasing use of raw materials, the pressure on the environment and thus biodiversity will only increase. In the Dutch government Circular Economy 2050 program, the circular economy is seen as a means of reversing this trend.

Much biodiversity has disappeared in the Netherlands over the past century, but in nature reserves the average loss of biodiversity has declined. However, in cities and agricultural areas, biodiversity is still deteriorating (PBL, 2020). For a long time, the starting point of Dutch biodiversity policy was that nature restoration should mainly come from more robust and larger nature areas. According to "Nederland Natuurpositief", however, measures in nature areas alone are not enough to halt the loss of biodiversity (Ministerie van LNV & Provincies, 2019). Therefore, a significant contribution from the Dutch agricultural sectors is also required to halt biodiversity losses. To meet this challenge, in 2018 the Dutch government expressed the ambition that the Dutch agricultural system should produce according to circular agricultural principles by 2030 (LNV, 2018). Circular agriculture means that agricultural biomass and its nutrients are retained in the food system (Thijssen, 2018).

However, the structural changes in agriculture that should lead to circular agriculture have, until 2021, hardly been translated into concrete policy measures (PBL, 2020). The policy for circular agriculture, nature and nitrogen was mainly aimed at adapting normal business operations. The current government's policy aims for a circular food system (LNV, 2022). Policies need to be (further) developed to stimulate circularity aimed at restoring biodiversity. Evaluating specific measures was beyond the scope of this study.

3 From planetary boundaries to footprints

Planetary boundaries, launched by Rockström et al. (2009), are defined as the safe workspace for humanity with regard to the functioning and resilience of the Earth system. They are associated with the following nine biophysical subsystems or processes that regulate the Earth system's functioning: climate change, biodiversity loss, interference with nitrogen- and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, land-use change, chemical and atmospheric pollution, and aerosol loading.

Four of these boundaries are already being violated by human activities: climate change, biosphere integrity, biogeochemical flows (nitrogen and phosphorus) and land-use change. The disturbances of biogeochemical flows and genetic diversity even fall outside the uncertainty zone (Steffen et al., 2015).

Steffen et al. (2015) have further developed the planetary boundaries to also account for boundaries at the regional level. Regional boundaries include biodiversity integrity, freshwater use, land-use change, biogeochemical flows and atmospheric aerosol load. The planetary boundaries for stratospheric ozone depletion, ocean acidification and climate change are only relevant globally, although the related effects can be very different locally (Vanham et al., 2019).

The link between footprint indicators and planetary boundaries is not new and was first identified by Wackernagel and Rees (1996), who linked the human ecological footprint to the means of nature. Fang et al. (2015) also analyzed the linkage between the two fields and presented a framework that brings different footprint indicators together with the planetary boundaries in a complementary way. While planetary boundaries indicate the threshold that should not be exceeded, footprint indicators measure the current environmental pressures exerted by human activities due to resource use and emissions. To prevent unwanted changes in the environment, humans should not simply reduce their footprints but ensure that these footprints remain within the planetary boundaries (Fang and Heijungs, 2014, Heijungs et al., 2014).

For the case of the Netherlands, Lucas and Wilting (2018) downscaled these global planetary boundaries to the national context. Using the Dutch footprints as a benchmark against the downscaled planetary boundaries, the footprints for CO_2, land use, nutrient pollution (N and P) and biodiversity loss were well above the global average. These footprints are also larger than what can be considered reasonable according to the various downscaling approaches analyzed (Lucas and Wilting, 2018). The objectives of the circular economy are aimed at reducing several of these footprints (related to carbon emission, land use, nutrient pollution), to assist in staying within planetary boundaries, while at the same time, reducing the drivers of biodiversity loss.

4 Quantification of the environmental impacts: Footprints

Which footprint indicators for biodiversity?
Environmental footprints are quantitative measures showing the appropriation of natural resources by humans (Hoekstra, 2009) and the resulting pressures on the environment. They provide insight into the environmental changes caused by these pressures (e.g. land-use changes, land degradation, reduced river flows, water pollution and climate change) and the resulting impacts (such as loss of biodiversity or effects on human health or the economy). The footprint family is a set of indicators able to track human pressures on the planet from different angles in a more comprehensive way (Galli et al., 2012). It represents the major categories of footprints developed to date, namely the ecological footprint (EF), the carbon footprint (CF), the energy footprint (ENF), and the water footprint (WF), and is related to climate, food, water and energy security (Fang et al., 2014). Vanham et al., (2019) expanded the list to further include, amongst others, the land footprint (LF), the environmental footprint (ENVF) and the biodiversity footprint (BF). Footprint indicators within the family cannot be analyzed individually because of potential side-effects (see Box 2).

The ecological footprint (EF) measures the appropriation of productive land- and sea areas necessary for human activities and the resulting waste absorption (Borucke et al., 2013). The land use (e.g. infrastructure), the use of biomass (e.g. fish stocks) and CO_2 emissions (e.g. from the use of fossil energy) are expressed in 'global hectares' (gha), which need to be compared to 'biocapacity'. Biocapacity measures the bio-productivity that our planet can provide within a specific area (e.g. arable land, grassland, forest and productive sea).

The land footprint measures the total amount of land needed to supply food, material, energy and infrastructure. It can be expressed in physical unit (hectares or km^2) or land equivalent unit (i.e. global hectares) (Thomas et al., 2014; Weinzettel et al., 2013).

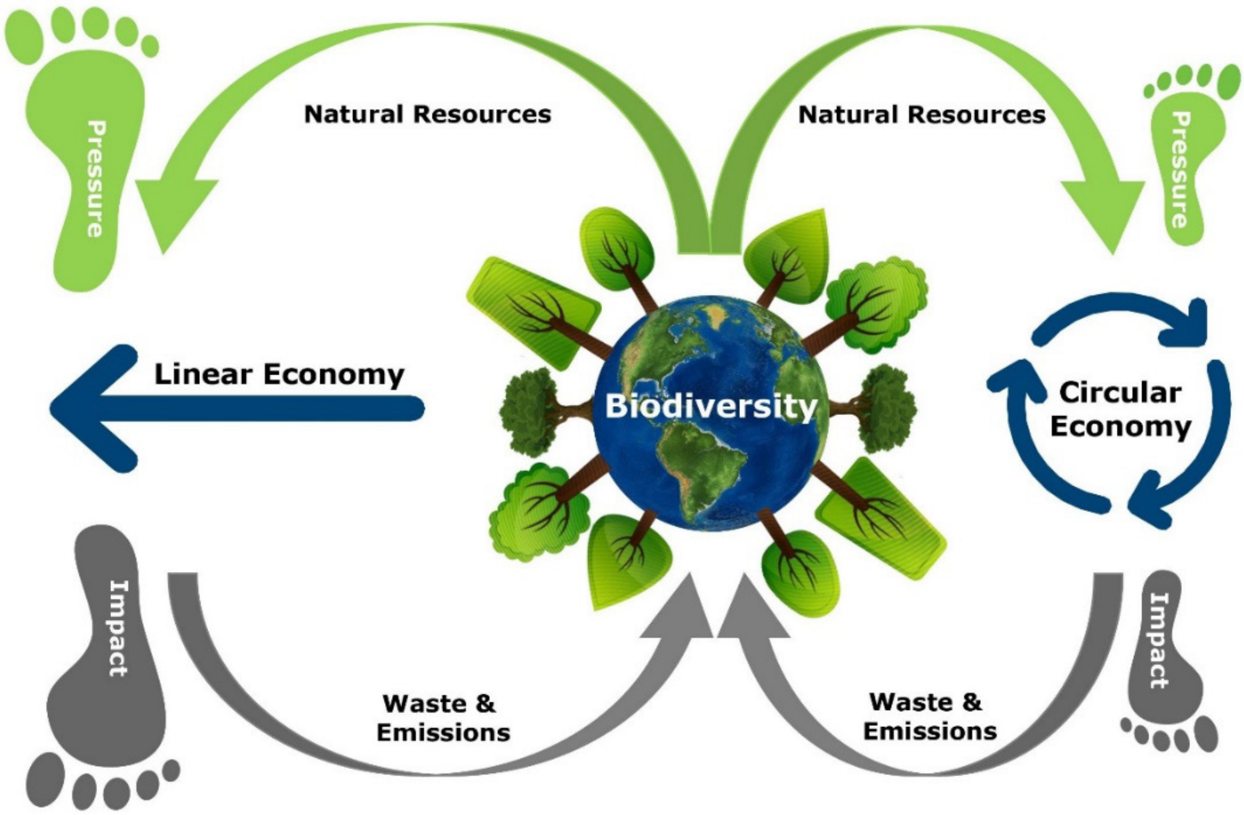

Figure 1 *Mitigating impact and pressure on biodiversity moving from linear to a circular economy.*

The carbon footprint (CF) measures the total amount of greenhouse gas (GHG) emissions (such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)) directly and indirectly caused by an activity or collected over the life stages of a product, including the production supply-chain and waste-processing. This includes activities of individuals, populations, governments, companies, organizations, processes, industry sectors, etc.

Conceptually, the carbon footprint also includes GHG emissions from land-use change, although this is not always the case in practice (Vanham et al., 2019).

The energy footprint (ENF) is expressed as the carbon part of the ecological footprint (Wiedmann, 2008), or the specific energy usage per functional unit when considering fossil-based and renewable-based energy (Sobhani et el., 2012).

The water footprint (WF) is an indicator of freshwater use that quantifies and maps water consumption and pollution in relation to production or consumption. It consists of blue, green and grey WFs (Hoekstra et al., 2011). The blue WF refers to the consumption of surface and groundwater resources. The green WF refers to the consumption of rainwater stored within the soil as soil moisture. The grey WF measures water pollution and is defined as the freshwater volume required to assimilate pollutant loads given natural background concentrations and existing ambient water quality standards (Chouchane et al., 2015).

The environmental footprint (ENVF) is an umbrella concept for the different footprints that have been developed over the past two decades. The concept is also used in the life cycle assessment (LCA) community that is related to a product or an organization's environmental footprint (Vanham et al., 2019).

Finally, the biodiversity footprint (BF) measures biodiversity loss due to different impact pressures, such as land use, water use and chemical pollution (Vanham et al., 2019). There is no standard unit of measure for the biodiversity footprint due to the many dimensions and complexities of biodiversity (Marques et al., 2017).

Dutch ambition to halve the ecological footprint

The only specific and direct policy concerning footprint indicators in the Netherlands is the objective announced in September 2019 to halve the ecological footprint of Dutch consumption by 2050. However, this ambition requires further clarification before a coherent policy can be defined and implemented. As mentioned before, besides the ecological footprint (EF) there are many other footprints (such as the carbon-, water- and energy footprints) that should be considered simultaneously, while there is also no unambiguous assessment of the size (quantity of ecosystems) and depth (quality of ecosystems) of the footprint (Van Oorschot et al., 2021). In addition, the impact of this size and depth of the footprint on biodiversity, ecosystem services and ecosystem service values must be mapped, and the effectiveness, private costs and public benefits of action options for reducing the footprint must be identified and quantified. Nevertheless, some indirect links can be made from other climate and biodiversity policies.

Footprint calculation methods: top-down and bottom-up

The methods used in calculating footprint indicators fall into two main approaches: the so-called bottom-up and top-down approaches. The bottom-up approach is part of the process analysis with detailed descriptions of production processes at the product level. To calculate the national footprint, the individual product results are aggregated based on the country's total consumption. The bottom-up approach usually utilizes the Environmental Footprint Assessment (EFA) and the Life Cycle Assessment (LCA) methods (see Feng et al., 2011b). EFA and LCA are both based on life cycle reflection, but differ in purpose and approach. EFA includes methods for quantifying and mapping land-, water-, material-, carbon- and ecological footprints, thereby, assessing the sustainability of these footprints and the efficiency, fairness and safety of resource use. LCA is a method of estimating and evaluating the environmental impacts that can be attributed to the life cycle of a product, such as climate change, stratospheric ozone depletion, tropospheric ozone creation, eutrophication, acidification, toxicological impact on human health and ecosystems, resource depletion, water use, land use, and others. EFA is resource use and emission or pressure oriented (i.e. inform users about the pressure that human activities exert on ecosystems), while LCA is impact-oriented (inform users about the possible consequences of these pressures) (Vanham et al., 2019).

The top-down approach uses an economical approach to economic- and ecological domains (Feng et al., 2011a) based on aggregated economic data and environmental pressures at the global level. The national pressure on the environment or the use of raw materials is calculated based on the supply chain, in monetary units, between sectors and countries at the global level. The top-down approach typically uses the Multi-Regional Input-Output (MRIO) method (see Feng et al., 2011a; 2011b), although the EFA method could be used (see, e.g. Van Oel et al., 2009). MRIO are one of the most widely used approaches to analyze the economic interdependence between different regions (Mi et al., 2012). MRIO focuses on understanding how to track natural resource use and environmental impacts across the economy.

Bottom-up methods are useful when calculating the footprint of specific products and product groups. Top-down models are more suitable for calculating and comparing the footprint of different countries. Both approaches converge with consideration on the scale of one country. One of the first steps in answering a footprint question should be a responsible choice of a particular approach.

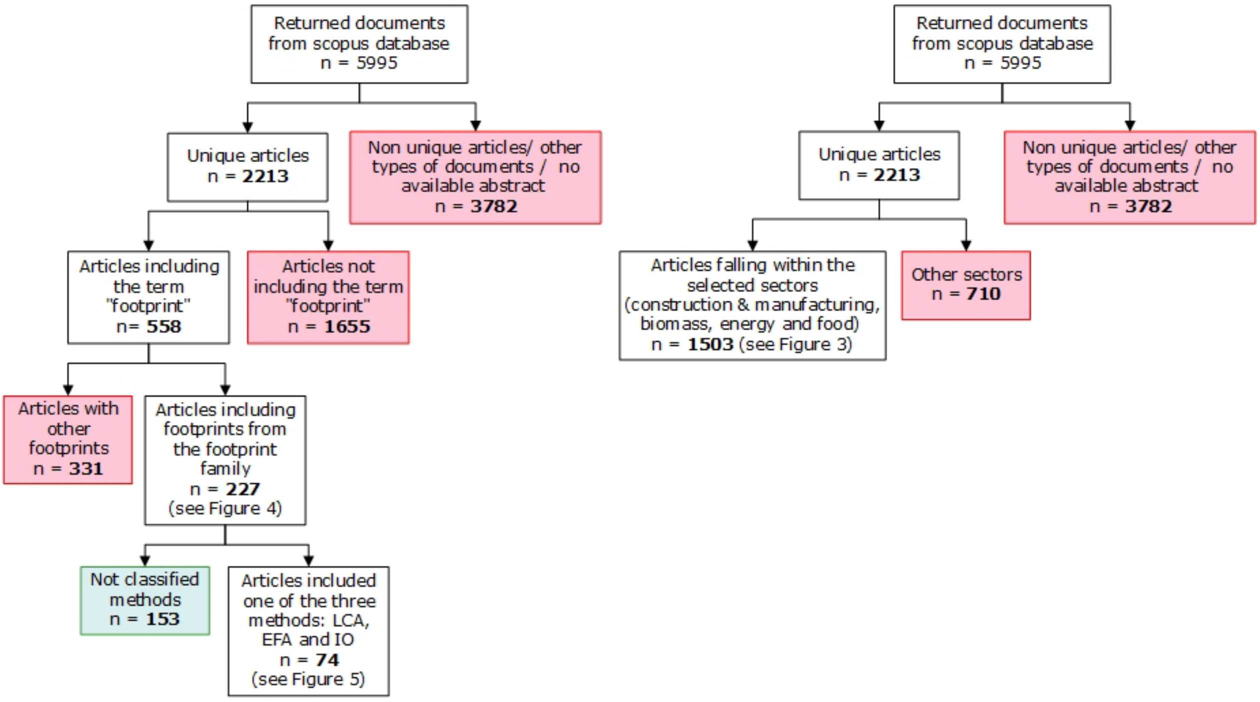

Figure 2 *Literature search strategy. The left side of the figure shows how articles are classified per footprint and method. The right side of the figure shows how articles are classified per sector. The red boxes mean that the articles are excluded, and the green box indicates that the articles still need to be classified in follow-up research.*

5 Explorative literature research

The search for relevant articles on biodiversity in relation to circular economy and footprints was performed using a systematic literature review based on the Elsevier Scopus database. Scopus is one of the most extensive citations and abstract databases, with approximately 75 million records. Combinations of search terms were used to perform searches in the selected database. Additionally, synonyms and wildcard search terms were used, ensuring comprehensive coverage of articles (see Table 1), for example: "planetary boundar* OR environmental threshold OR tipping point" AND "biodivers*"; "bioenerg* OR bio-energ* AND" biodivers*.

While the search strategies aimed to ensure that only relevant articles were obtained, inclusion and exclusion criteria were used to exclude irrelevant articles. The selection criterion focused on manuscripts written in English, published between 2000 and 2020, excluding magazine articles, books, book chapters, conference papers, letters, reviews and short surveys. Articles without an available abstract, representing 6% of the total articles, were also excluded since abstracts are necessary for the first screening of articles (see Figure 2).

Once potentially relevant papers were identified, duplicates were removed.

Table 1 *Number of articles per search term combinations, where 2213 are unique articles.*

Search terms combination	Number of articles
Biodiversity and bioenergy	1242
Biodiversity and footprint	1128
Biodiversity and biofuel	1119
Biodiversity and manufacturing	700
Biodiversity and natural capital	431
Biodiversity and planetary boundaries	268
Biodiversity and use value	257
Biodiversity, footprint and policy	227
Biodiversity, ecosystem services and footprint	129
Biodiversity, biomass and footprint	105
Biodiversity, Case Study and Footprint	85
Biodiversity and circular economy	73
Others	231

Sector of activity: Food and energy are dominant

Within the selected articles (2213 in total, see Figure 2), further search using specific terms was performed to group articles by activity sector (see Figure 3). The food and energy sectors were dominant research themes in articles published over the last two decades. Within the energy sector, bioenergy and biofuel were the most prevalent. Some articles did not fall within these sectors classification and will be left out in the follow-up research.

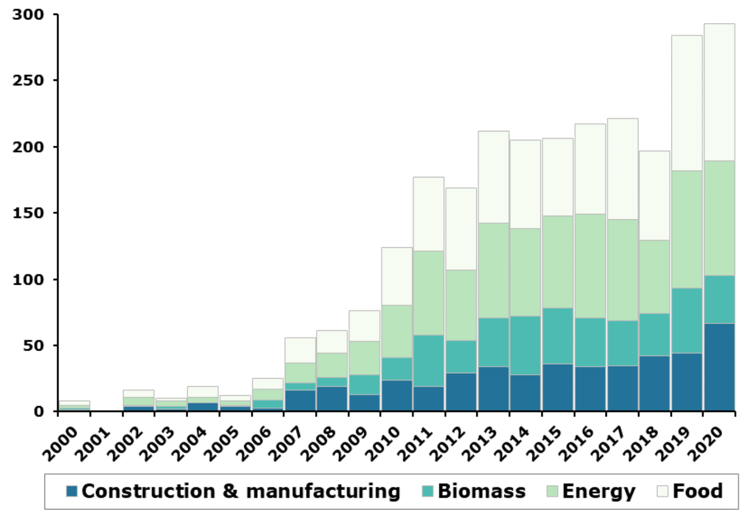

Figure 3 *Annual number of 2213 unique articles, 32% could not be classified and, thus, were not included in the figure.*

Footprint indicators: Insight into the footprint family

A scan was made through summaries and keywords to identify the various footprint indicators used in the selected articles. We found 558 articles that included the term 'footprint' (see Figure 2). Surprisingly, there was about a hundred unique footprint indicators used over the past twenty years. Footprint indicators were ranked based on their occurrence within the selected articles. The most commonly used indicators partly coincide with those listed in the footprint family developed by Vanham et al. (2019). We excluded articles in which footprint was not specified and those including 'human footprint', as they were not included in Vanham et al., (2019). This resulted in 227 unique articles.

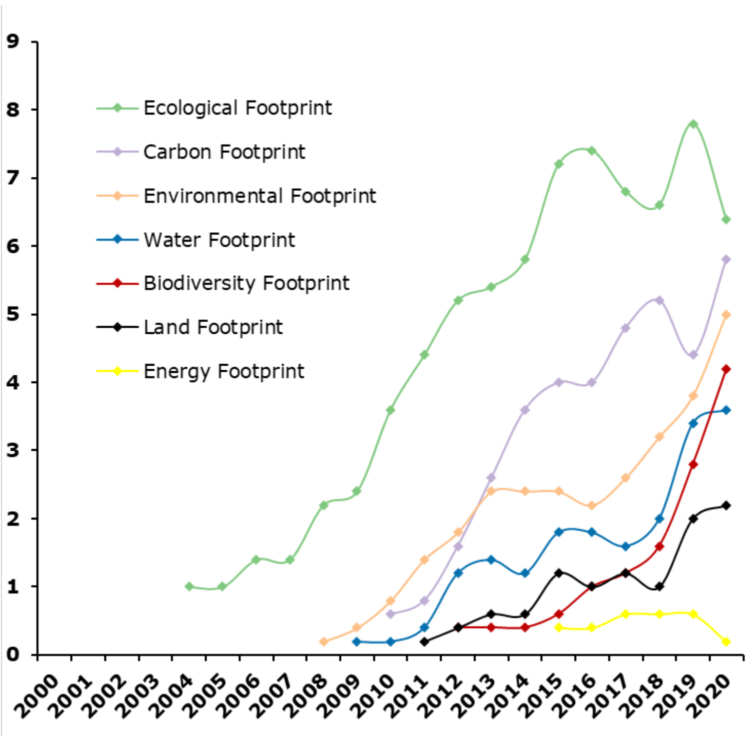

Figure 4 *The moving averages of articles per footprint indicator (2000-2020). In total, 227 articles included footprints from the footprint family, as developed by Vanham et al., (2019).*

Ecological footprint largely dominates other footprint indicators in literature, followed by environmental- and carbon footprint. Energy footprint was the least used indicator in the literature from the footprint family. It is also worth noting that literature on the biodiversity footprint has been steadily increasing since 2012 (see Figure 4).

Footprint methodology: LCA dominates
If we look at the footprint methods, it is clear that LCA has dominated over the last two decades (see Figure 5), while Input-output analysis and EFA were relatively rarely used. The classification of other articles will be carried out in follow-up research.

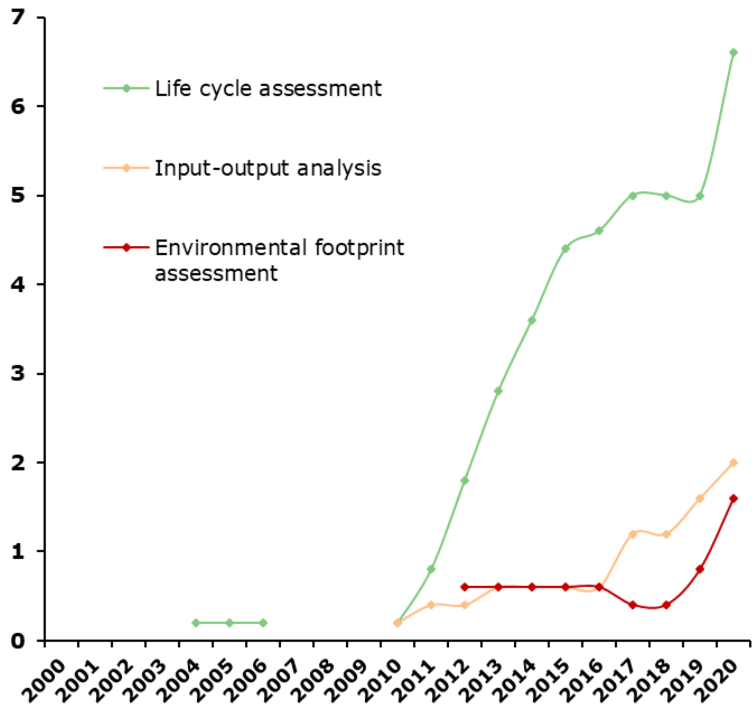

Figure 5 *The moving average of articles per footprint methodology (2000-2020). Of the 227 unique articles, 153 articles still require classification in follow-up research.*

6 In-depth policy and literature review

The scoping study charted the ‘playing field’ that surrounds the various policy objectives, and the knowledge gaps surrounding the relationship between circular economy, biodiversity, and footprint indicators.

In order to deepen the explorative scoping study, a co-elaborative research question identification approach was used (adapted from van Dijk-de Vries et al., 2020). In total, 14 policy documents (Appendix 2) and 30 scientific articles (Appendix 3) were separately analyzed.

The analyzed policy documents were taken from the initial explorative literature research. Whereas for the scientific articles, the selection was performed based on the following criteria:

- Ten of the most cited articles in the last two decades (2000-2020).
- Ten of the most cited articles in the previous two years of the selected research period, five from 2019 and five from 2020 respectively.
- Ten articles including at least one of the footprint methodologies identified during the scoping study and including articles on circular economy.

Using ATLAS.ti, the qualitative data analysis and research software, a manual coding technique of relevant documents using specific keywords (see Appendix 1) was adopted. To ensure the quality of this research, research questions were evaluated and confirmed during two workshops on policy and scientific relevance with experts in the last step. The final questions are presented in the following chapter.

7 Emerging research questions for policy support

What improvements are needed on current biodiversity indicators to increase their applicability in the context of circular economy?
An overarching indicator for biodiversity would appear to be pointless given the complexity of the problem and the lack of possible starting points for action perspectives among stakeholders. The context (such as region, scale, sector, and type of biodiversity) and the purpose of the evaluation largely determine the usefulness of the available indicators. The available references that treat the biodiversity footprint usually focus on a single indicator of biodiversity, covering a part of the biodiversity concept (Feley et al., 2011; Renwick et al., 2013). These different indicators focus on various dimensions of biodiversity (such as species abundance, species richness or the species disappearance fraction) and lead to different interpretations. Within the so-called 'footprint family' (Vanham et al., 2019), several options have been distinguished for choosing a footprint on different drivers for biodiversity loss (such as land use, nitrogen or water footprint). Many studies are based on the impact of land use on biodiversity (e.g. Weinzettlen et al., 2013; Renwick et al., 2013). However, there is as yet no holistic picture in the references studied, which means that there are no unambiguous starting points for policy.

What effects do the applied circular policies in the Dutch agro-food sector have on biodiversity elsewhere in the world?
The policy analysis showed that there is still relatively limited knowledge of the effects of a circular economy in the Netherlands on biodiversity in the regions that Dutch imports originate from. Available biodiversity footprint studies usually only provide a general picture of supply-chains, and their effects on biodiversity. More specific information on supply-chains and the local context with regard to biodiversity (protected areas, threatened species, etc.) is needed for action at the company level. In order to gain insight into the potential of the circular economy for our food system, and, thus, to actually halve the ecological footprint of Dutch food consumption, more knowledge is required about the relationship between the production phase that takes place both within, and outside, our national borders and the consumption phase that takes place within our national borders.

What is needed to make 'upscaling, outscaling and downscaling' of local- and specific regional level applications of biodiversity and footprint indicators possible?
Both theoretical and empirical applications of footprint and biodiversity indicators were found in the literature studied (e.g. Röös et al., 2013; Prechsl et al., 2017; Di Fulvio et al., 2019). However, these remain mainly local and limited to specific cases (such as reducing the biodiversity footprint of energy crops and water footprint analyses aimed at specific catchment areas). There is still little insight into possibilities for 'upscaling, outscaling and downscaling' of local- and regional cases (impediments and facilitating circumstances). Insights from the literature analyzed on the possibilities for the 'transfer' of knowledge and experiences between sectors is also limited. In order to achieve a broader application of the results (valorization), there is a need to assess the usefulness of existing applications. This question is asked in the context of the mainline, *"A circular economy with green solutions and halving our ecological footprint"*. This fits in with the development that decision-making about nature is increasingly taking place in places other than those exclusively within nature policy and linked to other tasks.

What is the impact on biodiversity of the reuse of materials and the shift from abiotic to biotic primary resources in construction?
The Dutch government formulated the ambition to halve the ecological footprint of consumption in the Netherlands by 2050. Reducing the ecological footprint of Dutch consumption, therefore, also means reducing the footprint of product groups and sectors, such as construction, due to their high consumption of raw materials such as metals and concrete. By 2030, the government wants to halve the use of these primary abiotic raw materials. They want to achieve this goal by realizing a transition to a circular economy (CE), along with other means. As the Integrated Circular Economic Report 2021 (ICER) shows, an intensification of policy and more specific targets is necessary to achieve objectives and contribute to

reducing the loss of biodiversity (Hanemaaijer et al., 2021). However, the scientific articles studied in this project on research in the field of circular economy (CE), footprints and biodiversity focus mainly on energy (e.g. Chmelíková and Wolfrum, 2019, Di Fulvio et al., 2019) and the food sector (e.g. Muscio and Sisto, 2020), and less on sectors, such as mining, manufacturing and construction.

What additional indicators are needed to support the development of holistic policy analysis of the circular economy, footprints and biodiversity for actions at different scale levels and relevant sectors?

The literature studied showed that there is a policy demand for additional indicators for an integral analysis of the circular economy, footprints and biodiversity (see the Transition Agenda for Consumer Goods (2018) and Transition Agenda for the Manufacturing Industry (2018)). There is a need to develop indicators for monitoring and value creation on multiple scales that are currently insufficiently elaborated (e.g. biodiversity in regions from which we import or export).

This fits in with the development that decision-making about nature increasingly occurs in places other than those exclusively within nature policy and linked to other tasks. The aim is to provide insight into indicators that support the prospection for actions at different scale levels and relevant sectors (construction, food and biomass and manufacturing industry). Preferably, for increased policy relevance, different biodiversity footprint indicators should be available that can be related to the targets of the CBD convention (conservation, restoration, sustainable use, zero-deforestation). This contributes to nature-inclusive decision-making by the central government and the provinces in a broad sense.

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Annex 1 Codes used to perform the qualitative research analysis in ATLAS.ti

Code abbreviation	Full code
KG- expl, th, emp	Knowledge gap – type research type (e.g. explorative, theoretical, empirical)
FP- EF, ENGF, CF, WF, LF, BDF, ENVF,	Which footprint (Ecological, Energy, carbon...).
P- level (international, EU, country, regional, local)	Policy (which policy and at which level?)
CE	Circular Economy
BD-Loc, Reg, GL	Which level of biodiversity (local, regional or global)
I-TR, Syn	Impact (trade-offs or synergies)
MD- IO, LCA, EFA, Hyb, oth	Methodology – category (input-output (= IO), LCA, EFA, hybrid, other)
S-FD, Cstr, Eng, Manuf	FD (food), Cstr (construction), Eng (energy), Manuf (manufacturing)
AT	Action Type (stakeholder– promising- legislation - transition - policy evaluation)
V	Vision (objectives)

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