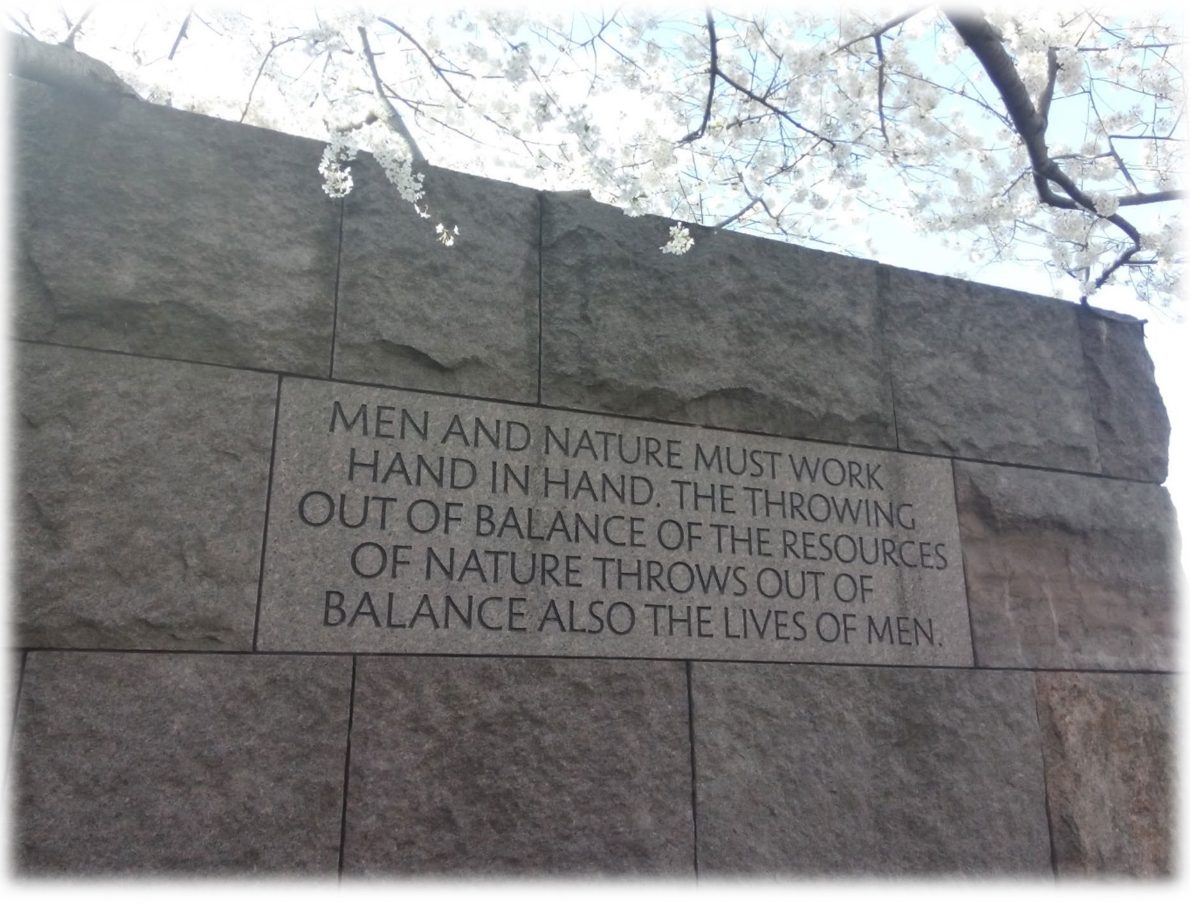
BIOPHYSICAL HUMAN-NATURE CONNECTEDNESS

CONCEPTUALIZING, MEASURING, AND INTERVENING FOR SUSTAINABILITY



Franklin D. Roosevelt

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BIOPHYSICAL HUMAN-NATURE CONNECTEDNESS

CONCEPTUALIZING, MEASURING, AND INTERVENING FOR SUSTAINABILITY

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Christian Dorninger
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Author's address:
Leuphana University
Faculty of Sustainability Science
Universitätsallee 1, 21335 Lüneburg, Germany
e-mail: christian.dorninger@leuphana.de; christiandorninger@hotmail.com

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Preface

This dissertation is presented as a series of manuscripts. The main chapters in the supplement to this framework paper (Chapter I) are designed to be stand-alone articles intended for scientific journal publication. Due to journal requirements, stylistic differences (e.g. British vs American spelling or differences in formatting requirements) are possible among articles. Chapters II and VII, and Appendices I, and II have been published. The content of each chapter or appendix is the same as the published journal article. The published articles are included in their original format as they appear in the journals. Chapters III, IV, V and VI have been submitted to international scientific journals and are formatted in a similar style to the framework paper. A reference to the journal each manuscript is published in or submitted to and the contributing co-authors are presented on the title page of each chapter or appendix. The style used for citing literature in the text and for the references sections at the end of each chapter and appendix respects the formatting requirements of the journal where the respective manuscript was published in or submitted to. Chapter I uses the reference formatting style of the journal *Ecological Economics*.

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Abstract

Through the expansion of human activities, humanity has evolved to become a driving force of global environmental change and influences a substantial and growing part of natural ecosystem trophic interactions and energy flows. However, by constructing and building its own niche, human distance from nature increased remarkably during the last decades due to processes of globalization and urbanization. This increasing disconnect has both material and immaterial consequences for how humans interact and connect with nature. Indeed, many regions across the world have disconnected themselves from the productivity of their regional environment by: (1) accessing biological products from distant places through international trade, and (2) using non-renewable resources from outside the biosphere to boost the productivity of their natural environment. Both mechanisms allow for greater resource use then would be possible otherwise, but also involve complex sustainability challenges and lead to fundamentally different feedbacks between humans and the environment.

This dissertation empirically investigates the sustainability of biophysical human-nature connections and disconnections from a social-ecological systems perspective. The results provide new insights and concrete knowledge about biophysical human-nature disconnections and its sustainability implications, including pervasive issues of injustice. Through international trade and reliance on non-renewables, particularly higher-income regions appropriate an unproportional large share of global resources. Moreover, by enabling seemingly unconstrained consumption of resources and simultaneous conservation of regional ecosystems, increasing regional disconnectedness stimulates the misconception of decoupling. Whereas, in fact, the biophysically most disconnected regions exhibit the highest resource footprints and are, therefore, responsible for the largest environmental damages.

The increasing biophysical disconnect between humans and nature effectively works to circumvent limitations and self-constraining feedbacks of natural cycles. The circumvention of environmental constraints is a crucial feature of niche construction. Human niche construction refers to the process of modifying natural environments to make them more useful for society. To ease integration of the chapters in this thesis, the framework paper uses human niche construction theory to understand the mechanisms and drivers behind increasing biophysical disconnections. The theory is employed to explain causal relationships and unsustainable trajectories from a holistic perspective. Moreover, as a process-oriented approach, it allows connecting the empirically assessed states of disconnectedness with insights about interventions and change for sustainability.

For a sustainability transformation already entered paths of disconnectedness must be reversed to enable a genuine reconnection of human activities to the biosphere and its natural cycles. This thesis highlights the unsustainability of disconnectedness and opens up debate about how knowledge around sustainable human niche construction can be leveraged for a reconnection of humans to nature.

Chapter I

Biophysical human-nature connectedness: conceptualizing, measuring, and intervening for sustainability

Introduction

Social and natural systems have coevolved over millennia. Social systems form institutions which shape the natural environment and the environment shapes social institutions. The recent decades, however, brought about an unprecedented acceleration and intensity of reciprocal interference with profound implications for the future stability of human-nature coevolution (Ellis, 2011; Steffen et al., 2015a, 2018). Through the expansion of the human activities, humanity has evolved to become a driving force of global environmental change (Crutzen, 2006; Ellis et al., 2018; Waters et al., 2016) and influences a substantial and growing part of natural ecosystem trophic interactions and energy flows (Krausmann et al., 2013; Sullivan et al., 2017). However, human distance from nature increased remarkably during the last decades due to processes of globalization and urbanization (Cumming and Cramon-Taubadel, 2018).

Through those processes, which also involve the industrialization of land use and growing social-ecological teleconnections (i.e. social-ecological connections over distances, often incurred by trade), humans are becoming ever more disconnected from (the productivity of) their regional environment in material and mental terms. This increasing disconnect has both material and immaterial consequences for how humans interact and connect with nature (Kissinger and Rees, 2010). Materially speaking, humans in disconnected societies consume more goods distant places and non-renewables, which lead to certain regions appropriating much more resources compared to others (Cumming et al., 2014; Dorninger and Hornborg, 2015). From an immaterial perspective, societal disconnection from nature threatens individual's well-being, involves a mental separation (Soga and Gaston, 2016; Zylstra et al., 2014), and evolves institutions that are not adequately reflecting natural limits (Seppelt and Cumming, 2016). Consequently, to limit human impact on natural systems there are growing calls for a reconnect of human activities to the biosphere and its natural cycles (Cooke et al., 2016; Cumming et al., 2014; Folke et al., 2011). However, the ways in which a genuine human-nature reconnection could work in and sustainability implications are involved, remains largely unexplored.

In this dissertation, focus is laid on the biophysical realm of human-nature interactions, i.e. the material and energetic relationships humans maintain with the natural environment through the extraction, use, and disposal of natural resources. An integrated methodological approach is used to study biophysical human-nature disconnections. Land use activities – e.g. agriculture and forestry – are at the core of human-nature relationships and were investigated to assess contemporary connections and disconnections. The results provide empirical evidence for a globally increasing biophysical human-nature disconnect. In an increasingly globalized and industrialized world, it is essential to explicitly account for the substituting effects of external inputs and teleconnections which work to circumvent constraining feedbacks from the local environment. Through the use of non-renewable resources from outside the biosphere ('biospheric disconnection') and the reliance on spatially remote biological resources via trade ('spatial disconnection'), humans are able to decouple activities from the natural productivity and cycles of the regional environment. The twofold disconnect obscures the fundamental reliance of humans on intact ecosystems while simultaneously destructs important life-supporting natural systems. This combination – the obscuration and concurrent increase of human impacts – leads to deleterious self-reinforcing feedbacks as it only defers environmental consequences or outsources them to spatially distant generations, which might even exacerbate negative impacts but, crucially, does not resolve them.

The increasing biophysical disconnect between humans and nature effectively works to circumvent limitations and self-constraining feedbacks of natural cycles. The circumvention of environmental constraints is a crucial feature of niche construction (Odling-Smee et al., 2003). Ecological niche construction is the process in which organisms actively shape their biophysical environment to make it more useful for themselves (Laland et al., 1999). Much more than other animals and linked to cultural processes, humans have actively shaped their natural surroundings and decreased the selective pressure from the environment (Boivin et al., 2016; Laland et al., 2014). While the suspension of self-constraining feedbacks due to cultural evolution has tremendous effects on societal development (Rammel et al., 2007), the implications of such suspension are largely overlooked in the strive for sustainable futures (Waring et al., 2017). Hence, there is a need to understand how modern land use and infrastructure function as niche construction and which evolutionary pathway dependencies are entailed (Laubichler and Renn, 2015). Therefore, increasing forms of human-nature disconnections should be grasped as a form of human niche construction[1] (Boivin et al., 2016; Laland et al., 2016).

Applying niche construction on increasing human-nature disconnections is the novel idea of this present paper that shall link the different parts of this cumulative thesis. While the articles constituting this dissertation did not explicitly relate to niche construction theory, the present paper uses this influential theory as a framework that can help identify causal relationships, mechanisms and drivers of an increasing disconnect between humans and nature from a holistic perspective. Moreover, as a process-oriented

[1] While the literature often refers to 'sociocultural niche construction' or 'cultural niche construction' (Ellis et al., 2018; Laland et al., 2014; Laland and Brien, 2011) I here refer to the same process as 'human niche construction'. Note that the use of 'niche' within the evolutionary theory is different from the niches identified in sustainability transitions by the multiple-level perspective literature (Geels, 2011).

approach that explicitly recognizes the central role of culture in transitions (Bell et al., 2009), it allows connecting the empirically assessed states of disconnectedness with insights about interventions for sustainability transformation in coupled social-ecological systems. In niche construction theory, culture is understood as the evolution of "the technologies, lifestyles, consumption patterns, norms, institutions, and worldviews that ultimately shape human impacts on the environment" (Brooks et al., 2018) over time. Culture, rigorously framed from an evolutionary perspective, is essentially that deeper dimension that needs to be leveraged so as to allow for transformation.

Increasing disconnectedness results in the destruction of natural equilibria – a destruction documented in the 'great acceleration' (Steffen et al., 2015a), the 'Anthropocene' (Crutzen, 2006), and 'planetary boundaries' literature (Rockström et al., 2009; Steffen et al., 2015b). While this literature provides invaluable knowledge about system states, it does not tell much either about the historical and co-evolutionary processes that have led to the current planetary crisis or to how humankind might be able to overcome the unsustainability of complex social-ecological systems. The lens of niche construction theory provides a systemic approach to processes of change and understanding the complex relationships between cultural, social, environmental factors. Its historical depth allows for the explanation of social-ecological as well as evolutionary processes underpinning the emergence of the current disconnect of our society from nature. The intention of using niche construction theory is, thus, to explain contemporary human-nature connections and disconnections with a causal model of the evolution of complex social-ecological systems (Laubichler and Renn, 2015).

The thesis is structured as follows: after laying out the motivation and driving research questions, I will introduce the concepts and methods being used in this dissertation, which is followed by the summary of the six articles included in this thesis. The synthesis chapter relates the findings from the articles to the notion of human-nature disconnection as a form of niche construction. Subsequently, I will discuss how new insights gained influence the perception of interventions for transformative sustainability change. The supplement to the framework paper provides all articles in full length and is split into three sections: from conceptualizing biophysical human-nature connectedness (Section A), over measuring (Section B), to intervening for sustainability (Section C).

Motivation and primary research questions

> "*The idea of sustainability arose in response to the spreading gulf between rich and poor and the continued degradation of biospheric systems*" (Gibson, 2006: 171).

The motivation for this thesis stems from the observation that humans are increasingly taxing the planet and thereby threaten our own existence while reproducing inequality and injustice (see, for example, FAO, 2019; Folke et al., 2011; Martinez-Alier, 2003; Steffen et al., 2018, 2015b; Temper et al., 2015). This thesis is an attempt to integrate critical thought and concepts with robust empirical data and analysis.

With my research I aim to address two broad overarching questions: what are the mechanisms and processes that led us to threaten our own life-supporting systems (i.e. 'how did we get here'); and how do we change paths to reconcile human development with planetary boundaries and natural cycles (i.e. 'how do we get out of this')?

While my research aims to capture holistic societal and economic developments, for the largest part I focus on the land use system as a central and crucial platform of human-nature interaction and coevolution. Land use represents the most important and extreme example of human niche construction (Laland and Brien, 2011). It is closely connected to cultural evolution and is characteristic of how humans relate to nature (Fischer-Kowalski, 2011; Fischer-Kowalski and Haberl, 2007). The current mainstream vision and development trajectory of land-use systems can largely be characterized by an industrial intensification and by neoliberal globalization (Asafu-Adjaye et al., 2015; Balmford et al., 2018; Pretty et al., 2018). There are plenty of immediate sustainability problems tied to industrial intensification and the outsourcing of biomass extraction, e.g. the unsustainable use of agrochemicals causes eutrophication, GHG emissions, pollution, soil acidification, or biodiversity decline (Denison, 2012; Pretty, 2018; Rudel et al., 2009). However, sustainability transformation requires not just isolated symptoms treatment, but a system-wide change.

The present dissertation, therefore, goes beyond a critical examination of single variables by embracing a systems perspective that includes off-site and deferred spillover effects such as environmental burden shifting to spatially distant places (Jiborn et al., 2018; Meyfroidt et al., 2010; Schierhorn et al., 2016; Wood et al., 2018) or long-term legacies related to unsustainable resource use (Krausmann et al., 2017; Weis, 2010; Winiwarter et al., 2016). To provide a common framework for this thesis I bridge explorations of social-ecological systems research (e.g., Haberl et al., 2016), systems thinking (Meadows, 1999, 2008), and ecologically unequal exchange (Hornborg, 2014, 1998), with human niche construction theory (Laland et al., 2016). Human niche construction and cultural evolution theory in social-ecological systems research are relatively new fields (Brooks et al., 2018). While there have been efforts in the past to develop an integrative perspective on niche construction, coevolution, and social-ecological sustainability (Weisz and Clark, 2011), there is a need to further examine the potential of niche construction as a conceptual tool to grasp lock-in situations (e.g. institutions requiring unlimited growth) as an evolutionary problem (Laland et al., 2014).

With this, it is possible to reveal the importance of suppressed feedbacks, eminent trade-offs and spillover effects, and the emergence of lock-ins leading to adverse pathway dependencies.

More details about concepts and methods can be found in chapters 1.2 and 1.3, as well as in the articles in the supplement to the framework paper.

To answer the two broad primary research questions of the thesis, each section and chapter elaborate on specific sub-questions:

> *How can we conceptualize biophysical human-nature connectedness, how can we measure it and how can it be useful for sustainability change?* (Section A; Chapters II-III)
>
> *What is the current state of biophysical human-nature disconnectedness in the world? What is the role of teleconnections in maintaining uneven development?* (Section B; Chapters IV-V)
>
> *How can we intervene in complex social-ecological systems to induce change towards sustainability transformation? How can a re-connection of humans to nature leverage such a transformation?* (Section C; Chapters V-VI)

In answering these more specific questions I will draw on an interdisciplinary mix of methods (see 1.3) and concepts (see 1.2). However, in order to approach the two overarching primary questions, I set the individual results of each chapter in a broader theoretical context and ask:

> *How can we understand increasing human-nature disconnections from a niche construction perspective and which dynamics inherent in this process can be used to leverage a reverse direction towards human-nature re-connection?* (Chapter I)

To answer this question, below I conceptualize a niche construction framework for sustainability that is able to combine the different approaches and insights on the state of biophysical human-nature connections. The application of the framework yields in new theoretical insights by fathoming underlying evolutionary mechanisms which are relevant for identifying pathway dependencies and opportunities for change.

A Niche Construction Framework for Sustainability

This chapter presents a new theoretical framework that integrates different social-ecological approaches with human niche construction theory from cultural evolution to conceptualize, assess (measure) and help to address human-nature connectedness at regional or national scales. The framework explicitly sheds light on trade-offs between different types of justice which are all crucial for sustainability (Gibson, 2006) (compare Figure 2 below). In order not to overlook such trade-off and spillover effects I apply a systems perspective on land use activities. The land-use system is not only relevant with regards to quantities of inputs and outputs, but also to which types of feedbacks social institutions and individuals get from biophysically connected, disconnected, or reconnected systems – where shorter self-constraining feedbacks might be crucial in motivating transformative change (Lambin and Meyfroidt, 2011, 2010; Sundkvist et al., 2005). However, humanity has evolved cultural programmes to construct niches which precisely work to suspend and defer self-constraining feedbacks, i.e. decrease selective pressure, from the environment.

Before I will present the theoretical framework, I will introduce why cultural evolution is relevant to sustainability in general, and why it is important to look at cultural evolution to understand how and why we got to the current state of disconnectedness and how we can move beyond.

Cultural evolution for sustainability

Within evolutionary theory literature, both cultural evolution and human niche construction research directions recently gained increasing attention and interest (Brooks et al., 2018; Hanes and Waring, 2018; Mesoudi, 2017). The development of human culture follows theoretically derived patterns of evolution (Mesoudi, 2011; Mesoudi et al., 2004; Rogers and Ehrlich, 2008).[2]

Culture is here broadly understood as the evolution of "the technologies, lifestyles, consumption patterns, norms, institutions, and worldviews that ultimately shape human impacts on the environment" (Brooks et al., 2018) over time. Cultural evolution gives a way to avoid limitations and constraints of genetic evolution.

However, instead of being inherited, cultural evolution is based on social and cultural transmission, e.g. sociality, language, technology, economics, medicine (Creanza et al., 2017; Laubichler and Renn, 2015). Therefore, cultural evolution is said to develop much faster than genetic evolution (Mesoudi, 2017; Rendell et al., 2011). While cultural evolution allows us to adapt faster than everything else (Perreault, 2012), it has largely been overlooked in diagnosing unsustainable social-ecological states and tracks of society (Waring et al., 2017).

A central thesis of this dissertation is that absolute decoupling of cultural evolution from its environment is not feasible for the long term (Fletcher and Rammelt, 2017; Ring, 1997; Ward et al., 2016). However, as they are biophysically disconnected from their regional environment, societies manage to temporally circumvent and defer direct consequences from natural interference.

[2] Note that the acknowledgement of cultural evolution as a distinct human feature outside natural spheres of causation is a counterargument to Social Darwinism thought (Kaye, 2017).

From this point of view, increasing human-nature disconnections are a success story in the history of human-nature coevolution (Henrich, 2017). Since human culture emerged, it coevolves with nature, and since the Neolithic revolution, humans colonize nature to transform natural systems for higher usability, i.e. through agricultural practices, species breeding, or domestication. The maintenance of colonizing efforts also changes societal structures and institutions (Fischer-Kowalski and Weisz, 1999). The reciprocal interference increased with the expansion of the human niche through expansion and intensification of land use, as well as the use of non-renewable materials that came with the industrialization of land use. The continuing large scale transformation of ecosystems and changing of the global climatic conditions evoke new forms of social responses, which are often associated with controlling and engineering nature: genetic engineering, ecosystem engineering, or geoengineering (Ellis, 2011; Ellis et al., 2018). The unintended side-effects that come with the increasing domination of nature are increasingly costly and risky for society. Additionally, there are socio-metabolic and physical limits (limited resources, friction, thermodynamics) on the evolutionary degrees of freedom of culture (Sieferle, 2011), i.e. human development cannot fully be decoupled from natural conditions. Chronic and pervasive environmental problems call for a process-orientation (Ring, 1997), which the human niche construction perspective offers.

Human niche construction for sustainability

To reconnect social development to natural cycles and to halt the destructive expansion of the human niche we need to acknowledge humans as niche constructing beings. Therefore, by understanding increasing biophysical human-nature disconnectedness as a process of human niche construction allows for innovative insights into the evolvement of the phenomenon, including crucial features like the circumvention of self-constraining feedbacks from the environment or pathway dependencies (Laland et al., 2016, 2014). This might help to identify and leverage the dynamics involved in this process and to reverse self-reinforcing feedbacks.

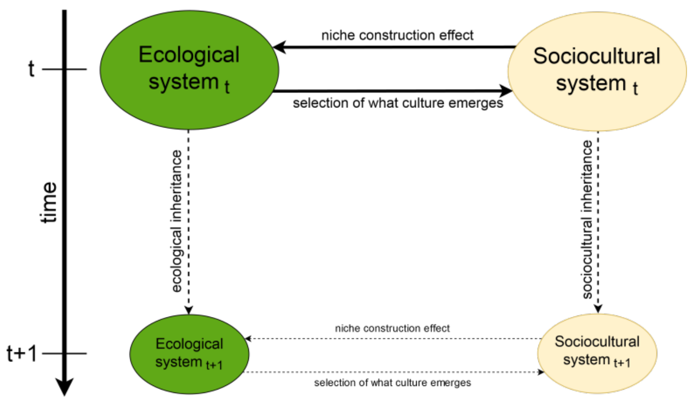

Figure 1: The human niche construction framework. It shows the reciprocal interference between natural (ecological) and cultural (sociocultural) systems via niche construction and selection. Both systems involve an inheritance over time.

Figure 1 conceptually represents the human niche construction process (Laland et al., 2014). While the environment (ecological system) exerts selective pressure on the population (sociocultural system), through concerted action (culture) the society modifies its environment to decrease selective pressure and to make it more useful for its own purposes. This process is called human niche construction and its evolutionary character leads to a sociocultural inheritance over time, similar to the ecological inheritance of ecological systems.

Human societies can better evolve when the environment is not very selective or tamed in its selection mode. Social systems will start to prosper when they can avoid environmental selection while still being able to grow. Over time, the niche construction arrow becomes larger than the arrow of environmental selection on culture. The strength of natural selection's impact on cultural adaption was very pronounced before humans settled down. Vice versa, the impact of cultural adaption on ecological systems was very small when we were still primates. Especially when we started doing agriculture, the niche construction effect became larger and the natural selection effect smaller. Critically, humans developed group-level cultural adaption which acted to decrease exposure to the environment (Gowdy and Krall, 2016; Kline et al., 2018; Waring et al., 2015). This trend continued even more with the industrialization of agriculture (Krausmann, 2004) and the emergence of global trade regimes (Hornborg, 2016; Krausmann and Langthaler, 2019).

However, modern industrial human niche construction comes with certain peculiarities, which are due to the cultural processes characterizing human evolution (Creanza et al., 2017), but also entail far-reaching biophysical consequences which decrease natural equilibria and, therefore, will increase selective pressure again in the long-term. In particular, modern industrial global human niche construction does not merely function as an interference with the immediate surrounding environment anymore but it entails crucial interactions over distances (teleconnections) and the use of lithospheric energy and materials (non-renewable resources) from outside the living sphere of the environment, i.e. the biosphere. Therefore, it is not enough to focus on the apparent on-site interaction with the biosphere, but the scope has to be widened to encompass the exploitation of non-renewables from outside the biosphere as well as the appropriation of resources from spatially distant places (Figure 2).

The environment is no longer predominantly driving adaptive change. Instead, we are driving change in the environmental sphere. The remaining effect of the environment on the society can be anticipated, humans can slow it down, stop to move, or outsource its consequences. Figure 2 depicts the modern human niche construction process that is enlarged to explicitly recognize the effects occurring from the industrialization of agriculture and the emergence of international trade regimes. The use of non-renewables from outside the biosphere, to boost and energetically substitute the natural productivity of the biosphere, has a significant evolutionary influence on how human niches are constructed. While the local niche construction effect will be eased, it creates long-term and legacy effects, like climate change or radioactive disposals, for future generations and their interaction with the environment. In addition, the globally sharply increasing trade relations result in major social-ecological teleconnections between distant places. This phenomenon affects both the local niche construction and the construction of niches in distant places. Making this connection explicit points to the uneven outcomes of processes of niche construction around the world and also to how they are interconnected and even interdependent in sustaining their niches, i.e. certain niches could not exist if they did not have strong ties to other places.

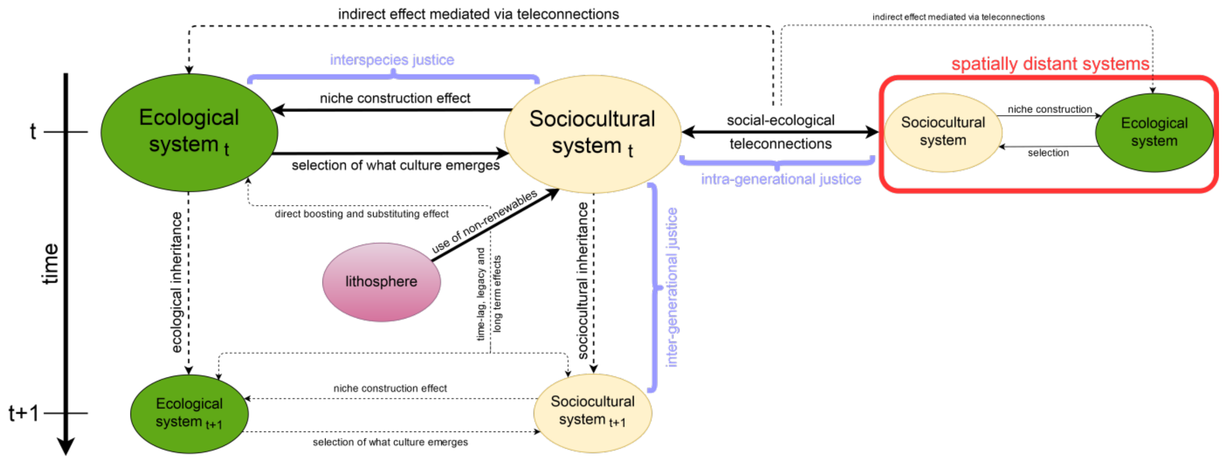

Figure 2: Industrial human niche construction framework. In addition to the established conceptualization of human niche construction, it explicitly involves effects from interactions with spatially distant systems and their niche construction (spatial disconnect due to teleconnections) and the effect of biospheric disconnection due to the use of non-renewables in the niche constructing process. Curly brackets in blue indicate potential sustainability issues emerging from industrial niche construction.

Consequences of niche construction are usually causal feedbacks between what organisms do and responses from the environment. In industrialized countries, niche construction intensified but simultaneously brought about a disconnect between the engineering humans and the responding environment. This disconnect enables a suspension of self-limiting feedbacks and allows seemingly endless accumulation and growth. Disconnecting human activities from regional natural productivity does not completely escape but temporarily avoids and defers direct consequences from the environment until it might be "too late" for change. Compare Laubichler and Renn (2015) for the path-dependent nature of evolutionary change and Boivin et al. (2016) for the ecological long term consequences of expanding human niche construction.

This is especially important because effects of niche construction can also involve destructive consequences (Boivin et al., 2016), i.e. it can involve niche destruction of other species and hamper the capability of future or spatially distant human generations to construct their own niches. It is precisely the runaway evolutionary process (i.e. the process is not completely manageable and there are unintended side-effects with potential legacy) of human niche construction that enabled humans to transform the planet without intending to (Ellis et al., 2018). Due to cultural evolution, human niche construction is indeed an extremely powerful process, but unfortunately does not only possess constructive but also destructive power. It involves lasting changes to the physical environment and modifies selection not only for humans but also for other species. The global expansion of the human niche, e.g. the expansion of agriculture, managed forestry, industrial infrastructure and urban development, causes habitat degradation, deforestation, biodiversity decline and often destroys ecosystem's integrity (Laland et al., 2014).

For this reason Figure 2 indicates where a sustainable human niche construction needs to pay special attention (in blue): First, in constructing its niche, humans take an unproportional large share of the trophic energy from ecosystems over other species (Krausmann et al., 2013) which threatens biodiversity (FAO, 2019) and, thus, interspecies justice. Second, unbalanced trade relationships with spatially distant systems might fuel uneven conditions for niche construction, which hamper intra-generational justice. Third, the large scale reliance on non-renewables decreases inter-generational justice for destroying healthy ecosystems, changing climatic conditions, and the exhaustion of non-renewable materials. These three dimensions of justice are very much intertwined and may not be played off against each other.

In the box below I outline the more technical concepts which are relevant to operationalize the concepts described so far and which will subsequently be directly translated into the applied methods.

Box I: Socio-ecological Concepts

Hybrid Society

A basic and central feature of this research is the understanding of society as a hybrid between cultural and natural realms. Human societies are subject to both spheres of causation – the cultural and the natural (Fischer-Kowalski and Weisz, 1999). Like organisms, societies do need to maintain metabolism through the exchange of matter and energy with their environments. This exchange is vital to build internal order and to resist thermodynamic decay, while it increases entropy in its environments (Walsh, 2018). However, unlike other organisms, the human species developed cultural programmes to transmit social learning. Societal properties –infrastructure, livestock, human population – are subject to natural laws and are simultaneously transformed by cultural meaning (Schaffartzik and Kastner, 2019). The study of cultural evolution is, therefore, essential for an analysis of human-nature coevolution (Waring et al., 2017; Weisz, 2011).

Human colonization of natural ecosystems

With the emergence of agriculture, humans started to colonize nature to make it more useful for their own purposes (Haberl et al., 2004, 1997). Humans transform natural ecosystems to produce more food, feed, or fibre (Fischer-Kowalski et al., 1997). The colonization of natural ecosystems requires continuous work input to keep ecosystems in the transformed state. While agricultural societies require a considerable share of labour for the maintenance of colonization and control of nature, the industrialization of land use induced a dramatic decrease of direct labour input. However, the large scale application of industrial products, like machines and agrochemicals, did not decrease the human colonization of natural ecosystems in absolute terms. In fact, human colonization of nature steadily increased over time and reflects the domination of trophic energy flows by only one species – the humans.

Social metabolism

Social metabolism is the study of the energetic and material throughput of a societal entity (Fischer-Kowalski and Haberl, 2007; Haberl et al., 2011). Similar to organisms, society needs to maintain a metabolism to secure its own persistence. The metabolism is ensured through an exchange of energy and matter (inputs and outputs) with the environment. Societies extract resources from the environment as inputs for their maintenance and expansion, large parts are used to build up stocks and infrastructure (Krausmann et al., 2017), outflows occur as waste flows and emissions to nature.

Here I am especially interested in two aspects of social metabolism: (1) the parts of social metabolism that are concerned with the land-use system (inputs of energy and materials, outputs of emissions) are used to complement measures of the human colonization of natural ecosystems and to assess the disconnect from the energetic base of the biosphere; and (2) trade in biophysical terms, including so-called embodied flows which reveal the full extent of teleconnections to distant places (Friis et al., 2016; Liu et al., 2013), which inform about the spatial disconnect from the regional natural productivity.

Box II: Evolutionary concepts

Niche construction

Ecological niche construction is the process in which organisms actively shape their biophysical environment to make it more useful for themselves (Laland et al., 1999). The goal of this environmental modification by organisms is to change and cause selection. It describes a basic characteristic of all organisms to re-build their own environment with the goal to decrease environmental selective pressure. Thereby, niche constructing organisms influence processes and feedbacks within their environment, as for example the flow of trophic energy and matter in ecosystems. That again impacts other organism's evolution and capability of constructing their own niches (Laland et al., 2014).

Cultural evolution

Culture is here broadly understood as the evolution of "the technologies, lifestyles, consumption patterns, norms, institutions, and worldviews that ultimately shape human impacts on the environment" (Brooks et al., 2018) over time. Cultural evolution gives a way to avoid limitations and constraints of genetic evolution. However, instead of being inherited, cultural evolution is based on social and cultural transmission, e.g. sociality, language, technology, economics, medicine (Creanza et al., 2017; Laubichler and Renn, 2015). Therefore, cultural evolution is said to develop much faster than genetic evolution (Mesoudi, 2017; Rendell et al., 2011). Cultural evolution allows us to adapt faster than everything else (Perreault, 2012).

Human niche construction

Cultural evolution and human niche construction are clearly linked (Ellis et al., 2018). Like all other species (Odling-Smee et al., 2003), humans too modify their environment to influence and reduce the environmental selection. However, as human evolution is different from other species' evolution for we have culture, so too is the human niche construction different from other species' niche construction. Human niche construction works at multiple levels and modifies the selective feedback from the environment (Kline et al., 2018; Laland and Brien, 2011). Humans born today are born into a highly modified environment with infrastructure, technology, and institutions of any kind. Also the process responsible for cultural inheritance – social learning – is largely institutionalized (Wheeler and Clark, 2008). The most prominent and tangible example of human niche construction is clearly agriculture, including practices like domestication, livestock husbandry, and irrigation etc. (Ellis et al., 2018). The niche construction perspective explicitly recognizes that humans, and other species, are not merely passive agents in the natural evolution, but that they actively shape the conditions of evolution and inheritance themselves.

Methods

The investigation of biophysical human-nature connectedness requires cooperation between disciplines capturing the human and the environmental spheres. In my empirical work, I employed quantitative statistics and data modelling to capture measurable human-nature interactions which are relevant to assess niche construction processes. The concrete methods used to operationalize biophysical human-nature connections are based on the concepts described above. Here I present the methods laid out in Chapter II and empirically applied in Chapters IV and V.

In Chapter IV we relied on a quantitative methodological toolset that combines approaches from social ecology (Haberl et al., 2016) and ecological economics (Kitzes, 2013). We applied an innovative combination of HANPP (human appropriation of net primary production) (Haberl et al., 2007) social metabolism (Fischer-Kowalski and Haberl, 2007), and specifically environmentally-extended input-output modelling (Lenzen et al., 2013; Tukker et al., 2018) to measure human-nature connections and disconnections as a mix of the human colonization of nature and the metabolism of societies. Input-output analyses are used to account for upstream trade flows and to capture how teleconnections affect niche construction at distant places.

Human societies are inherently connected to, and dependent on, the biosphere through the flow of materials and energy. In concrete terms, how humans are connected biophysically to their surrounding terrestrial biosphere is measured by the (HANPP) indicator (Erb et al., 2009; Haberl et al., 2012). The indicator captures how much of the trophic energy in the terrestrial ecosystems, within a given system boundary, are directly and indirectly appropriated by humans, and how much energy is remaining in the ecosystems for other species thriving and reproducing. The process captured by this indicator represents basic human niche construction through agricultural activities. The following two approaches capture two processes that are specific to modern industrial niche construction: industrialization and globalization of land use.

How societies are disconnected from the renewable natural productivity of the biosphere in energetic terms is assessed by material and energy flow accounting tools, which operationalize the concept of social metabolism (Fischer-Kowalski and Haberl, 2007). Here we used environmentally-extended multi-regional input-output analysis to account for the direct and indirect flows required by land-use sectors (agriculture and forestry) to produce outputs. This includes energy, material, and labour inputs, as well as CO^2 from the combustion of fossil fuels.

The same method was used to measure the spatial disconnect incurred by teleconnections. We added the domestic HANPP values of a country as an environmental extension to the agricultural and forestry sectors of the input-output tables in order to model the HANPP values embodied in the trade between all countries in the world. Embodied HANPP is an indicator of land use based teleconnections and distant responsibility of apparent consumption. This is particularly relevant for assessing biophysical human-nature disconnections because the intensity of domestic land used is increasingly related to spatially distant demand for biological resources (Erb et al., 2009; Haberl et al., 2009; Kastner et al., 2014).

Direct and indirect trade connections with other countries and regions are modelled with the same large data matrices capturing not only the input-output relations of sectors within an economy but also the international trade relations with every single other sector worldwide (Lenzen et al., 2013; Stadler et al., 2018). The method enables us to assess the direct and indirect requirements of energy, material, and labour from every single sector in the world that a specific land-use system requires to produce its outputs (i.e. biomass yield).

In Chapter V we used the same method to measure material, energy, land, and labour embodied in internationally traded goods of the whole economy. Special emphasis was laid on the inequality in trade relationships in terms of asymmetries of trade volumes between richer and poorer countries and the discrepancies in the monetary valuation of embodied flows.

To display global datasets in a feasible way it is often necessary to aggregate data into groups or clusters of cases. However, statistical analyses are crucially relevant to investigate variance within the dataset. Consequently, we also made use of methods of statistical interference such as regression analyses in all chapters of this thesis. To detect typologies we grouped cases with cluster analyses (Chapter IV and Chapter VI) or based on income (Chapter V). To reveal patterns and causal effects between predictor (e.g. income) and independent variables (e.g. footprints or net-imports) we employed regression analyses (Chapter IV), structural equation modelling (Chapter V), or simple Chi^2 tests (Chapter VI).

Summary of included chapters

In the following section, I briefly summarize each paper included in this cumulative dissertation one by one. The dissertation consists of three sections, each containing two papers, which are ordered according to the previously outlines narrative: from conceptualizing over measuring biophysical human-nature disconnections to intervening for sustainability. Each paper is co-authored and information on authors' contributions, publication status and conference contributions is available in the appendix (Article Overview). The supplement to the framework paper provides full manuscripts for each of the papers.

How can we conceptualize biophysical human-nature connectedness, how can we measure it and how can it be useful for sustainability change?

Section A conceptualizes the framework of biophysical human-nature connectedness (**Chapter II**) and discusses it in relation to how people feel connected to nature (mental modes of human-nature connectedness) (**Chapter III**).

In **Chapter II** we introduced a methodological framework to empirically assess biophysical human-nature connections and disconnections. We used HANPP as a baseline indicator of human connectedness to nature. Domestic HANPP informs about the degree of human domination of terrestrial ecosystems and can be decoupled from harvest or kept stable while demand for biomass products (food, fibre, feed, bioenergy) increases. There are two major mechanisms enabling the circumvention of exerting increasing pressure on ecosystems: (1) Through trade of embodied HANPP flows (Erb et al., 2009; Haberl et al., 2009) regional natural productivity can be supplemented and substituted; and (2) by using external energy and materials in land-use activities, natural productivity can be boosted, supplemented, and substituted. In this paper, we refer to these two different mechanisms as "spatial disconnect" and "biospheric disconnect" respectively.

Through the imports of biomass products, countries are (tele-)connected to spatially distant regions. Recent research suggests that these teleconnections did not only surge in the last few decades (Kastner et al., 2015, 2014) but also follow patterns of increasing inequality between countries (Dorninger and Hornborg, 2015; Lenzen et al., 2012; Prell et al., 2015). From a human-nature connectedness perspective, both imports and exports possess a disconnecting quality. Both types of trade flows decrease the share of natural productivity appropriated and also consumed domestically in relation to the total availability of natural productivity; i.e. domestically appropriated and imported net primary productivity (NPP).

By drawing on external energy (from non-renewables) for land use inputs, societies create another sort of biophysical disconnect to the renewable productivity of its environment. Non-renewables are sourced from outside the biosphere, i.e. the lithosphere, to produce goods like fertilizer, pesticides, tractors, fuel, irrigation facilities, or infrastructure, and are used to boost the natural productivity or the conversion efficiency from NPP to the final biomass product for consumption (Erb et al., 2012; Gingrich et al., 2015; Gingrich and Krausmann, 2018). The use of external energy enables urbanization and a dramatic decrease in labour input in land use. While that might be desirable outcomes of niche construction, it involves undesirable side-effects like emissions, pollution, and biodiversity decline, but also less perceptible pathway dependencies, i.e. the dependencies on high-tech infrastructure and related resources for maintaining high-yield farming.

In **Chapter III** we focused on the integration of insights from biophysical human-nature connections research and from studies on socio-psychological or mental human-nature connections. We argue that the two broad approaches address human-nature connections from different angles, i.e. assessments focusing more on structural (biophysical) versus agency (socio-psychological) aspects of human-nature connectedness. Socio-psychological research of human-nature interactions tries to identify processes that influence a personal commitment to nature or affinity for protecting the natural world. For example, to what extent do people identify themselves as being part of nature? Thereby the literature notices a growing gap between humans and nature due to urbanization, technological change, and indoor lifestyles (Ives et al., 2017; Zylstra et al., 2014).

However, in fact, both approaches – the biophysical and the socio-psychological – study two parts of the same reinforcing feedback loop. They share the same underpinning causes: urbanization, globalization, materialism, technological changes etc. A biophysical disconnect implies a spatial disintegration between producers and consumers and seemingly unconstrained consumption of biological goods. This, in turn, creates a mental separation of people from nature, as for example an extinction of experience (Soga and Gaston, 2016). People still remain dependent on natural cycles, but the artificial separation induced by material and mental modes of disconnection fuels reinforcing feedback where people do not know any more "if they do it right" or if they overconsume and outsource damages to spatial or temporal distant generations. In this chapter, we argue that a better alignment of these two approaches would be beneficial in the context of sustainability.

What is the current state of biophysical human-nature disconnectedness in the world? What is the role of teleconnections in maintaining uneven development?

Section B contains the largest part of the empirical assessments of this dissertation. In **Chapter IV** we applied the methodological framework of biophysical human-nature connections (described in Chapter I) to the countries of the world. Looking at the global scale there are clear patterns of increasing biophysical human-nature disconnect as the predominant development trajectory. Our empirical results reveal how highly intensified and globalized land-use systems heavily rely on both domestic natural productivity and distant ecological and non-renewable inputs. Without those latter two external inputs pressure on domestic ecosystems would increase even more and environmental feedbacks regarding resource depletion, land-use change, and biodiversity loss, would be more directly visible. The distal nature of contemporary human niche constructions obscures both natural resources constraints and the impacts of transgressing natural cycles, without actually decreasing resource consumption or diminishing the impacts of resource use.

Moreover, the results reveal that in richer industrialized countries only a fraction of the total NPP appropriated domestically is also consumed at the same place. A significantly larger share is imported, exported, re-exported or indirectly associated with trade flows. In addition to external energy entries, these global ramifications cause a disconnect from the natural productivity of the regional environment. Our research confirms that with growing income countries tend to decrease dependency on their own natural productivity or labour inputs while increasing dependency on external energy and distant ecological goods (as well as the energy and labour embodied in those goods). This biophysical disconnect by no means implies a decoupling from total resource use, but it displaces and postpones resource constraints to distant generations. This disconnecting trend causes globally unsustainable and uneven human niche construction.

In accordance to the scientific literature on cultural evolution (Henrich and McElreath, 2003; Laland et al., 2000; Laubichler and Renn, 2015) and evolutionary economics (Boschma and Lambooy, 1999; Boulding, 1991; Witt, 2008), institutions (like international trade arrangements, general-purpose money, and technology, industrial agriculture and high-tech production) play a vital role in describing contemporary biophysical human-nature disconnections (Dorninger et al., 2017). As an example, prolonged resource supply chains have evolved as an economic institution (Waring et al., 2017) seemingly indispensable from an economic point of view.

However, according to Beddoes et al. (2009), our institutions are designed to maximize energy and resource throughput but are poorly adapted to the needs of the global human population. In that regard, in my PhD research, we also measured the global material and energy throughput and the role of global teleconnections from an equality point of view. **Chapter V** opens up the scope from a focus on land use systems to the teleconnections of the whole economy and sheds light on global inequalities that are reinforced by an international ecologically unequal exchange. We found that richer regions do not only have footprints ten times larger than the poorest regions in the world, but, with the help of global trade institutions and the redistributive power of industrial technology, exhibit a net appropriation of resources from relatively poorer regions every year and even achieve a monetary surplus from this net appropriation of embodied materials, energy, land, and labour.

In this article, we derived hypotheses from the theory of ecologically unequal exchange (Hornborg, 2016, 2014) to test them with a global dataset of trade flows including embodied resources. Splitting the countries into income classes reveals that the high-income nations are net-importers of raw material equivalents, embodied energy, land, and labour throughout the examined time period of 1990-2015. All other countries and income classes acted as net exporters. What makes this exchange even more unequal is that the high-income countries are able to generate a significantly higher monetary value for their own resources embodied in exports than compared to all other countries. For the high-income countries, this sums up to the aforementioned accumulated net appropriation of resources and generation of monetary surplus from international trade at the same time. Structural equation models disclose that with growing income a country tends to net import resources and to generate a higher monetary value added for its exports. We conclude that economic growth is fundamentally a matter of appropriation. Moreover, the resource-intense standard of living experienced by the high-income countries cannot be universalized nor sustained, precisely because they rely on the continuous net appropriation of resources from other parts of the world. These findings carry far-reaching implications for global sustainability, growth potentials, and the interdependence of niches constructed by different countries in the world.

How can we intervene in complex social-ecological systems to induce change towards sustainability transformation? How can a re-connection of humans to nature leverage such a transformation?

Finally, **Section C** discusses possible intervention strategies for reconnecting people to nature and more broadly for triggering sustainability transformation.

Chapter VI presents the findings of a paper that reviewed the scientific literature for sustainability interventions from a leverage points perspective (Abson et al., 2017; Meadows, 1999), where a leverage point is a place of intervention in a system where small changes might trigger system-wide change. We performed a systematic quantitative review by applying a coding scheme to 301 scientific articles which were identified with a search string applied to literature databases. We used the energy and the food system as exemplary case studies and focused on empirical articles only. We were interested in which types of interventions the literature focused on and how they are related to the researcher's understanding of the sustainability problem, the method applied, data used, and the disciplinary approach. We related this information to the intervention proposed and ranked it according to the leverage points scale (Abson et al., 2017; Meadows, 1999). In doing so we found that the literature splits into four groups of 'scientific approaches' which are significantly different in regards to the leverage points they address. Often technology-focused approaches tend to promote interventions on the rather shallow end of the leverage points scale, i.e. interventions which are easy to envision but have limited potential for system-wide change. On the contrary, interdisciplinary approaches are more diverse and target different, partly also deeper, leverage points. However, the deepest leverage points, which are concerned with a system's intent and its underpinning paradigm, are rarely addressed.

Chapter VII specifically explores different types of human-nature connectedness for their leverage potential for a materially and mentally more (re-)connected society. Human-nature connectedness is identified as a multifaceted concept spanning from material, over cognitive, experiential, emotional, to philosophical perspectives on human-nature relationships. We argued that these dimensions are interrelated and each of them will be important in leveraging human-nature connectedness as a trigger for sustainability transformation. However, while many different disciplines worked on human-nature connectedness, their insights remained largely siloed. For leveraging a sustainability transformation work on all of the above dimensions of human-nature connectedness will be necessary. However, more integrated research approaches that explicitly account for material outcomes as well as for an individual's perceptions of nature need to be developed and applied. We concluded that a fundamental rethinking and reorganisation of how humans relate to nature must take place. Eventually, we need to change our worldviews and the goals most people pursue in life to genuinely reconcile human activities with planetary boundaries.

The two chapters of **Section C** provoke a rethinking of how to change systems behaviour for more sustainable outcomes and how to overcome systemic pathway dependencies. From a human-nature connectedness perspective the underpinning paradigm with which we relate to nature will be key: are we as humans part of nature or are we apart from nature (Catton and Dunlap, 1980, 1978)? The answer to this question will influence the way humans will construct their niches in the environment and might either take the course of increasing our distance to nature by further dominating and fully controlling it or arranging a 'living with nature' and its spatiotemporal limitations and natural cycles.

Synthesis

How can we understand increasing human-nature disconnections from a niche construction perspective and which dynamics inherent in this process can be used to leverage a reverse direction towards human-nature re-connection?

Within the broader spectrum of accelerated society-nature coevolution, this contribution focuses on the biophysical connections human societies create with their surrounding terrestrial biosphere and how these can be understood using niche construction as a theoretical framework (Kline et al., 2018; Laland et al., 2016). While my PhD research had a solid empirical component to reveal biophysical foundations of current development pathways, a strong theoretical embedding of the research results is vital for identifying causes of increasing biophysical disconnections and opportunities for change to overcome them.

The last section of this framework paper synthesizes the insights and findings of my doctoral research with the help of a novel theoretical perspective and highlights future research avenues. Increasing biophysical human-nature disconnections are framed in evolutionary terms, which take into account processes such as the circumvention and deferral of natural constraints by industrial technology and unequal exchange with distal systems. By using niche construction theory we can get a better understanding of the dynamics that lie behind the observed patterns of disconnectedness and outcomes (e.g. human domination of ecosystems, use of renewable and non-renewable resources, teleconnections) and how they came about from a historical perspective. Applying a niche construction perspective helps us to see the bigger context and provides a more systemic and processual view of contemporary human-nature interactions. This, in turn, might be helpful to leverage the dynamics driving human niche construction to suspend or reverse unsustainable pathway dependencies.

Human-nature disconnectedness as unsustainable niche construction

A central part of evolutionary theory, cultural evolution, and adaptation is that there is some kind of individual with certain traits that create outcomes which when "successful" will lead to a spread of that trait. Describing biophysical human-nature disconnectedness from a niche construction perspective necessitates the identification of such traits (Brooks et al., 2018; Waring et al., 2015), their variation over time, their modification as a result of previous adaptation, fail and inheritance. Connectedness or disconnectedness is an assessment of the system state and the niche construction is the corresponding process. The evolution of agricultural practice is a key example of how the evolution of traits has happened over history. Its industrialization and land use based teleconnections are certain traits that only evolved over the last few centuries (Kastner et al., 2014; Krausmann, 2004) (and are still spreading around the globe) and have proven well in avoiding environmental impact and selection.

In our analyses, the individual is the nation state and traits are mostly policies, like trade or agricultural policies, but also endowment with biophysical resources. The created outcome is measured with indicators like HANPP, embodied HANPP flows, or external inputs in land use. The traits deemed "successful" and consequently spread might be agricultural intensification, monocultures, export orientation, subsistence farming, etc. Outcomes of these traits are then, for example, land use expansion or intensification, exportation, net-imports, energy and material use, or emissions.

Our results indicate that especially those traits are perceived successful, and spread accordingly, that cause a higher degree of biophysical disconnection between humans and nature. We see that with increasing income countries tend to rely less on domestic NPP and direct labour input but more on traded embodied HANPP and external inputs. Through industrial human niche construction, societies get ever more disconnected from nature – both materially and mentally via cognitive dissonance. We found that intensified and globalized land-use systems heavily rely on both domestic natural productivity and distant ecological and non-renewable inputs. Without those latter two external inputs, pressure on domestic ecosystems would increase and environmental feedbacks regarding resource depletion, land-use change, and biodiversity loss, would be more directly visible. The distal nature of current human niche construction obscures both natural resource constraints and the impacts from the overuse of such resources, without actually decreasing them.

Consequences of niche construction are usually causal feedbacks between what organisms do and responses from the environment. Yet, cultural evolution gives way to avoid limitations and constraints of genetic evolution and natural selection. Cultural innovations are set to circumvent these feedbacks by anticipating them and by a temporal avoidance of direct consequences. However, while that certainly has beneficial aspects in the short term, it might create undesired lock-ins for the long term. I argue that facing and being constrained by natural limits is indeed relevant to avoid falling beyond the so-called fitness cliff edge (Mitteroecker et al., 2016), where fitness continuously increases until it suddenly drops. What is arguably one of the main success features of human evolution – the development of cultural tools and programs that anticipate and avert negative feedbacks from the environment – might, in our industrialized and globalized world, endanger our own survival and lead to violent conflicts or collapse (Ehrlich, 2009).

While social-ecological consequences of niche construction are not always immediately obvious (Laland et al., 2014) they affect the space of future possibilities for transforming systems (Laubichler and Renn, 2015). Humans are exceptionally well adapted to counteract environmental change through niche construction, however "[n]iche construction typically benefits the constructor in the short term, but need not benefit other species that share its ecosystem" (Laland et al., 2014). Adverse side-effects and spillover effects of unsustainable niche construction might eventually add up to a more destructive than constructive form of human niche construction. The key question is, thus, how to create alternative pathways that avoid the unsustainable consequences of current trajectories (Ellis et al., 2018).

Cultural evolution has indeed to work faster than natural selection to prevent collapse (Harari, 2016; Perreault, 2012; Sieferle, 2011). But how will the cultural response look like – to reconnect or further disconnect? Researchers describe key alternative pathways as either taming human growth and impact (reconnect) or as increase geoengineering to further delay negative feedbacks of increasing colonization and metabolism (disconnect) (Catton and Dunlap, 1978; Haberl et al., 2011; Harari, 2016). I propose that the initial positive circumvention of balancing feedback mechanisms from the environment might lead society on pathways that are pushing social limits and planetary boundaries evermore, but lead to lock-ins and are insupportable in the long run. The continuous suspension of self-limiting feedbacks might add up to a situation where fitness, after steadily increasing, suddenly drops. Compare the cliff-edged model in Mitteroecker et al. (2016).

Yuval Noah Harari (2016) frames this dilemma as a double race in which humankind is locked in: on the one hand we feel compelled to speed up the pace of scientific progress and economic growth (avoid natural selection), on the other hand, we must stay at least one step ahead of ecological Armageddon (continue increasing unsustainable niche construction). The colonization of natural systems via niche construction requires an ongoing control of material and energy flows. We have to keep investing in constructed niches to keep them running and to prevent them from being dangerous; for instance, the anticipation of pests in agriculture, infrastructure for energy production or waste disposal. Feedbacks of already existing stocks on societal functioning need to be considered more explicitly for inherent path dependencies and lock-ins. Wicked long term legacies of human niche construction lead to irreversible system states which again lead to path dependencies (Winiwarter et al., 2016).

How to think about change?

There is a need to understand how unsustainable niche construction affects the possibilities of future transformation of these systems (Laubichler and Renn, 2015). Precisely because human niche construction developed a far-reaching destructive potential, we need to think about changing the underlying driver.

Like sustainability, niche construction is a process, not a state (Miller, 2013; Miller et al., 2014). The dynamics in this process are the following: humans, like every other organism, want to reproduce and therefore aim to diminish natural constraints. However, unlike other organisms, humans developed cultural traits that exceed this basic need and potentially unfold destructive powers which threaten previous achievements of niche construction. Human dominated coupled social and natural systems often involve a predicament of thriving versus destroying. The dynamic that needs to be leveraged to reconnect human development to natural cycles has to lie within cultural evolution again, but less on the side of how to further circumvent environmental feedback, and more about how to reconnect human activities to the natural biosphere. Thus, a fundamental reconstruction of the industrial niche is needed. If we would better understand niche construction processes, we could potentially design more effective interventions and leverage the same dynamics inherent in niche construction to move beyond unsustainable pathway dependencies (compare Figure 3).

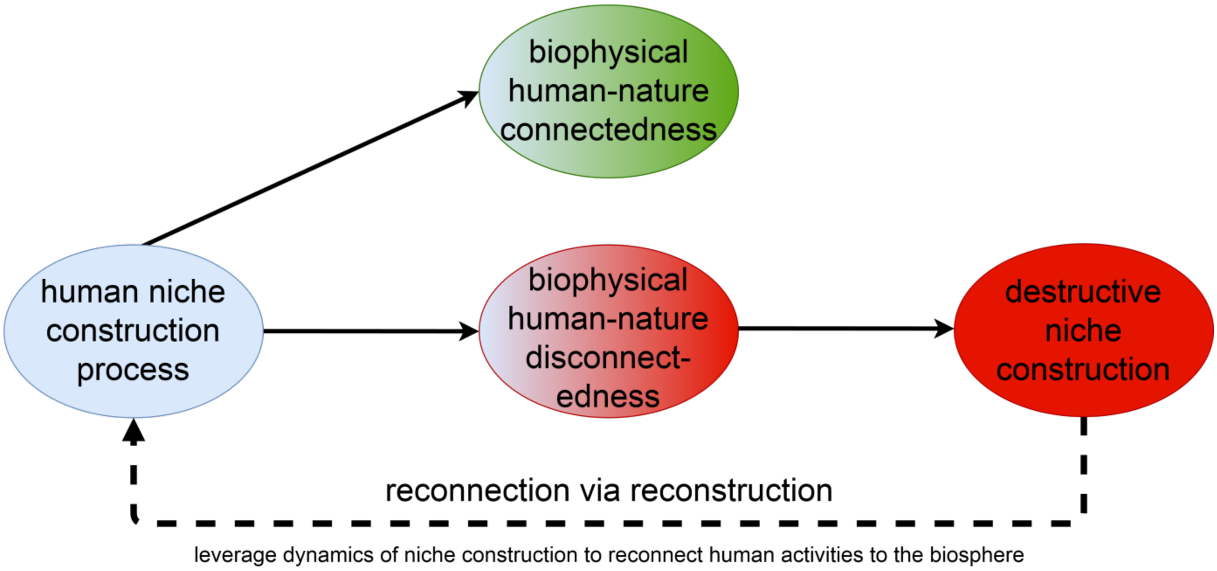

Figure 3: A conceptual representation of how the process of human niche construction leads either to a state of biophysical human-nature connectedness or disconnectedness. Disconnectedness, in turn, might lead to the destruction of ecological integrity. A reconnection of humans to nature might be achieved via a reconstruction of the human niche.

Instead of further taming nature, we need to think about how to tame human growth and impact. Cultural evolution has enabled humanity to control large parts of nature, now we need to mobilize it to tame the human impact on nature. We need a foresightful society (Haberl et al., 2011) with institutions realizing that our species will thrive better in the long term if we do not take as much from nature as we would potentially be able to. Cultural evolution has to be more than technological progress and adaptation but requires a deep reflection and rethinking of human culture, including human perspectives on nature, aspirations, technologies, norms, and worldviews (Beddoe et al., 2009; Brooks et al., 2018). The real challenge of our cultural evolution will be if we are able to change the underlying paradigm with which we relate to nature: Will it remain the full control and domination of nature, or living with nature and within natural limits and cycles?

In terms of leverage points (Meadows, 1999), the changing of a paradigm under which systems are operating has a great power to transform systems' behaviour and outcomes. In the late 1970s Catton and Dunlap (1978, 1979, 1980) outlined two broad ways of how humans relate to nature and describe the underpinning paradigm as either *human exceptionalism paradigm* (i.e., humans are distinct from nature for we have culture, with cultural evolution we can overcome every natural constraint) or *new ecological paradigm* (i.e., humans are part of nature, we must constrain consumption and tame human impact). While the former is predominantly prevailing in contemporary politics (at least the industrialized world) the latter represents a radical alternative. If we were truly able to change the paradigm underlying human-nature relationships, we might be able to overcome systemic roadblocks and adverse lock-in situations. Of course, truly changing this paradigm would impact not only our direct interaction with nature, i.e. nature experience in wildlife parks or agriculture, but our whole life and the structure of institutions.

Conclusion and outlook

The global sustainability crisis has been described as a result of the uniquely human form of adaptability and niche construction (Kline et al., 2018). While any sort of niche construction entails destruction for entailing a process of resource use and deconstruction of other niches, the progressive industrial niche construction ultimately threatens the pure existence and survival of future generations and of other species. There is a need to better understand how niche construction affects the possibilities of future transformation of coupled social-ecological systems (Laubichler and Renn, 2015). Specifically, growth-dependent systems and pathways must be scrutinized for their adverse lock-in effects, like global inequality, resource demand, and pervasive environmental pollution (Cumming and Cramon-Taubadel, 2018; Prell, 2016; Ring, 1997).

Life is inherently expansionist, but naturally also confronted with limitations and barriers that curb uncontrolled expansion and growth. Every living organism is surrounded by other organisms that provide balancing feedback. Through niche construction, humans widely circumvent self-limiting processes. While humans will remain niche constructing organisms, we need to find radically new ways to adopt niche construction principles that go beyond the established process of merely avoiding self-limiting feedbacks from the environment in the short term and only for the constructing agents. In contrast, a sustainable human niche construction explicitly and actively anticipates and respects the needs of spatially and temporally distant generations and for the thriving of other species. Thus, it internalizes a self-imposed constrain on growth.

My doctoral research challenges the mainstream perception of the "efficiency" of industrialized and globalized land-use systems and provokes discussions for alternatives – i.e. biophysically reconnected land-use systems, which would, in turn, imply very different feedback structures between humans and nature. My thesis provides many important new insights into the sustainability of human-nature relationships. I am confident it will significantly contribute to the critical academic debate on human-nature interactions, sustainable agriculture in a globalized world, justice and inequality, growth and other path dependencies, and interventions for sustainability transformation. However, there is much more work needed to complement this one. For example, I just opened an important avenue for future research on social-ecological systems research and niche construction theory. Crucially, to create more generalizable knowledge, there is more need to connect critical thought and concepts with empirical data and analysis. The present thesis is an attempt to do just that.

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Section A

Conceptualizing biophysical human-nature connectedness

Chapter II

Assessing sustainable biophysical human–nature connectedness at regional scales

Christian Dorninger, David J Abson, Joern Fischer, Henrik von Wehrden

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Abstract

Humans are biophysically connected to the biosphere through the flows of materials and energy appropriated from ecosystems. While this connection is fundamental for human well-being, many modern societies have—for better or worse—disconnected themselves from the natural productivity of their immediate regional environment. In this paper, we conceptualize the biophysical human–nature connectedness of land use systems at regional scales. We distinguish two mechanisms by which primordial connectedness of people to regional ecosystems has been circumvented via the use of external inputs. First, 'biospheric disconnection' refers to people drawing on non-renewable minerals from outside the biosphere (e.g. fossils, metals and other minerals). Second, 'spatial disconnection' arises from the imports and exports of biomass products and imported mineral resources used to extract and process ecological goods. Both mechanisms allow for greater regional resource use than would be possible otherwise, but both pose challenges for sustainability, for example, through waste generation, depletion of nonrenewable resources and environmental burden shifting to distant regions. In contrast, biophysically reconnected land use systems may provide renewed opportunities for inhabitants to develop an awareness of their impacts and fundamental reliance on ecosystems. To better understand the causes, consequences, and possible remedies related to biophysical disconnectedness, new quantitative methods to assess the extent of regional biophysical human-nature connectedness are needed. To this end, we propose a new methodological framework that can be applied to assess biophysical human–nature connectedness in any region of the world.

Keywords: biosphere, embodied energy, HANPP, land use, sustainability, teleconnections

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Assessing sustainable biophysical human–nature connectedness at regional scales

Christian Dorninger[1], David J Abson, Joern Fischer and Henrik von Wehrden

Faculty of Sustainability, Leuphana University Lüneburg, D-21335 Lüneburg, Germany
[1] Author to whom any correspondence should be addressed.

E-mail: christian.dorninger@leuphana.de

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Abstract

Humans are biophysically connected to the biosphere through the flows of materials and energy appropriated from ecosystems. While this connection is fundamental for human well-being, many modern societies have—for better or worse—disconnected themselves from the natural productivity of their immediate regional environment. In this paper, we conceptualize the biophysical human–nature connectedness of land use systems at regional scales. We distinguish two mechanisms by which primordial connectedness of people to regional ecosystems has been circumvented via the use of external inputs. First, 'biospheric disconnection' refers to people drawing on non-renewable minerals from outside the biosphere (e.g. fossils, metals and other minerals). Second, 'spatial disconnection' arises from the imports and exports of biomass products and imported mineral resources used to extract and process ecological goods. Both mechanisms allow for greater regional resource use than would be possible otherwise, but both pose challenges for sustainability, for example, through waste generation, depletion of non-renewable resources and environmental burden shifting to distant regions. In contrast, biophysically reconnected land use systems may provide renewed opportunities for inhabitants to develop an awareness of their impacts and fundamental reliance on ecosystems. To better understand the causes, consequences, and possible remedies related to biophysical disconnectedness, new quantitative methods to assess the extent of regional biophysical human-nature connectedness are needed. To this end, we propose a new methodological framework that can be applied to assess biophysical human–nature connectedness in any region of the world.

1. Introduction

Human societies are inherently connected to and dependent on the biosphere and its functions (Boulding 1966, Daily 1997, Folke *et al* 2011) through the flow of materials and energy (Haberl *et al* 2014, Cooke *et al* 2016). However, modern societies have increasingly disconnected themselves from their immediate regional environment by accessing material and energy flows from distant places (Kastner *et al* 2014, Bergmann and Holmberg 2016) and from outside the biosphere (Wiedmann *et al* 2015). Industry, technology and long-distance trade have enabled a disconnect of human activities from the primary production of their regional environment (Yu *et al* 2013), and from the biosphere by relying on industrial mineral resources (i.e. fossils, metals, and other minerals extracted from the lithosphere (Cumming *et al* 2014)). Hence, despite growing calls for societal reconnection to the biosphere (Folke *et al* 2011, Andersson *et al* 2014, Folke *et al* 2016), what this means from a biophysical perspective remains poorly understood.

The notion of biophysical human–nature connectedness is in conflict with the notion of decoupling socio-economic activities from natural resource use. In parallel to growing calls to 'reconnect' to the biosphere, other scholars have noted a relative decoupling of material throughput and economic growth for some regions (e.g. Fischer-Kowalski and Swilling 2011). Nevertheless, the economy is embedded in the environment (Martínez-Alier and

Muradian 2015, Folke *et al* 2016), all resources used in the economy are drawn from the environment, and all waste must return to the environment. Therefore, complete and sustained decoupling of economic activities from the environment is, by definition, untenable. Moreover, Cumming *et al* (2014) argued that a disconnect weakens direct feedbacks between ecosystems and societies, thereby potentially causing overexploitation and collapse. Others have claimed that disconnections provide opportunities for wild nature to be sustained by decoupling human development from environmental impacts (e.g. Asafu-Adjaye *et al* 2015). The purported benefits of purposeful disconnection are premised on intensified, more efficient land use. However, there is considerable debate regarding the efficacy and sustainability of such moves (Loos *et al* 2014a). For example, human–nature disconnectedness can increase inter- and intragenerational injustice by taxing future generations and distant regions (Haberl *et al* 2002, Martinez-Alier *et al* 2014) via overconsumption, depletion of natural resources, and pollution of the environment (Pearson 2007, Wiedmann 2016). In addition, disconnection from the natural environment may foster a systemic cognitive distancing of land use related activities from their environmental impacts (Cumming *et al* 2014, Seppelt and Cumming 2016).

Both perspectives—increasing or decreasing our distance to nature—share the goal of reducing pressure on ecosystems, but with different underpinning assumptions. By increasing our distance to nature we pin our hopes on the 'efficiency' of industrial technology in order to 'spare' land (Waggoner 1996)—a core idea of ecomodernism (Asafu-Adjaye *et al* 2015). We argue that this view fails to recognize spillover and distal effects, and is largely blind to issues of justice. For this reason, we instead argue for a reconnection of human activities to the biosphere and its regenerative cycles. This, in turn, implies not only a reduction of industrial material use and a limitation of human domination of ecosystems, but also a strengthened sense of being connected with and knowing the limits of nature (Folke *et al* 2011).

To facilitate constructive debate on whether we should reconnect to or disconnect from the biosphere, in this paper, we propose a conceptual framework to analyze regional-scale biophysical human–nature connectedness. The proposed framework builds on the regional land use system as unit of analysis. Yet it explicitly recognizes not only regional land use, but also global material trade and energy flows. By accounting for both economic and biophysical processes, we integrate concepts such as self-sufficiency, land use intensity, resource use, biophysical and embodied trade flows, waste generation, and environmental feedback loops into the framework. Thus, the framework provides a new lens through which land use sustainability can be investigated, which goes beyond 'on site' efficiency thinking (Fischer *et al* 2014, von Wehrden *et al* 2014). Our focus in this paper is primarily conceptual, but we also provide an outlook for how existing methodological approaches can be used to operationalize the proposed framework.

The paper is structured as follows. First, we outline our conceptual model, distinguishing between different types of biophysical disconnection. Second, we provide concrete examples to illustrate how the proposed framework can help to understand the sustainability challenges facing different regions. Finally, we provide a methodological outlook showing avenues how the proposed framework can be operationalized in order to generate quantitatively robust measures of regional-scale biophysical human–nature connectedness.

2. Conceptualizing regional biophysical human–nature connectedness

Regional land use systems are an appropriate unit to analyze biophysical human–nature connectedness because (1) energy and material flows across larger extents are typically too heterogeneous to be usefully aggregated; and (2) humans meaningfully experience life at regional scales (Kissinger and Rees 2010, Wu 2013). The spatial boundary of a 'region' will most often be defined by sub-national political-administrative units (e.g. from municipalities to federal states), as this is a vital scale for many political decisions (Dearing *et al* 2014) and usually the finest scale at which relevant material and energy flow data is available.

There are multiple ways in which humans' connectedness to natural ecological productivity can be conceptualized. For example, Seppelt *et al* (2014) suggest a framework based on distinguishing between renewable and non-renewable resource use. However, for regional assessments clear system boundaries are required, therefore, our framework distinguishes between two realms of land use related disconnectedness from the regional biosphere. The first possible realm is 'biospheric disconnectedness', and stems from the use of materials external to the biosphere, such as artificial agrochemicals, fossils or machinery. The second possible realm is 'spatial disconnectedness', and relates to the appropriation of distal ecological goods to bolster local production via imports of biomass, including food, timber, or feed for livestock. Moreover, one could consider the import of mineral resources used to extract and process ecological goods in the region as an additional form of spatial disconnect.

Both biospheric and spatial disconnectedness have potentially far reaching consequences for sustainability. Biospheric disconnection is characterized by a strong dependence on industrial inputs which delay or displace ecological constraints (Norgaard 1988, Martinez-Alier *et al* 2014). This raises concerns about intergenerational justice, because it creates societal structures that cannot be maintained indefinitely, and diminishes the biosphere's life-supporting conditions for future generations (e.g. through causing climate change). Similarly, spatial disconnection can result in the net appropriation of resources which create unsustainable lifestyle patterns (Brand and Wissen 2012, 2013) through teleconnections (Tukker *et al* 2014, Wiedmann *et al* 2015) that potentially disadvantage the 'source' regions. Spatial disconnectedness may thus compromise intragenerational justice, especially if the teleconnections are strong and unbalanced (Dorninger and Eisenmenger 2016, Teixidó-Figueras *et al* 2016).

2.1. Intraregional connectedness

Before considering the effects of biospheric and spatial disconnectedness in detail, it is necessary to develop a regional baseline for comparison. To this end, we first define *intraregional connectedness* as comprising the extent to which humans appropriate net primary production (NPP) for their own purposes, in combination with the labor used to appropriate this energy. A balance is required between regionally self-sufficient use of (ecologically derived) material and energy by humans and the availability of such flows to other species. The extent to which humans appropriate the NPP of the terrestrial ecosystems and the amount of trophic energy remaining in the ecosystems for other species indicates the level to which humans directly interact with, and source energy and materials from, ecosystems. In practice, intraregional connectedness may be measured via estimates of human appropriation of net primary production (HANPP) (Imhoff *et al* 2004, Haberl *et al* 2007b) and the labor inputs required to appropriate the NPP.

Direct human and animal labor in land use activities must be considered in the assessment of intraregional connectedness for several reasons. First, labor input is an important factor in the appropriation of net primary production: A system where net primary production is appropriated mainly by human and animal labor is likely to have very different sustainability outcomes than one where the appropriation is largely enabled by fossil fuel usage, even if the two systems have similar levels of HANPP. Second, direct labor is a form of internal input as long as working people and animals are 'fueled' by regional biomass products (Tello *et al* 2016). Third, from a human–nature connectedness perspective direct labor input in land use activities fosters rather than decreases biophysical and cognitive human–nature relationships (Cumming *et al* 2014, Webber *et al* 2015, Soga and Gaston 2016).

2.2. Biospheric disconnectedness

The relevant systems boundary for identifying *biospheric disconnectedness* is formed by the biosphere—the sphere of Earth where living organisms are found (Allaby 2008)—excluding, for example, the lithosphere, where minerals are sourced from. Thus, all mineral and non-renewable material and energy flows, no matter if they were sourced from inside or outside the spatial boundaries of the region, are considered as non-internal flows. However, considering the increase in global trade flows it is still useful to differentiate between regionally sourced and imported minerals that are used for land use related activities, i.e. the production, extraction and processing of ecological goods. In fact, minerals imported for land use related activities create both biospheric and spatial disconnection (see section 2.3 and figure 1).

The degree of biospheric disconnectedness is determined by (1) the direct and embodied flows of mineral inputs (in the form of agrochemicals, fossil fuels, or materials embodied in machinery) that are drawn from outside the biosphere; and (2) waste flows and emissions caused by the use of such inputs (e.g. greenhouse gas emissions). To grasp the full extent of material and energy requirements within the land use system, it is necessary to account not only for direct non-biospheric inflows, for example, the use of fossil fuel based artificial fertilizers, but also for indirect flows, for example, the energy, material, and labor inputs which were necessary to build an agricultural vehicle or the energy required for producing chemical fertilizers (see table 1).

Intensified agricultural practices from the 1950s onwards have led to increased yields (Pimentel *et al* 1973, Pimentel 2009, Martinez-Alier 2011). However, this short-term boost of regional net primary production (NPP) is typically driven by phosphorus, nitrogen and fossil fuels drawn from outside the biosphere (Erb *et al* 2012, Niedertscheider *et al* 2016). The exhaustion of non-renewable materials and the associated production of wastes and pollution during the use of such resources cause serious sustainability problems (Daly 1990). Addressing the 'displaced' impacts of those problems (Haberl *et al* 2002) both temporally (e.g. resource depletion, climate change) and spatially (trade related environmental burden shifting to distant regions), is particularly problematic without a detailed understanding of the non-biospheric energy and material flows that cause them.

2.3. Spatial disconnectedness

Regional land use systems are increasingly connected to distal regions via global markets (MacDonald 2013, Henders *et al* 2015, Chaudhary and Kastner 2016). It is, therefore, vital to include and identify interregional exchange relationships in any framework that describes biophysical connectedness. Trade flows of crops and other biomass commodities create biophysical connections to distant places, increasing the disconnect from the regional natural productivity (NPP) (Krausmann *et al* 2008, Mayer *et al* 2015). We define biological resources drawn from within the defined regional boundaries as internal flows, and consequently understand all other biological resources

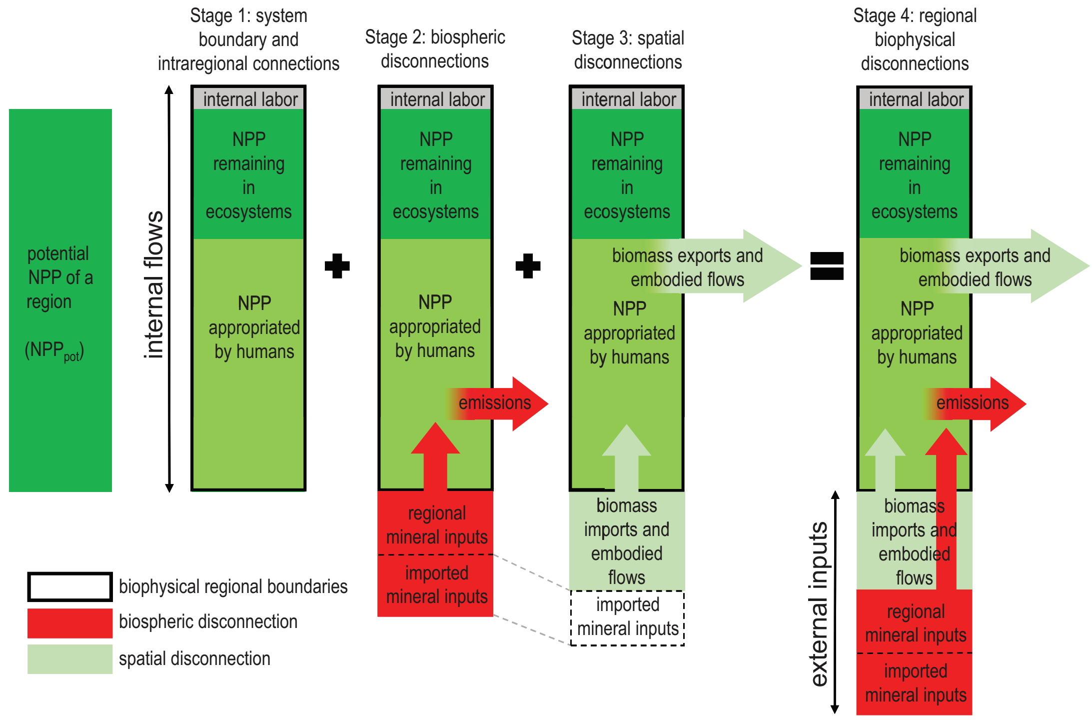

Figure 1. Conceptual steps towards assessing levels of biophysical human–nature connectedness and disconnections. From left to the right: the first bar shows the potential net primary production of a specific region (NPP_{pot}). Stage 1 indicates the fraction of the NPP appropriated by humans and what remains in the ecosystems for other species. Stage 2 shows biospheric disconnection by means of extra-biospheric inputs and emissions, whereby it is important to differentiate between regionally sourced and imported mineral inputs as indicated by the dotted line. Stage 3 shows spatial disconnections caused by intraregional biomass imports and exports. As indicated by the dashed area at the bottom, imported minerals can additionally be considered as causing spatial disconnectedness. Applying both aspects of disconnectedness to the intraregional connectedness results in the full assessment of biophysical human-nature disconnectedness at regional scales (Stage 4).

Table 1. External inputs into the land use system (Pimentel *et al* 1973 2008, Tello *et al* 2016). The left column lists material and energy inputs that enter the land use system from outside the biosphere and cause biospheric disconnectedness. These inputs may either come from regional sourcing or imports. The right column includes relevant intraregional trade of biomass based commodities which cause spatial disconnectedness.

External inputs	
Industrial mineral inputs (differentiated by regional sourcing or imports)	Biomass imports
- Machinery use - Associated fossil fuels for machinery - Agrochemicals (e.g. artificial fertilizers, pesticides) - Irrigation and water pump facilities - Industrial seed production - Embodied flows of materials, energy, and labor for the production of all that items	- Embodied HANPP flows (section 4) of: • Livestock feed • Food • Fiber and timber for textiles and construction • Livestock • Biomass for bioenergy purposes - Embodied flows of materials, energy, and labor in all that commodities

flowing into the region as 'external inputs' (table 1). *Spatial disconnectedness* can therefore be quantified via the amount of biomass based commodities imported to and exported from a region. Moreover, the import of minerals for land use related activities can be considered as an additional form of spatial disconnection. In order to reveal the full extent of disconnectedness, the embodied flows of material and energy associated with those biomass based imports and exports should also be accounted for.

Here it is important to note that trade-enabled material and energy exchanges between regions do not per se compromise sustainability. Some studies stress the economic and ecological efficiency gains that arise from free trade and long distance relationships (Bhagwati 2007, Martinez-Melendez and Bennett 2016). Other scholars observe asymmetric power relationships and systematic inequalities in 'ecologically unequal exchange' relationships (Hornborg and Jorgenson 2013, Dorninger and Hornborg 2015) which provide only the pretense of efficiency and decoupling gains (Weinzettel *et al* 2013, Wiedmann *et al* 2015, Bergmann and Holmberg 2016). Regardless of the contention regarding the benefits of such land use related trades, we can say that distal trade relations always cause spatial human–nature disconnections.

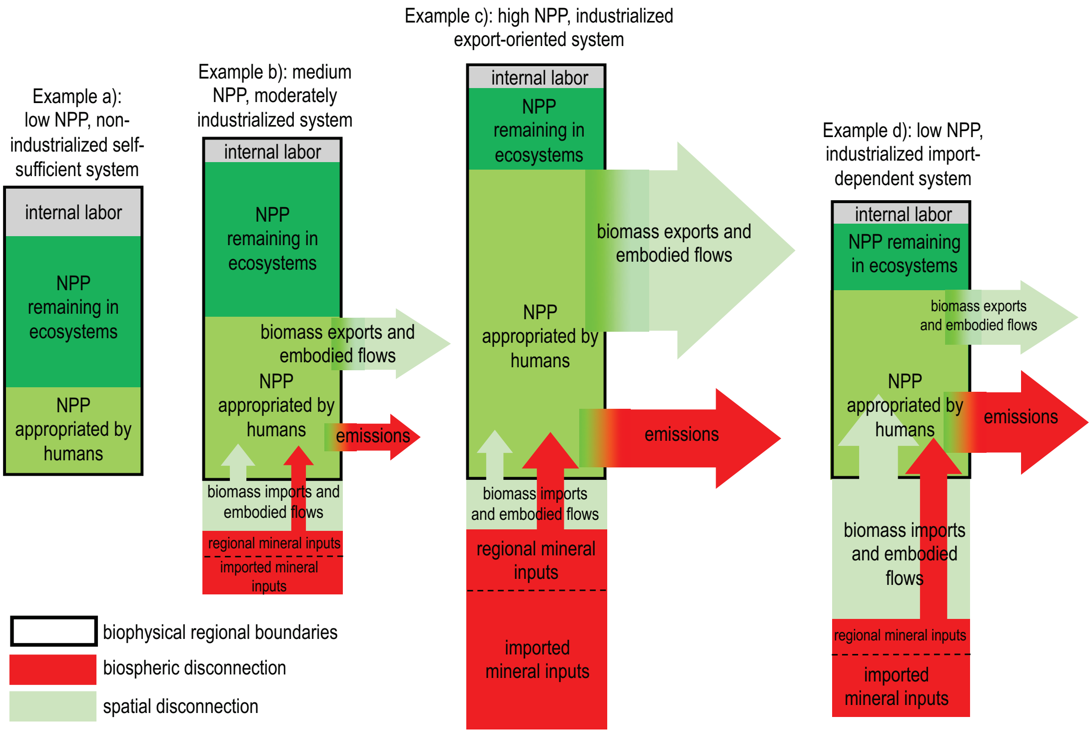

Figure 2. Four exemplary regional land use systems illustrating regional connectedness and different degrees of biophysical disconnectedness respectively. The four examples exhibit varying levels of potential NPP (NPP_{pot}). Example (*a*) represents a system that does not access non-renewable or distant goods, meaning that human-induced energy inputs only come from labor. Example (*b*) draws on resources from both outside the region and outside the biosphere, which allows internal labor input to decrease significantly. Example (*c*) heavily relies on mineral inputs in order to produce commodities for exportation. Additionally, major parts of NPP are appropriated and emissions released. Example (*d*) shows largely human controlled regional ecosystems, which uses considerable shares of the available NPP and additionally heavily draws on external inputs which are mostly being imported.

These distal relations, or 'teleconnections' (Adger *et al* 2009, Haberl *et al* 2009, Yu *et al* 2013), not only involve long distance transportation (Cristea *et al* 2013) and environmental load displacement (Peters *et al* 2011, Peng *et al* 2016), but crucially also the substitution of regionally available biospheric resources by distal ones. This increases the complexity of the environmental and societal impacts arising from a given land use and cognitive and psychological disconnectedness from the environment (Kissinger and Rees 2010).

Figure 1 shows the conceptual steps towards assessing the levels of biophysical human–nature connectedness and potential disconnections.

3. Archetypical examples

We illustrate our conceptual framework for different regional land use systems with four archetypal systems. For each of the four systems the height of each component indicates the relevant throughput of energy and materials related to intraregional connectedness, spatial and biospheric disconnections (figure 2). A self-sufficient, non-industrialized, subsistence system which does not use any non-renewables in their land use practices, but relies solely on biomass goods and on relatively high labor input, has neither spatial nor biospheric disconnections (figure 2(*a*)). Such systems represent subsistence farming regions which were common especially before the 20th century in most parts of the world (Krausmann 2001, Erb *et al* 2008). Moderately industrialized systems exhibit moderate levels of external inputs which allow a comparatively higher NPP appropriation with significant lower labor input (figure 2(*b*)). Such systems may include regions in transition from an agrarian to a more industrial society, for example, regions of Eastern Europe (Hanspach *et al* 2014, Loos *et al* 2014b). In contrast, a strongly exported oriented, highly industrialized system with high NPP availability is both spatially and biospherically more disconnected (figure 2(*c*)), for example, export-oriented soybean production regions in Brazil (Wittman *et al* 2016). Finally, an industrialized system with a high HANPP and high external inputs indicates strong regional disconnection and both temporal and spatial displacement of environmental burdens (figure 2(*d*)). Similar systems are likely to be found in densely populated, largely urbanized and wealthy regions such as Western Europe (Niedertscheider *et al* 2014).

Regions where direct labor input has largely been displaced by external inputs may exhibit a similar HANPP, but differ greatly with regard to the other two dimensions—biospheric and spatial disconnection (figures 2(*b*) and (*d*)), this has far reaching sustainability outcomes not only for the focal regions, but also for the distant regions they are connected to. Identifying the nature and extent of such regional disconnections is a crucial first step in addressing the

Table 2. Methods register and key references. The left column lists the methods to quantify regional biophysical human–nature connectedness. The relevant key references for each approach are provided in the right column. The ideal units of measurement are given in square brackets (where applicable), where [t] stands for metric tons, [J] for joules, and [h] for hours.

Methods and models of environmental accounting	Key references
Human appropriation of net primary production (HANPP) [t] [J]	• Vitousek *et al* 1986, Haberl *et al* 2007a
Material and energy flow analysis (MEFA) [t] [J]	• Haberl *et al* 2004, Fischer-Kowalski and Haberl 2007
Accounting of embodied flows	
• environmentally extended input output analysis (EEIOA)	• Leontief 1970, Kitzes 2013
• extension factors	• Pimentel *et al* 2008, Kastner *et al* 2015
Types of embodied flows	
• embodied HANPP (eHANPP) [t] [J]	• Erb *et al* 2009, Haberl *et al* 2009
• raw material equivalents [t] [J]	• Schaffartzik *et al* 2015b, Eisenmenger *et al* 2016
• embodied labor [J] [h]	• Alsamawi *et al* 2014, Simas *et al* 2015
• embodied energy [J]	• Agostinho and Siche 2014, Aguilera *et al* 2015

cross-scale sustainability challenges related to such interconnected systems. Without genuine reconnectedness, humans are only at best peripherally aware of the full range of impacts their lifestyle has on other and future generations, and on other species. A more complete understanding of human–nature connectedness and opportunities to reconnect, might increase the leverage potential of actions set in land use systems towards transformational change (Meadows 1999, Abson *et al* 2016). It is to be hoped for that biophysically reconnected regional land use systems ultimately promote a more foresightful, responsible and conscious society, based on a living with rather than dominating nature.

In regionally connected land use systems, largely reliant on (transformed) solar energy and labor as major energy inputs, in- and outputs will then be reconnected to the natural cycles—the regeneration and uptake rate —of the biosphere (Folke *et al* 2016). A reconnected land use system will strengthen self-sufficiency, circularity in production and consumption; involve less teleconnections, less specialization, more diverse land uses, and relations of trust (Tregear 2011, Weatherell *et al* 2003). Here the major balancing challenge is ensuring that sufficient biospheric resources are appropriated for human well-being while retaining resources available for the flourishing of other species.

In all cases the assessment of regional biophysical connectivity, particularly if linked to other regional indicators, can help identify regionally specific challenges in transitioning towards more sustainable land use systems. In addition, multi-scalar assessments may help identify 'natural' scales of biophysical connectedness and appropriate scales for managing material and energy flows.

4. From theory to practice: methodological guidelines

In this section we present methodological guidance to operationalize our concept of biophysical human–nature connectedness at regional scales. Building on well-established methods (table 2) this operationalization will allow assessment of the extent to which systems are built on and driven by intraregional connectedness and biospheric and spatial disconnectedness respectively (figure 3).

As discussed above, we consider HANPP as an appropriate starting point to quantify intraregional connectedness. HANPP is based on not only appropriated biomass yields from farming, grazing, and forestry, but also harvest related losses, unused biomass extraction, conversion losses, and land use conversion—changes in the HANPP fraction due to indirect changes to NPP. A land use conversion effect can only be quantified in relation to the potential net primary production (NPP_{pot}) that would occur at a certain area without any human interference. A range of different models exist that allow for a computation of site-specific photosynthesis performance (Haberl *et al* 2014). For example, the Miami model (Lieth 1975) calculates NPP_{pot} from average precipitation and annual mean temperature of an area. Other models additionally include information on soil texture, latitude, and CO_2 availability (Sitch *et al* 2003). By subtracting the HANPP, i.e. all harvest and related flows plus the land use conversion, from the NPP_{pot}, one arrives at the NPP that remained in the ecosystem after harvest and which is available for other species (NPP_{eco}) (Krausmann *et al* 2013, Plutzar *et al* 2015). By going beyond simple harvest or yield assessments HANPP reveals the connectedness to the productivity, and the potentially renewable resources, of ecosystems.

From an ecological perspective, low HANPP may be a desirable goal because it leaves a large amount of energy to other species (Haberl *et al* 2007a). In contrast, if low HANPP values are achieved via the use of non-renewable resources or distant biomass the overall outcomes for sustainability may still be negative (with regards to future generations and distant regions). However, as the conventional HANPP method neither captures external inputs, such as the materials and substances that are used to

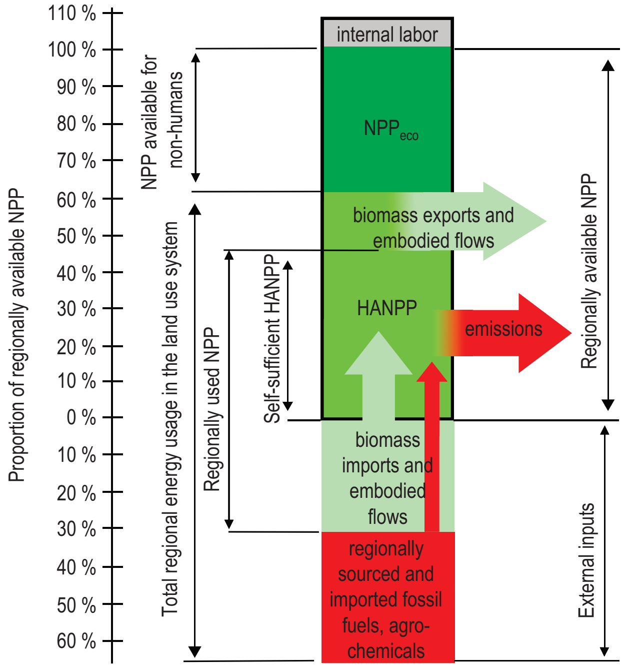

Figure 3. The parts of biophysical human–nature connectedness framework that need to be quantified. NPP_{eco} shows how much trophic energy is available for non-human species after harvest. Internal labor input and HANPP are both influenced by the extent of external inputs and biomass imports. Outflows of the system are exports of biological resources, their embodied flows and emissions to air, water, and land. All components constituting the intraregional connectedness, internal labor input, NPP_{eco}, and HANPP, as well as the external inputs, traded biomass and mineral inputs, can all be expressed in terms of energy [J]. Thus, they can be given as proportions of the regionally available NPP. Only emissions and generated wastes cannot be directly expressed in terms of energy.

produce and harvest goods in the land use system (Haas and Krausmann 2015), nor trade related teleconnections (Haberl *et al* 2009, Kastner *et al* 2015), nor the labor inputs to those systems, further methodological steps are required to evaluate regional scale biophysical human–nature connectedness.

Biospheric disconnections can be assessed via a social–metabolic analysis of the regional land use system. Social metabolism quantifies, similar to the metabolism of organisms, the biophysical inputs and outputs of a social–ecological entity. It is operationalized by material and energy flow accounting analysis (MEFA) (Fischer-Kowalski and Haberl 2007). While analysis of socio-ecological energy and material flows is well established, particularly at the national level (Fischer-Kowalski *et al* 2011, Haberl *et al* 2004), the notion and consequences of changes to 'regional biophysical human–nature disconnections' is hardly explored in that literature. However, by conducting such a MEFA analysis one is able to calculate the throughput of materials and energy of the land use system and subsequently relate these flows to regional and cross-scalar sustainability challenges.

The system boundaries of the adopted MEFA analysis are defined by the spatial boundaries of the region (Sastre *et al* 2015) and the boundaries of the biosphere. In order to account for differing levels of teleconnectedness, it is important to differentiate between regionally sourced mineral inputs and imported ones. Doing so can help reveal related additional transport costs, patterns of ecologically unequal exchange and outsourcing of material and energy intensive processes. Industrial mineral inputs, such as machinery use, fuels, or agrochemicals, enter the system from outside the biosphere (left column of table 1) and potentially from outside the region. Outflows are those materials and substances that are not reused in the land use system but create pollution, wastes, and emissions.

Artificial fertilizer, seeds and machinery production processes are an energy and material intensive endeavor (Pimentel *et al* 2008). In order to reveal the full extent of energy, materials and labor required for the external industrial inputs into the land use system, the embodied flows of those inputs must be accounted for. We suggest using either product and region specific extension factors (Kastner *et al* 2015, Schaffartzik *et al* 2015a), or regionally adjusted environmentally-extended input-output analysis (EEIOA) (Miller and Blair 2009, Kitzes 2013, Schaffartzik *et al* 2014) where intersectoral linkages can be retraced, i.e. the flows between the land use sector and other socio-economic sectors of the region.

The third and last methodological measure of the framework is to collect data on the biomass based inter-regionally traded goods for quantifying the spatial disconnect. In short, all directly traded biomass commodities (table 1) such as crops, animal products, textiles, other fibers, bioenergy products, and wood products, and the indirect flows of NPP, materials, energy, and labor embodied in these goods need to be captured. The latter are usually not reported in trade statistics. Still, the methodological goal is to redistribute the flows embodied in the goods from the place of origin to the place of final consumption (Kastner *et al* 2015, Wiedmann 2016).

To comprehensively reveal the biophysical processes necessary to produce a specific commodity and to disclose how the consumption of traded goods affects connectedness an environmentally-extended input-output table or extension factors, which are adjusted for the specific region and year, would potentially provide the best systematic approach to assess the embodied flows of traded products. The results of embodied HANPP (Erb *et al* 2009), raw material equivalents (Schaffartzik *et al* 2015b, Eisenmenger *et al* 2016), embodied energy (Agostinho and Siche 2014, Perryman and Schramski 2015), or embodied labor (Alsamawi *et al* 2014, Simas *et al* 2015) are established indicators, increasingly used in the scientific literature to reveal international inequalities and related environmental pressures (Teixidó-Figueras *et al* 2016).

Different types of flows have different metrics: NPP and HANPP can be expressed in terms of dry matter [t], carbon [t] or energy units [J]; labor input in time units [h] or energy [J]; materials in units of mass [t] or enthalpy [J]; emissions in GHG potentials [t CO_2 equivalents] and nitrogen leaching [NO_3]. For achieving comparability between regions we suggest to evaluate connectedness on a per unit area, or per capita basis; comparability within regions may be achieved via an expression of flows in energy units (except emissions), i.e. flows of HANPP, material, and labor. The final result of the framework provides a measure of the degree to which a regional land use system is biophysically connected to the productivity of the regional ecosystems (NPP) and disconnected in terms of external inputs (figure 3).

The empirical application of this framework will likely involve challenges with regards to data availability and the computation of critical embodied flows. In particular, identification and assessment of interregional trade flows from material accounting data will involve region-specific difficulties. For example, physical trade relations between regions might not be reported by authorities. Therefore, we encourage consultation of relevant stakeholders to assure the validity of data where necessary. Likewise, the calculation of embodied flows is a sensitive methodological endeavor (Schaffartzik *et al* 2015b). It will therefore be important to provide detailed information on steps of the decisions that have been made regarding data sources and estimations to ensure transparency and traceability.

5. Outlook

We argue that the regional land use system is an appropriate unit of analysis for investigating biophysical connectedness as it provides a focal unit for understanding cross scale interactions between land use systems, revealing key environmental feedback loops in and between regions. We recognize that we take a relatively pragmatic definition of 'region'. Yet, in principle it should be possible to use this approach to identify spatial extents within which there are high levels of connectedness or across which significant disconnections occur.

Biophysical human–nature connectedness is increasingly overlain and suppressed by modes of industrial land use, which entails teleconnections and external non-renewable inputs. In this paper we introduced a new approach to conceptualize biophysical human–nature connectedness at regional scales and related it to potential sustainability outcomes. Building on *a priori* state of biophysical connectedness, we identified two major realms of disconnectedness: (1) external non-renewable inputs that enter the land use system and (2) teleconnections with distant systems, both of which decrease regional connectedness.

While the conceptual framework itself represents a novel perspective on land use management, the combined methods for each part are well established. Together these methods allow for comparisons of different 'types' and degrees of the connectedness between different regions, which in turn can be related to other regional characteristics or sustainability outcomes (e.g. Wittman *et al* 2016). The framework is designed to be applicable to regions anywhere in the world and to encourage researchers and policymakers to develop a more holistic approach regarding cross-scale, sustainable land management issues not captured by other frameworks (e.g. sustainable intensification (Barnes and Thomson 2014, Loos *et al* 2014a), or land sparing (Fischer *et al* 2014)).

Instead of making human–nature connections evermore complex and opaque by increasing external inputs via industrial technology, a genuinely reconnected system will have a higher internal self-reliance, through a more self-sufficient land use system. Such regionally reconnected systems may facilitate more foresightful, responsible and conscious behaviors. We believe that there are various opportunities to strengthen connectedness of humans to nature. For example, by a re-regionalized economy, a higher degree of self-sufficiency, lower degrees of dependence on external (non-renewable or distant) inputs, by internal biomass reuse (Galán *et al* 2016, Tello *et al* 2016), permaculture, agroforestry, organic farming, small-scale farming, low external input technology farming (Tripp 2005), lower consumption patterns (especially of NPP intensive products, like animal products), less overproduction and consequently less food and biomass 'wastes'. The operationalization of this model can be applied as a heuristic tool to reveal complex social–ecological interlinkages, raising awareness of the challenge in managing biophysical connections across scales. This in turn might help to shift the focus from 'on site' efficiency thinking in land use management to a more comprehensible and holistic perspective on human–nature connectedness.

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Chapter III

Human-nature connections: aligning biophysical and sociopsychological approaches for sustainability

David J. Abson, Kathleen Klaniecki, Christian Dorninger, Henrik von Wehrden, Christopher D. Ives, Maraja Riechers

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Abstract

1. Human-nature connections are recognized, across multiple scientific fields, as important factors in various aspects of sustainability. The scientific literature is broadly split into biophysical and sociopsychological approaches to conceptualizing such human-nature connections.

2. Both approaches provide useful insights; however, the linkage between biophysical and psychological human-nature connections has received very little attention.

3. The two approaches are interdependent, yet retain specific (siloed) focuses on structural (biophysical) and agency (socio-psychological) related connections, addressing different scales of analysis and different potential places to intervene in complex systems in order to lead to transformative change towards sustainability.

4. In this paper we briefly outline the characteristics of these two broad approaches to human-nature connections, noting the key differences and commonalities. We then discuss the potential advantages of aligning these two approaches, and the potential challenges in doing so. Finally, we suggest some directions for future research on sustainability and human-nature connections.

Keywords: human-nature connections, environmental psychology, integration, leverage points, sustainability, systems thinking

1. Introduction

Individuals and societies are increasingly disconnected from nature, as a result of urbanization and globalized patterns of natural resource usage (e.g., Seto et al., 2012) as well as adopting lifestyles with infrequent contact with natural environments (Soga & Gaston, 2016). These disconnections have consequences for human wellbeing and health (Sandifer, Sutton-Grier & Ward, 2015), attitudes and behaviours towards nature (Nisbet, Zelenski & Murphy, 2009), and material use and consumption (Folke et al., 2011). Recognition of the adverse consequences of human-nature disconnections has led to calls for a better understanding of human-environmental interactions as a key component of sustainability (Folke et al., 2011, Ives et al., 2017, Schultz, 2002).

Within this research field, which for brevity we refer to as human-nature connections (HNC), two main narratives/perspectives have arisen that engage with the (dis)connection between people and nature and the need to reconnect with nature for sustainability: (1) the first perspective, which here we call 'biophysical HNC' (Dorninger, Abson, Fischer & Von Wehrden, 2017) focuses on notions of sustainable resource use and material and energy flow between societies and the environment (e.g., Fischer-Kowalski et al., 2011, Haberl et al., 2007, Wackernagel et al., 1999). This perspective primarily focuses on 'systems' – rather than individuals – highlighting the need to consider the impact of human activity on the environment. (2) The second perspective, which for brevity we refer to 'socio-psychological HNC' focuses on the emotional, experiential, philosophical and cognitive connections with nature (e.g., Ives et al., 2018) and how these relate to well-being, pro-environmental values and attitudes, and behaviours (e.g., Andersson et al., 2014, Nisbet et al., 2009, Soga & Gaston, 2016). This perspective focuses on individual behaviours, and calls for increased cognitive, emotional, and psychological connections to nature.

These two perspectives (biophysical and socio-psychological) have conceptualized and operationalized HNC from different theoretical and disciplinary position, which has led to a diverse but sometimes conflicting perspectives on the role of HNC in transformative change towards sustainability. Moreover, each perspective provides insights into different places in which intervention can be made to halt or reverse human-nature disconnections. While each approach is of considerable value, in this paper we argue that there is a pressing need to better align and integrate these approaches due to the unavoidable interdependence between biophysical and socio-psychological HNC. It is not simply that they share the same underpinning causes (urbanization, globalization, materialism, technological changes etc.), but that they are two parts of a single reinforcing feedback loop. As societies become biophysically disconnected from nature, this leads to the loss of opportunity and ability to experience nature, which in turn reduces humanity's emotional affinity with nature. This loss of affinity with nature (loss of socio-psychological HNC) decreases concern for further erosion of biophysical connections (Soga & Gaston, 2016). This reinforcing feedback loop has been described by Robert Pyle in his memoir *The Thunder Tree* as the "extinction of experience" (Pyle, 1993). The artificial separation of socio-psychological and biophysical aspects in current HNC research crucially misses this reinforcing feedback dynamic.

In this paper we discuss the characteristics of the biophysical and socio-psychosocial HNC perspectives, challenges and opportunities for better aligning these perspectives, and suggest some tentative approaches to bridge biophysical and socio-psychological HNC research. We are aware that characterizing large, diverse and vibrant bodies of work in a few paragraphs is likely to lead to oversimplification. Therefore, the intention is not to provide a detailed review of the literature, or authoritative definitions of these two perspectives on HNC; rather, we attempt to highlight some overarching characteristics, the value of their individual contributions, and the potential of better aligning the two approaches in the context of sustainability. We note there are other important approaches to conceptualizing human environment interactions in relation to sustainability including socio-ecological systems research (e.g., Fischer et al., 2015, Ostrom, 2009); ecosystem services approaches (e.g., Riechers, Strack, Barkmann & Tscharntke, 2019, Schröter et al., 2017) and relational values (e.g., Chan et al., 2016, Díaz et al., 2015) that are beyond the scope of this current discussion.

2. Biophysical human-nature connections

Biophysical human-nature connections (Dorninger et al., 2017) encompass different methodological approaches for assessing humanity's appropriation of material and energy flows from the environment. From a biophysical perspective, societies are intrinsically connected to nature through their social metabolism of material and energy via economic activity (e.g., de Molina & Toledo, 2014). This research strand has a long history including early earth system dynamic models that sought to understand the material and ecological limits to economic growth (e.g., Meadows, Meadows, Randers & Behrens, 1972). The research encompasses ideas such as emergy— all the energy used to generate a product or service— analysis and environmental carrying capacity (Odum & Odum, 1976) and attempts to quantify ecological 'footprints' of human activity in terms of available productive land (e.g., Rees, 2006). The 'planetary boundaries' concept (Rockström et al., 2009) is a recent example of this broad biophysical HNC research strand, situating human activity within maximum material and energy flows to the environment while maintain a "safe operating space for humanity".

Specific biophysical HNC approaches include measures of material and energy flow accounting (e.g., Fischer- Kowalski & Haberl, 2015), and human appropriation of net primary production (e.g., Haberl et al., 2007) used to operationalize spatio-temporally explicit interactions between humans and the environment. More recently, scholars have begun to explore material and energy flows between spatially distant systems, giving greater emphasis to understanding teleconnected, distal environmental impacts (e.g., Liu et al., 2007) and the unequal appropriation of material and energy flows through trade (Dorninger & Hornborg, 2015, Hornborg & Martinez-Alier, 2016).

Despite the diversity of approaches found within the biophysical HNC literature, the research shares some key characteristics. An important commonality of biophysical HNC research is the creation of integrated and robust quantitative measures of biophysical human-nature connections used to evaluate the ecological or social consequences of socio-economic activities. Quantitative biophysical assessments are considered important in providing decision-makers with evidence about unsustainable biophysical human-nature connections. Most biophysical HNC research employs societal entities, such as urban populations, or the nation state, as units of analysis. Biophysical HNC research primarily applies a systems perspective on society-environmental relations where humans shape the environment via socio-economic institutions related to economics, resource use and trade relations (Challies, Newig & Lenschow, 2014), with little consideration of individual human agency. Human-nature disconnections are conceptualized in terms of resource appropriation that exceeds the carrying capacity of a given system, or that is dependent on appropriation of resources from distal systems.

3. Socio-psychological human-nature connections

Socio-psychological HNCs reflect the degree to which one considers or experiences a personal relationship, bond, commitment, or affinity with the natural world. While efforts to understand and describe how humans interact with nature have occurred throughout time, the last 30 years brought a wave of research focused on the growing gap between humans and nature, and the implications of this gap for sustainability. While humans have been purported to have an innate attraction to and dependence on nature (Wilson, 1984), scholars argue that these relationships have been strained and fractured due to technological advancements, urbanization trends, and increasingly indoor lifestyles, leading to an extinction of experience (Pyle, 1993).

The scope of socio-psychological HNC research is broad. Various scholars have characterised these relationships in terms of emotional (e.g., Kals, Schumacher & Montada, 1999), identity and self-concept (e.g., Clayton, 2003), commitment (e.g., Davis, Green & Reed, 2009), and belonging (Mayer & Frantz, 2004) (for similarities and differences between these concepts, see Tam, 2013). Socio-psychological HNC has been measured and operationalised in many ways; often encompassing emotional, experiential, philosophical and cognitive relationships that occur between humans and nature (several reviews show the breadth of this field; see, Ives et al., 2017, Restall & Conrad, 2015, Zylstra, Knight, Esler & Le Grange, 2014).Social sciences have primarily studied socio-psychological HNCs, with conceptual and empirical contributions from the fields of environmental psychology, human geography, education, and tourism (Ives et al., 2017).

While the strands of socio-psychological HNC research operate with different aims and investigate different outcomes, the field can be characterized by a series of overarching trends. Psychological HNC research primarily measures connections to nature at the individual scale and uses on a mix of quantitative (e.g. psychometric scales) and qualitative (e.g. semi-structured interviews) methods. This approach is primarily focused on positive outcomes related to environmental attitudes and beliefs (e.g., Nisbet et al., 2009) and pro-environmental behaviours and actions (e.g., Geng, Xu, Ye, Zhou & Zhou, 2015) and on how connections to nature are formed (e.g., Barthel, Belton, Raymond & Giusti, 2018). Findings from socio-psychological HNC studies have been used to inform projects and interventions with the aim of influencing the adoption of pro-environmental attitudes, values and behaviours (e.g., DEFRA, 2018).

4. Challenges of aligning biophysical and socio-psychological HNC research

The very different problem framings, operationalization and methodologies employed in the biophysical and socio-psychological HNC research (Table 1) represents a particular challenge for integrating the two approaches.

At the most basic level socio-psychological HNC research focuses on individual agency, well-being, identity and pro-environmental behaviours or intentions that arise from individual experience of and connections to the natural world. In contrast, biophysical HNC research focuses on systemic patterns of resource use and their relation to societal level sustainability outcomes. Biophysical and socio-psychological HNC research also differs in terms of their scale and units of analysis, problem framings, methodological approaches and terminologies. Table 1 highlights a number of key characteristics that distinguish the two HNC approaches.

Socio-psychological HNC research primarily measures connections to nature with individuals as the unit of analysis and uses a mix of quantitative (e.g. psychometric scales) and qualitative (e.g. semi-structured interviews) methodology to investigate the relations between degree of connectedness and environmental attitudes and beliefs (e.g., Nisbet & Zelenski, 2013) and pro-environmental behaviours and actions (e.g., Geng et al., 2015). Human-nature disconnections are concpetualized in terms of loss of cognitive, affective or experiential links to nature. In contrast, most biophysical HNC research employs societal entities, such as urban populations, nation states, as units of analysis. Biophysical HNC research primarily applies a systems perspective on society-environmental relations where humans shape the environment via socio-economic institutions related to economics, resource use and trade relations (Challies et al., 2014), with little consideration of individual human agency. Human-nature disconnections are conceptualized in terms of resource appropriation that exceeds the carrying capacity of a given system, or that is dependent on appropriation of resources from distal systems.

Table 1: Characteristics of and key integration points for biophysical and socio-psychological HNC approaches

Characteristics	Biophysical HNC	Psychological	Key Integration point
Problem framings	Connections via resource and land usage related to ecological limits, and distributional issues.	Disconnection from nature as a cause, symptom or treatment of unsustainable behaviours (Ives et al 2018).	Recognition that these phenomena are mutually reinforcing; problem framings that focus on the feedback between individual agency and societal structures.
Level/scale/focal unit of analysis	Societies, or socio-ecological systems.	Individuals, or individual human-nature interactions.	Conceptual approaches such as landscape sustainability science(Wu, 2013) that explicitly seek to integrate such cross scale issues.
Human-nature relationship terminology	Interactions: relatively neutral, passive and descriptive (what is), interactions as 'means'.	Connections/disconnections: relatively normative (what could be) and alterable; connections as both 'means and 'ends'.	Common language to improve shared problem understanding.
Methodology	Descriptive-systems dynamics and system behaviour.	Hypothesis driven relating to individual agency and behaviour behaviour or descriptions of lived experiences of people in different environments.	Linking community level socio-psychological HNC connections to nature to structural patterns for biophysical HNC.
Targeted sustainability outcomes	Decreased pressure on ecosystems from resource use systems.	Increased pro-environmental behaviour of individuals or their health/well-being	Focus on barriers to transformative change, particularly across the biophysical socio-psychological divide.

From a biophysical HNC perspective transformative sustainability solutions are generally related to identifying, and living within, societal scale biophysical or ecological limits (e.g., Daly, 1991, Folke et al., 2011). While biophysical HNC research generally has a strong focus on sustainability outcomes in relation to distributional justice (inter- and intra-generationally equitable resource use), increasingly procedural elements via governance of teleconnections (e.g., Challies et al., 2014, Hornborg, McNeill & Alier, 2007) investigate how biophysical states of systems are generated and institutionalised. In contrast, the overarching aim of socio-psychological HNC approach is to understand "the broad underlying structure of relational motives for environmental behaviours" (Davis et al., 2009 p258). While scholars recognize that social and environmental factors shape opportunity to connect with nature, the socio-psychological HNC approach is oriented to means by which individuals can strengthen or build connections to nature through changes in individual activity and behaviour (e.g. spending more time in nature). The socio-psychological approach reflects societal-level trends, highlighting underpinning worldviews, values, and attitudes of societies that shape human-nature relationships and interactions (Schultz, 2011).

Aligning biophysical and socio-psychological approaches begins with acknowledgement of the interdependences between these two aspects of human-nature connections. This will include the need to draw system boundaries explicitly including the feedback between societal scale patterns of natural resource use and individual opportunities for and attitude towards experiencing nature. Here we argue that doing so will not just enrich both fields of research, but provide new insights about where to intervene in human-nature connections in the pursuit of more sustainable human-nature relations.

5. Opportunities to align biophysical and socio-psychological HNC research

Human-nature connections have been conceptualized as both a symptom of, and a treatment for, unsustainable behaviour (Ives et al., 2018). Biophysical HNC research largely describes the symptoms of unsustainability (often in terms of unsustainable resource use), without explicitly addressing the perceived root causes (e.g., the worldviews, and economic and institutional paradigms) that shape those outcomes. For example, while ecological footprint (e.g., Wackernagel et al., 1999) and planetary boundaries (e.g., Rockström et al., 2009) concepts describe important aspects of biophysical disconnections they do not directly explain the reasons for such disconnections. In contrast, socio-psychological HNC research focuses increasing on human-nature connections as a possible treatment for unsustainable behaviour (via changing individuals' value systems and relations to the natural world), without considering the structural factors that disconnect people from nature. As such, neither approach alone is capable of fully describing the reinforcing feedback that relate human-nature disconnections to unsustainable human-nature relations. This in turn limits the ability of these approaches to suggest solutions to the problems of human-nature disconnection.

To bridge the gap between biophysical and socio-psychological HNC research in relation to sustainability it is enlightening to consider how the approaches relate to the types of interventions that they help facilitate. In 1999, Donella Meadows published a seminal heuristic framework that identified 12 'leverage points' — places in complex systems where a small intervention in one part of the system can lead to systemic change — ranging from parameters (such as subsidies, taxes, standards), through to the "mindsets and paradigms out of which a system arises" (Meadows, 1999 p3).

The framework has recently been adapted to reduce the 12 leverage points to four broad system characteristics where interventions can occur (Abson et al., 2017): the first characteristics are tangible, physical 'system parameters' (resources consumed; time spent in nature etc.); the second 'System feedbacks' - the interactions and feedbacks that drive system dynamics. The third characteristic, 'System design', is the characteristic rules, social structures and institutions that manage feedbacks and parameters. Finally the fourth, 'system intent', describes the characteristics of the underpinning values, goals and worldviews that shape the emergent direction to which a system is oriented (Abson et al., 2017) and therefore system design.

Biophysical HNC research is largely focused on understanding key 'system parameters' (the scale and nature of resource use) and the 'system design' (trade relations etc.) that determines the ecological and socio-economic impact of particular patterns of human activity with regard to ecological and environmental limits of material and energy flow. Biophysical HNC research has generally not considered the agency of individuals within such systems of resource use, or considerations of the individual values and intentions that shapes institutional design and resource usage. In contrast, socio-psychological HNC research is strongly focused on the how worldviews, values and mindsets determines individuals' intentions and behaviours. This research has relatively little focus on how these values and worldviews are shaped and constrained by the system design within which agents act, or what might constitute system level, rather than individual level, intents. The difference between these two approaches is important because transformative change toward sustainability is likely to require multiple interventions that together address all four of these key system characteristics. While socio-psychological HNC can provide knowledge regarding how interactions with the environment shape the intentions that influence behaviour, it has limited ability to investigate the system structures that shape and constrain such environmental interactions. Similarly, while biophysical HNC research can describe the material and energy flow that shape and define human society and its relation to the environment, it has relatively little to say regarding the underpinning societal values that ultimately drive such flows. Here, we suggest that the key notion of feedbacks provides a bridge between the two approaches and the missing system characteristic that would allow for a complete system model to operationalize Pyle's notion of the reinforcing mechanism of the extinction of experience (Pyle, 1993).

6. Strategies for aligning biophysical and socio-psychological HNC research

We propose three broad strategies for bridging the divide between biophysical and socio-psychological HNC approaches.

Meaning and HNC research

In order to bridge the divide that has arisen between these two approaches there is a need to explicitly acknowledge what it means to be connected to nature. Specifically, this means acknowledging that biophysical and socio-psychological HNCs are not distinct phenomena. Our connections to nature result from the complex interplay between: (1) the societal structures that influence our material use of the environment, and (2) the experiences, beliefs, values and worldviews that shape individual environmental behaviours. Expanding the definition of HNC to encompass both the notion of biophysical and socio-psychological connections opens the space to ask key questions such as: how do societally shaped biophysical connections to nature mediate individuals' affective, cognitive and experiential connections to nature? How does an individual's experience of nature affect their acceptance of societal structures that biophysically disconnect them from nature? Are pro-environmental intentions mediated via socio-psychological connections to nature constrained by systemic biophysical connections of natural resource use (the classic values-action gap (e.g., Kollmuss & Agyeman, 2002))? To what degree are individuals' worldviews about humanity's rights and obligations towards nature reflected in the values of social, institutional, political and financial systems?

Models and HNC research

Biophysical and socio-psychological HNC research approaches have created very different formal and mental models of human-nature connections, with the former focused on describing the biophysical parameters of societies' connections to nature and the later focusing on individual behaviour intents arising from connections to nature. Yet, neither set of models emphasises issues of systemic characteristics that determine these connections to nature (e.g., Samuelsson et al., 2018). From a conceptual perspective, research that focuses on 'system design' may be particularly fruitful for relating biophysical and socio-psychological HNC research. This requires a shift from the more descriptive, indicator-based models that dominate research to the material and energy connections between people and their environments, as well as towards consideration of formal and informal institutions that shape such patterns (e.g., Borgström Hansson & Wackernagel, 1999, Challies et al., 2014, Hornborg et al., 2007, Seto et al., 2012). From the socio-psychological HNC perspective, a shift is required from modelling HNC as a 'treatment' that can influence pro-environmental behaviour (Ives et al., 2018) towards a better understanding of the underpinning drivers of socio-psychological disconnections to nature (e.g., Castree, 2008, Dickinson, 2013). This in turn may require a move away from individuals as the primary unit of analysis in socio-psychological HNC research.

Focusing on the formal and informal institutions, rules, and structures that shape both societal-level material and energy connections to nature, as well as individuals' experiential, cognitive and philosophical connections to nature, may provide a boundary object that links these two crucial aspects of HNC in the context of sustainability. Such an approach not only provides specific places where interventions may be effective in transforming both biophysical and socio-psychological HNC, but also potentially enables and integration across scales as well as units of analysis.

Methods and HNC research

One methodological approach for aligning biophysical and socio-psychological HNC approaches is the use of place-based (e.g., Fischer, Sherren & Hanspach, 2014, Stedman, 2002), or landscape-based (e.g., Wu, 2013), research approaches, where a physical space acts as a boundary object that transcends disciplinary boundaries (e.g., von Wehrden, Luederitz, Leventon & Russell, 2017). For example, regional based assessments of material and energy flow analysis (e.g., Dorninger et al., 2017) could be linked to quantitative assessments of socio-psychological HNC across the same regions (for a discussion of spatial scale in socio-psychological HNC research see Klaniecki, Leventon & Abson, 2018). To move beyond the individual as the unit of analysis, researchers may assess socio-psychological HNC through a random sample with a fitting sample size for the given population (i.e. all inhabitants in that area) using standard empirical social science methods, such as questionnaires. By statistically extrapolating the results of the sample to the population, one can give probability estimates on the variance of socio-psychological HNC of the regions inhabitants. Finally, research that focuses on individuals with the ability to shape system dynamics (e.g. leaders or managers of key institutions could help link personal HNC to their structural decision-making. Aligning biophysical and socio-psychological HNC in such a way might highlight patterns of co-occurrence between the broad system characteristics captured by the two approaches.

6. Conclusions

Many sustainability challenges, including social and economic inequality, biodiversity loss, and over exploitation of the environment, are driven by how we as individuals, and as societies, relate to, and interact with, each other and the environment (Glaser, Krause, Ratter & Welp, 2012). Currently, societal and individual connections to nature are largely studied in isolation from each other. Acknowledging the interdependencies and relations between these societal (biophysical) and individual (socio-psychological) connections to nature is likely to be crucial for understanding how those working for positive change intervene in such relations order to move towards more sustainable human-nature connections. Utilizing place and landscape based approaches to bridge the methodological divide between the two HNC approaches and focusing on institutional drivers of such relations may provide to be fruitful means of better aligning a currently fragmented and siloed research field.

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Section B

Measuring biophysical disconnections at the global scale

Chapter IV

The myth of decoupling? A global analysis of humanity's biophysical connections to nature

Christian Dorninger, Henrik von Wehrden, Fridolin Krausmann, Martin Bruckner, Kuishuang Feng, Klaus Hubacek, Karl-Heinz Erb, David J. Abson

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Abstract

The disconnectedness of socioeconomic systems from their territorial ecological productivity, caused by trade teleconnections ('spatial disconnect') and the application of external inputs ('biospheric disconnect'), create formidable challenges for resource governance. Here we present a comprehensive global assessment of connectedness to domestic terrestrial ecosystem productivity. By quantifying globally increasing spatial and biospheric disconnections from 1995 to 2015, we show that the extent and intensity of telecoupled land use are closely related to international trade and inputs of non-renewable resources. Via a systematic account of the global human appropriation of net primary production, we demonstrate that the higher a country's per capita income the less it relies on local resources such as domestic labour inputs and the domestic ecological productivity, while simultaneously consuming more biomass goods produced in other countries and with higher energy inputs. These increasing disconnections reinforce the myth of decoupling and jeopardize sustainable global land use.

The global land-use frontier continues to expand and terrestrial ecosystems continue to be transformed by humans[1], leading to pervasive environmental changes that inspired scholars to claim a new geological epoch, the Anthropocene[2–4]. Among the most evident consequences of this expansion of human activities is the significant decrease of biodiversity[5,6], and the disruption of global phosphorus, nitrogen, and carbon cycles[7].

While humans are inevitably biophysically connected to the biosphere through flows of materials and energy, we observe an increasing disconnection of national socio-economic activities from the natural productivity of their domestic environment[8] – here defined as net primary production (NPP) of terrestrial ecosystems[9]. There are two main ways for countries to disconnect from, or overcome, the limits imposed by natural productivity: firstly, material and energy inputs from outside the biosphere (primarily via the use of fossil fuels) can be applied to intensify domestic land use (enhance NPP per unit area) and to increase conversion efficiencies of NPP to final biomass products[10,11], and secondly, land use can be outsourced to other countries, leading to land-use expansion elsewhere[12,13].

We empirically assess human land use activities in terms of biophysical connectedness of socio-economic systems to the biosphere[8], where biophysical human-nature connectedness is defined as the degree to which economies depend on the appropriation of domestic NPP. Consequently, biophysical disconnections are conceptualized as either teleconnected land use ('spatial disconnect'), or the reliance on external, lithospheric resource inputs into the land use system[8,13,14] ('biospheric disconnect'). Both processes contribute to a biophysical disconnect from domestic NPP. We operationalize biophysical human-nature connectedness by using the human appropriation of net primary production (HANPP)[9] as a baseline indicator. For a given area, HANPP measures the human appropriation of the products of photosynthesis (NPP) in absolute numbers (measured in Joules) or as a percentage of the potentially available net primary production (NPP_{pot}), that is the NPP of the natural vegetation thought to exist in the absence of land use[9]. HANPP, therefore, can be used to quantify the land-use intensity and is considered a proxy indicator for human pressure on biodiversity[15].

To combat biodiversity loss related to land use expansion the so-called notion of 'sustainable intensification'[16] has become a prominent strategy, research area and political discourse[17,18]. Land-use intensification allows harvesting more biomass from the same amount of land and, thus, increasing harvest while (theoretically) reducing the pressure for further land-use conversions. However, boosting conversion efficiencies and intensifying land use in most cases necessitates increased use of external energy[19,20] and non-renewable materials[21,22], e.g. for agrochemicals and agricultural machinery. At the same time, global trade with biomass products and, thus, land-use based teleconnections – i.e. socio-ecological connections over distances[23,24] – have increased over the last decades[12,13,25]. The outsourcing of production steps plays an increasingly important role in how countries are able to manage domestic land use and spare domestic land for biodiversity conservation[26,27], involving a shift of socio-environmental burdens related to land use intensification and expansion to the sourcing region[28–30]. Consequently, a disregard for the adverse spillover effects occurring from these processes represents a major obstacle for sustainable land use management. The opaqueness of these biophysical disconnections from natural productivity reinforces the potentially mythical notion that human activities can be decoupled from resource use[31].

Here we present an integrated and comprehensive empirical assessment of global land-use systems that not only concerns domestic land-use intensity[32] and the domestic balance between land use and natural protection[15], but also the system's spillover effects occurring from international trade and/or industrialization of land use[8], i.e. the large-scale reliance on infrastructure, machinery, and agrochemicals requiring non-renewable resources[33]. We argue that external inputs in land-use systems, teleconnections, and the domestic human domination of ecosystems must be analyzed in unison as they are part of one system of interconnected elements, feedbacks, and spillover effects determining an emergent system behavior that is crucial for sustainability outcomes[34].

We combine HANPP with an environmentally-extended multi-regional input-output analysis (EEMRIO)[35] to provide a comprehensive analyses of global, trade-related land use teleconnections. The HANPP content embodied in traded biomass goods (eHANPP) does not merely reflect the biomass required for their production, but also the socio-ecological teleconnections between distant places[36–38]. To model global eHANPP flows we use an input-output approach based on EXIOBASEv3[35]. By applying an input-output approach, we also quantify all labour, energy, and materials inputs that are directly and indirectly required by land-use sectors – e.g. for the production of agrochemicals, machinery, infrastructure – to produce their outputs.

In the following, we illustrate the decrease in domestic connectivity and self-supply due to the rise in international teleconnections from 1995 to 2015. Subsequently, we quantify the relative decoupling of biomass harvest from HANPP enabled by external energy inputs. Based on this we explore global patterns and typologies of biophysical connections and disconnections among countries (and world regions) by conducting cluster and regression analyses. Finally, we investigate the resulting clusters in more detail regarding their HANPP, eHANPP imports and exports, eHANPP footprint, and inputs of labour, energy, and materials.

Based on this systems approach, we reveal complex socio-ecological interlinkages and identify major challenges in managing biophysical connections across scales. For instance, to satisfy growing domestic biomass demand, land-use can be expanded (threatening biodiversity)[5], or intensified (causing exhaustion of non-renewables, emissions, and pollution)[17], or biomass can be imported (shifting both aforementioned burdens to spatially distant places)[13,25]. Our framework enables to analyze these major challenges in conjunction. Providing such insights regarding complex systems interactions across space and time is relevant for guiding sustainability transformation in global land use on an interconnected planet[39].

Increasing trade causes spatial human-nature disconnections.

Trade in biomass products – eHANPP flows – rapidly increased over the last decades, causing decreasing national biophysical connectedness, as indicated by the declining HANPP self-supply in the different world regions in Fig. 1 (detailed data for world regional are available in the SI). HANPP self-supply is the amount of NPP appropriated and consumed within the same territorial boundaries.

In 1995, 464 exajoules (EJ) of NPP were appropriated globally, of which 78 EJ eHANPP were directly and indirectly traded between the eleven world regions presented in Fig. 1. By 2015, global HANPP had increased to around 556 EJ, of which 138 EJ eHANPP were internationally redistributed. This means that inter-regional trade in eHANPP increased by 77 % between 1995 to 2015 while HANPP only increased by 20 %.

European HANPP self-supply decreased from 48 EJ in 1995 to 42 EJ in 2015, while eHANPP imports increased from 25 EJ to 29 EJ and exports from 5 EJ to 10 EJ. Similarly, the NPP appropriated in the USA and Canada which was also consumed within the same territory decreased from 43 EJ to 36 EJ during the same time period, while imports increased from 13 EJ to 18 EJ and exports from 12 EJ to 20 EJ.

HANPP self-supply as a proportion of total HANPP (i.e., the sum of domestic HANPP plus eHANPP imports) in Europe decreased from 61 % in 1995 to 52 % in 2015. For the USA and Canada, the same proportion decreased from 64 % to 50 % and for China from 85 % to 53 %.

In sum, the interconnectedness between regions increased, as indicated by increased eHANPP flows and declining relative self-supply in HANPP (Fig. 1). However, in 2015 HANPP self-supply, as a proportion of total HANPP is still high in some regions, e.g. 83 % in India, 76 % in Africa, and 65 % in Latin America. It is smallest in Japan and South Korea (23 %) and in the Middle East (27 %).

Here the focus is on the decreasing HANPP self-supply. The SI contains similar circular network plots showing only the embodied HANPP flows between world regions (Supplementary Fig. 1 and 2).

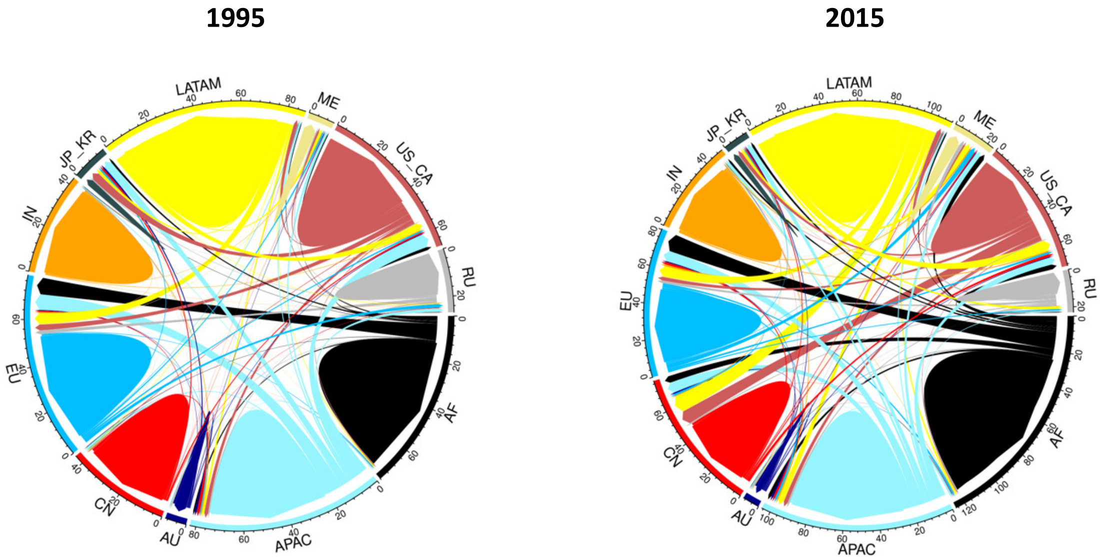

Fig. 1 | HANPP and embodied HANPP flows between world regions, including self-links capturing HANPP self-supply, which is the domestic HANPP flows occurring within a region (appropriation and consumption in the same region). Flows between regions denote embodied HANPP visualized as directed arrows. Values in the circular network plot are given in exajoules [EJ]. To reduce complexity, we here aggregated the 44 countries and 5 world regions of EXIOBASE into 11 world regions. LATAM = Latin America, ME = Middle East, US_CA = USA and Canada; RU = Russia, AF = Africa, APAC = Asia and Pacific, AU = Australia, CN = China, EU = Europe, IN = India, JP_KR = Japan and South Korea.

External inputs increase biospheric disconnectedness.

NPP is a crucial renewable but spatially and temporally limited resource. However, the NPP appropriated for human use can be boosted via land-use intensification, e.g. increased yield by increasing the input of labour or external resources in the land-use system.

While global direct labour inputs virtually stagnated (+0.71 %), the total, i.e. direct and indirect, energy inputs into the agricultural and forestry sectors increased between 1995 and 2015 by 29 % (1995: 23.4 EJ; 2015 30.2 EJ) (Fig. 2). This contributed to relative decoupling of the growing biomass harvest from HANPP[10]: Global biomass harvest grew from 214 EJ for 1995 to 290 EJ in 2015 (+35 %). HANPP increased in the same period by 20 %.

By investing in non-renewable lithospheric resources (fossil materials, fertilizer minerals, etc.) humans have pushed limitations of natural productivity resulting in a biospheric disconnect. However, this push is spatially and temporally limited, requires continuous resource inputs and causes emissions and pollution. Yet, in the absence of external energy applied to boost NPP and conversion efficiencies (for example, via minimizing the loss of biomass during harvesting), more land would be required to maintain harvest – resulting in greater HANPP.

However, during the observed period, world-regional trends diverged. Growing energy use contributed to a strong decoupling of harvest from HANPP particularly in Latin America, the Asia and Pacific world region, Australia, and to some lesser extent in China. While energy inputs in the Middle East and India increased strongly, there was only a little decoupling between HANPP and harvest apparent. In Africa energy inputs increased by 58 % supporting an increase in biomass harvest (+54 %), but also HANPP increased by 62 % (no decoupling). In regions where energy inputs did not increase compared to 1995, no sustained decoupling occurred (Europe, USA and Canada, Russia, Japan and South Korea). The SI provides detailed numbers for all regional trends (Supplementary Table 2 and 3).

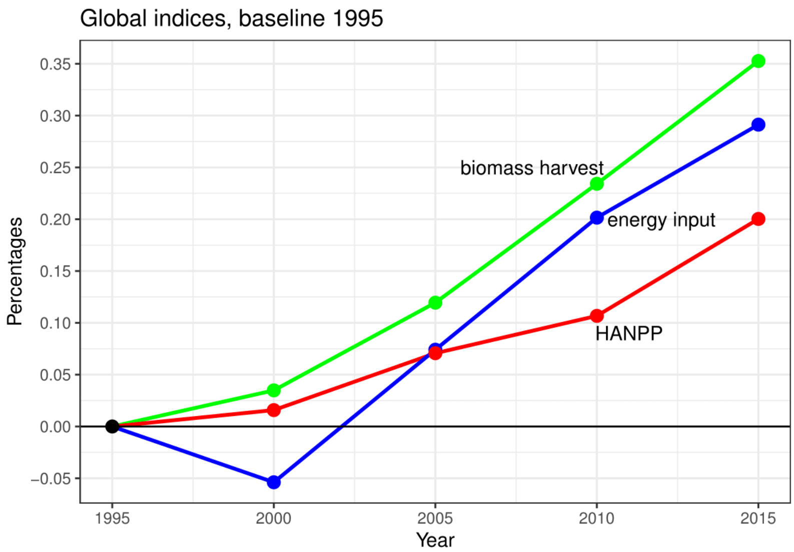

Fig. 2 | Index development of biomass harvest, energy inputs, and HANPP from 1995-2015; base year 1995. Note that there is a data point only every 5 years. Years in between are interpolated.

Global typologies and patterns of disconnectedness.

Using Ward's hierarchical cluster method[40,41] on a set of four HANPP and five input variables for the year 2015 (see methods section for details) we identified five groups of countries ('connection clusters') where within-group variance is low and between-group variance high (Fig. 3), denoted as (1) 'exporters', (2) 'outsourcers', (3) 'intermediate', (4) 'self-sufficient', and (5) 'intensifiers' (compare Table 1). Note that in EXIOBASE many countries of the world are already pre-grouped in world-regions (n = 46, compare Fig. 3 and Supplementary Table 1).

The 'exporters' cluster is made up of six countries, among them Australia and Canada, characterized by a high level of eHANPP exports per capita. Other major exporters of biomass, like Brazil or Russia, exhibit significantly lower levels of eHANPP exports on a per capita basis, as compared to the ones classified here as 'exporters'. The second cluster ('outsourcers') had a high dependence on imported biomass, as indicated by high values for eHANPP imports and for net eHANPP imports (eHANPP imports minus eHANPP exports). Among these 15 countries are many European countries with high per capita income and high population density. A third cluster captures 15 countries and world regions that are not characterized by strong patterns of HANPP or eHANPP (per capita) and represent the 'intermediate' in the dataset. The 'self-sufficient' cluster covers six countries/world regions mainly in Africa and Asia. However, they represent 69 % of the total world population in 2015. This cluster is characterized by high direct labour input and strong HANPP self-sufficiency. Finally, the fifth cluster comprises the 'intensifiers' characterized by high energy and materials inputs per unit biomass extracted.

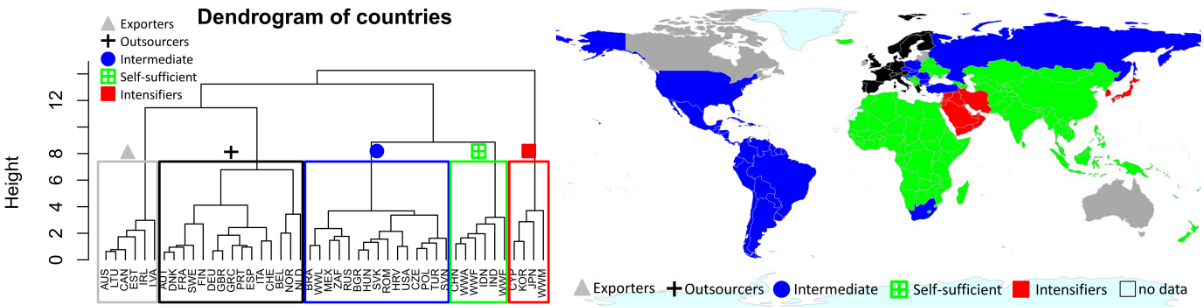

Fig. 3 | World map and dendrogram of countries as the result of a hierarchical cluster analysis. WWL = Rest of the World Latin America; WWA = Rest of the World Asia and Pacific; WWF = Rest of the World Africa; WWE = Rest of the World Europe; WWM = Rest of the World Middle East.

Table 1 | Land use typology. Clusters of countries and world regions and the defining coefficients. The value in parenthesis indicates the strength of the coefficient in distinguishing the cluster from others. All coefficients shown are significant at p < 0.01.

Land use typologies	Defining cluster coefficients
(1) Exporters (n = 6)	Embodied HANPP exports per capita (0.91)
(2) Outsourcers (n = 15)	Embodied HANPP imports per capita (0.55) Embodied HANPP net-imports per capita (0.52)
(3) Intermediate (n = 15)	-
(4) Self-sufficient (n = 6)	Direct labour input per biomass unit extracted (0.91) HANPP self-supply (0.66)
(5) Intensifiers (n = 4)	Energy inputs per biomass unit extracted (0.91) Materials inputs per biomass unit extracted (0.87) CO^2 emissions per biomass unit extracted (0.87)

To detect global patterns of biophysical connectedness and disconnectedness within the 'connection clusters' we built regressions with the economic development status of countries, reflected by their income (GNI/cap/yr), as predictor (Fig. 4). We chose four variables (direct labour input, HANPP self-supply, energy embodied in biomass goods consumed, and net-imports of eHANPP) which reflect crucial differences in countries' and regions' biophysical disconnections. Wherever it was necessary to standardize variables, we either used data per unit of biomass extraction or per capita values where trade was involved. We used simple linear regression analyses wherever possible. We used polynomial regressions (third-order) to capture non-linear shifts and relationships.

The negative non-linear relationship between direct human labour input and income indicates that there is a gap between countries relying on human labour as a significant input for land use activities ('self-sufficient' cluster) versus countries where human labour only plays a minor role (all other clusters) (Fig. 4a).

A similar trend is apparent for the proportion of NPP appropriated and consumed domestically (HANPP self-supply) in relation to the total HANPP (i.e. domestic HANPP plus eHANPP imports). While NPP is appropriated domestically, a certain share of this is embodied in exported goods and services (eHANPP exports), and a share of the total HANPP imported (eHANPP imports). In regions with higher per capita income only a quarter of total HANPP flows is neither exported nor imported but appropriated and consumed domestically (Fig. 4b).

More energy is used (across the global supply chains) to produce the biomass goods that are finally consumed in regions of the world with higher per capita income than compared to the final consumption requirements of lower-income regions (Fig. 4c).

Income less clearly predicts net-imports of eHANPP. Only 19 % of the variance can be explained by income (the regression is still highly significant). Higher-income regions are often more heavily exposed as either net-importers or net-exporters than compared to poorer nations. However, by trend, the richer a country the more it will net-import (Fig. 4d).

In sum, with increasing per capita income, countries and regions use less direct labour, rely less on domestic HANPP, and simultaneously, by trend, consume biomass goods with higher total energy inputs and net-import more eHANPP. This trend is a clear indication that with growing income countries get biophysically more disconnected from the natural productivity of their domestic terrestrial environment.

Interestingly, income has a slightly positive effect on the amount energy and materials used to extract biomass (along the whole supply chains), and how much CO2 is emitted in the course of fossil combustion during that process. While the effect is not significant there is no decoupling apparent (Supplementary Fig. 3, 4, and 5).

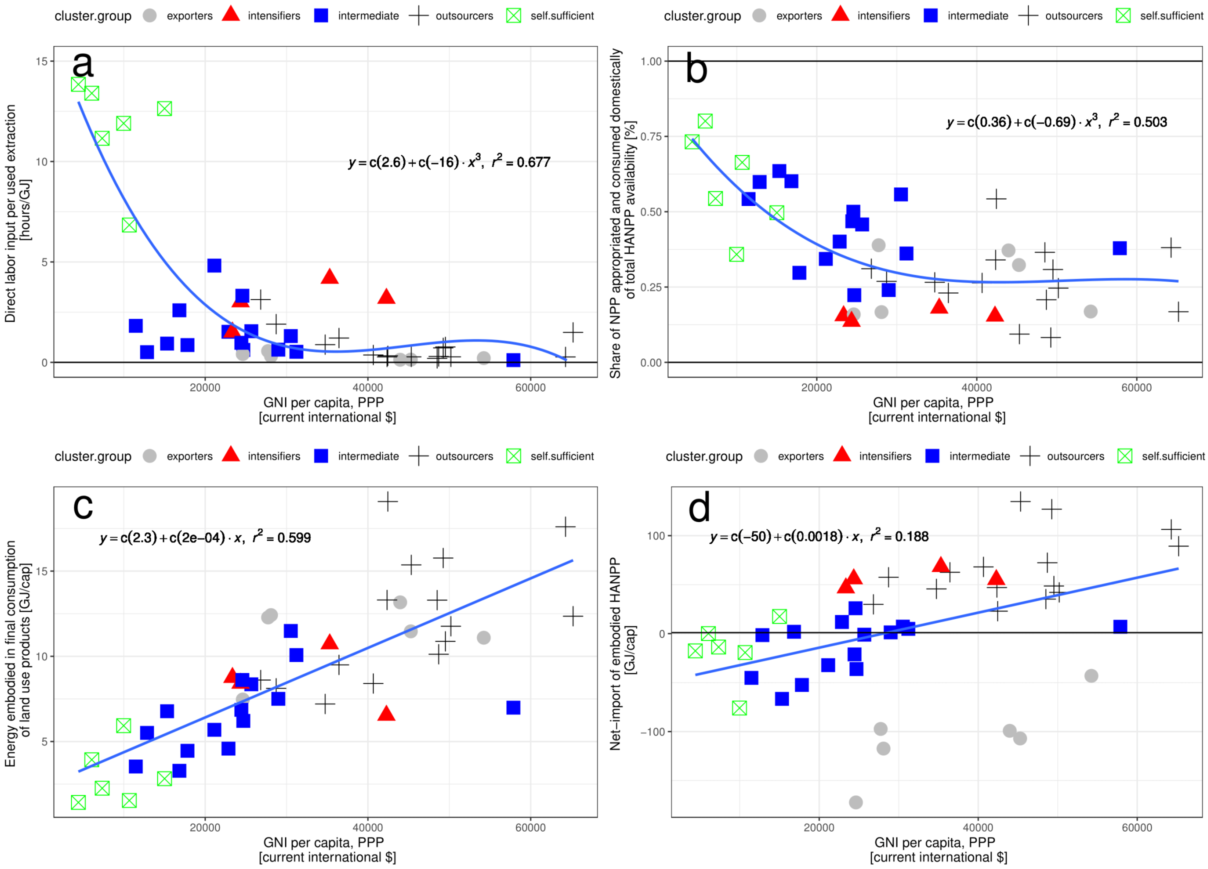

Fig. 4 | Polynomial (a, b) and linear (c, d) regression analyses with GNI per cap (PPP, current international $) as the predictor. All regressions are significant at a p-value <0.01.

Disconnectedness detailed in global typologies.

To illustrate the magnitude of connecting and disconnecting factors in more detail we depict key variables for the more distinctive clusters (leaving out the 'intermediate' cluster) on an average per capita basis. We present stacked bar plots to compare the different clusters with respect to their land-use intensity (HANPP), trade connections, as well as their labour, energy, and material inputs (Fig. 5).

In the 'outsourcers' cluster 43 % of NPPpot are appropriated by humans (65 GJ/cap/yr), indicating that on average 57 % of trophic energy remains in terrestrial ecosystems at the availability for others species to thrive (NPPeco). In the top row of Fig. 5, NPPpot – the potential NPP that would prevail in a region without any human interference – is the sum of HANPP and NPPeco. The high eHANPP net-imports (64 GJ/cap/yr) reveal that in the absence of trade, 'outsourcers' could not sustain their relatively low levels of domestic appropriation. In the 'outsourcers' cluster direct labour application (people actually working in agriculture and forestry) has almost vanished, however, indirect labour and labour embodied in imported biomass is still required on a larger scale. Indirect labour refers to the labour invested in the production of machinery, agrochemicals or infrastructure etc., used by the land-use sectors. Embodied labour imports reflect international labour investments that are directly and indirectly associated with biomass imports. The countries in the 'outsourcers' cluster significantly rely on both domestic and international energy and material resources to appropriate their domestic NPP. This includes the energy and materials embodied in tractors, fertilizers, irrigation facilities, farm buildings, or other infrastructure. Accounting for all the resources embodied in net-imports, that is, all the resources required worldwide to satisfy the final demand for biomass increases their resource footprints considerably (Fig. 5).

Compared to the other clusters, 'exporters' stand out in their better endowment with NPP resources, indicated by a high NPPpot/cap/yr, a high HANPP/cap/yr, and a relatively strong reliance on energy and materials inputs, which are then partly reallocated to other countries with exports. However, also the 'exporters' cluster is a net importer of labour embodied in internationally traded biomass.

The 'self-sufficient' cluster represents a counterexample to the other clusters. The cluster, encompassing almost 70% of the world's population, has a considerable share of NPPeco while remaining and a minor net-exporter of eHANPP per capita. At the same time, it features a high amount of labour invested directly in agriculture and forestry and is the only net exporter of embodied labour. Conversely, energy and materials inputs are significantly lower than for other clusters.

The 'intensifiers' exhibit the lowest amount of NPPpot per capita availability, which is bolstered by eHANPP net-imports and boosted by energy and material inputs. Interestingly, with these external flows in place, they are still able to spare a relatively high share of their NPPpot for biodiversity conservation (as indicated by a relatively high NPPeco).

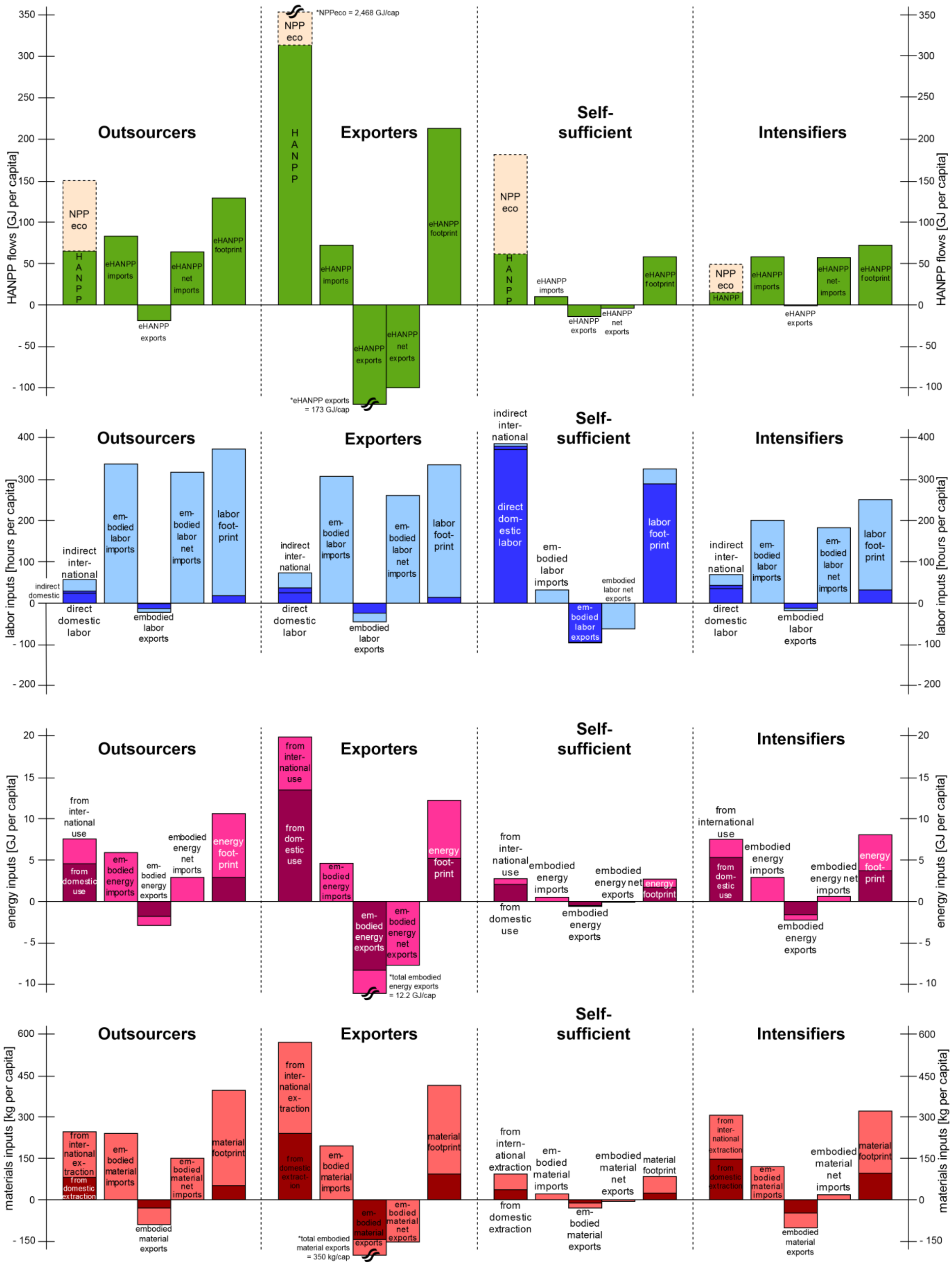

Fig. 5 | Barplots indicating HANPP, eHANPP trade flows, as well as labour, energy, and material inputs in the land-use system. The first row describes the HANPP flows, including domestic HANPP (and NPP$_{eco}$), eHANPP trade flows, and the eHANPP footprint. The subsequent rows show the inputs of labour, energy, and materials required to appropriate domestic NPP and those embodied in traded biomass. Materials comprise all fossil materials, metals, and non-metallic minerals used directly or indirectly by the land-use sectors to produce their outputs. The first stacked bar of each group distinguishes the origin of the input (domestic vs. international). The subsequent bars show the resources and labour embodied in biomass imports and exports. Their subtraction yields the net-trade and finally the footprint, which is the domestic appropriation plus net-trade. Note that each bar captures the same process, i.e. the first bar of each group presents the process of NPP appropriation and the resources required, the second row the eHANPP imports and the resources embodied in those imports, etc. All values are given on per capita levels. The share of domestic labour, energy, materials, and emissions exported is calculated by assuming an equal distribution of domestic and international resources for domestic consumption and exports.

Discussion and conclusions

Humanity faces the challenge to produce more biomass for feeding a growing world population[42] and for satisfying the rising demand for bioenergy and biomaterials[43] without further threatening biodiversity by replacing natural land ecosystems with human-dominated systems[44]. By intensifying land use, biomass production can be increased without further land conversion, which is seen as a crucial strategy to curb global land expansion and to still meet the dietary needs of a growing population[17,18]. This effect of intensification is also reflected in the HANPP patterns we identified in our analysis, which indicate that the demand for NPP from terrestrial ecosystems has been relatively decoupled from the growing demand for biomass goods by applying external energy.

However, by employing a global input-output model we scrutinized the interplay of land-use intensification and trade with biomass products in the form of global teleconnections and their role for the observed decoupling between biomass consumption and HANPP. Thereby we identified a twofold biophysical disconnect which challenges the sustainability improvements and purported decoupling capability of industrially intensified land-use systems. The two biophysical disconnect components are: (1) trade-related 'spatial disconnects', and, (2) external input related 'biospheric disconnects'. First, we find growing land-use based teleconnections, which reveal the import dependency of many 'outsourcing' countries that makes partial decoupling of biomass consumption from domestic HANPP possible. Second, through assessing the upstream resource requirements of land use systems we showed that industrial intensification requires more, often non-renewable, resources to be drawn from global supply chains. In the light of growing global resource demand and the need to reduce the use of non-renewable resources[45], the maintenance of the efficient functioning of industrial land-use systems represents a particularly vulnerable development pathway.

In the face of increasing globalization and industrialization of land use, wealthier countries, in particular, have become less dependent on the natural domestic NPP endowment of their own land ecosystems. However, this does not necessarily represent a genuine decoupling of economic activity from the environment or environmental impacts. With increasing eHANPP imports and use of lithospheric inputs domestic HANPP can be stabilized (that is, a certain level of NPP_{eco} can be sustained) while total domestic biomass consumption continues to grow. As countries mature economically, they tend to have a lower degree of HANPP self-supply, a smaller direct labour input per unit of biomass extracted, but a larger amount of energy embodied in biomass products for final consumption, and higher net-imports of eHANPP.

These patterns of land use have profound impacts on the global land-use system and largely determine its functions and outcomes: biophysical disconnectedness from domestic NPP enables countries a seemingly unconstrained consumption of biomass goods – creating the myth of decoupling. Both teleconnections and external inputs substitute and supplement domestic labour and domestic NPP. But this circumvention of self-constraining feedbacks creates potentially harmful path dependencies[21,46] with negative effects for future and spatially distant generations[21,46]. The increasing reliance on non-renewable inputs deprives future generations of sustaining similar land-use management by causing resource exhaustion, pollution, eutrophication, salinization, or climate change leading to the destruction of life-supporting ecosystem functions[47]. Spatially distant generations are adversely affected by the shifting of environmental burdens which come with unbalanced land-use based teleconnections[12,13,26], often described as ecologically unequal exchange[28].

In this regard, countries which have reduced their reliance on local ecosystems, created an illusion of decoupling and, hence, sustainability[46]. This is precisely because the spatial separateness of material production eliminates direct negative feedbacks from overstressing ecosystems[48]. Meeting the growing demand for biomass products while being able to preserve domestic environments (land ecosystems) via the twofold biophysical disconnectedness stimulates the misconception and misinterpretation of decoupling[46,49,50]. As we have shown, a disconnect from domestic natural productivity does not imply in any way a decoupling from total resource or land use from a consumption-based perspective. On the contrary, countries that exhibit a high degree of biophysical disconnectedness tend to have larger total resource use footprints (of eHANPP, labour, energy, and materials) than economies with tighter coupling to their natural resource systems.

We argue that while aiming to reduce human pressure on domestic terrestrial ecosystems, attention has to be paid on how market and political institutions are oriented towards industrial intensification and outsourcing of land use based production. We propose that instead of further fostering the mythical decoupling of the economy from the environment by making human–nature connections evermore complex and opaque via increasing teleconnections and industrial technology, a genuinely reconnected system will have higher self-reliance, stronger internal feedbacks, and, eventually, may facilitate more foresightful institutions which, in turn, might enable more sustainable production and consumption patterns.

Methods

Calculating global HANPP data

The human appropriation of net primary production (HANPP) is a socio-ecological indicator that measures the extent to which human activities affect flows of trophic energy (biomass) in ecosystems, namely net primary production (NPP), a key process in the Earth's biosphere[15]. HANPP is defined as the difference between the NPP of the natural vegetation assumed to exist in the absence of land use (i.e., the NPP of potential natural vegetation, NPP_{pot}) and the fraction of NPP remaining in the ecosystem after harvest under current conditions (NPP_{eco}). HANPP comprises harvested NPP ($HANPP_{harv}$) and changes in NPP related to land conversion ($HANPP_{luc}$). $HANPP_{harv}$ not only includes used extraction of biomass but also unused extraction (like leaves, roots, and by-products not further used)[15].

HANPP data were sourced from the global HANPP database available at the Institute of Social Ecology[10]. The database provides HANPP data at the national level for 176 countries for the years 1990, 2000 and 2005. We updated the database for the years 2010 and 2015 following the methodological guidelines and assumptions described in detail in the Supporting Information of Krausmann et al. (2013)[10]. To estimate $HANPP_{harv}$ we used data from the FAOSTAT database of the Food and Agricultural Organization of the United Nations (FAO 2018). To estimate $HANPP_{luc}$, which accounted for 33 % of global HANPP in 2005, we had to simplify assumptions, because NPP_{pot} data for 2010 and 2015 were not available. We extrapolated $HANPP_{luc}$ on grassland applying values of $HANPP_{luc}$ per unit of grazed biomass in 2005 derived from the HANPP database. $HANPP_{luc}$ on cropland was calculated by applying values of $HANPP_{luc}$ per m^2 of cropped area and per m^2 of cropland fallow in 2005 (derived from the database), taking into account that changes in $HANPP_{luc}$ on cropland are rather related to changes in the extent of cropland, since land use intensification on cropland typically increases harvest per unit of land without impacting total HANPP per unit of cropland[10]. Following Krausmann et al. (2013)[10] we did assume $HANPP_{luc}$ to be zero on forests and wilderness areas. HANPP on settlement and infrastructure land was not reallocated with trade flows but attributed to the eHANPP footprint of the appropriating country.

Allocating HANPP to sectors of EXIOBASE

We utilize the recently released environmentally-extended multi-regional input-output (EEMRIO) tables of EXIOBASEv3[35] which feature 44 single countries and five world regions from 1995-2015, representing 99.2 % of the world population in 2015. A full list of included countries is provided in the SI (Supplementary Table 1). The database further features eight different crop production sectors, seven livestock sectors, two manure treatment sectors, and one forestry sector. This represents a major advantage over input-output databases operating with only one single agricultural sector, as sectoral disaggregation is indispensable for a precise allocation of flows[51,52]. Applying HANPP values [1000 t C] to the respective appropriating sectors enables reallocation of HANPP embodied in traded goods to the country of final consumption[53].

EXIOBASE provides four matrices for each year from 1995-2015: the matrix of technical coefficients (A matrix), the matrix of final demand (Y matrix), the matrix of direct resource requirements of industry sectors (F matrix) and the matrix of direct resource requirements of final demand sectors (F_hh matrix).

We allocate the national HANPP values to the NPP appropriating sectors with the help of the land use satellite accounts provided in the F and F_hh matrices. The F matrix of EXIOBASE contains 1,104 satellite accounts (environmental extensions) which are allocated to 7,987 sectors of 49 countries (and world regions), i.e. 163 different sectors per country. In sum, 20 of the 1,104 satellite accounts concern land use, including 13 'cropland' types, three types of 'permanent pastures', 'forestry area', 'other land use', 'infrastructure land', and 'forest area – marginal use'. The latter two are fully allocated to households and thus only appear in the F_hh matrix. Therefore, following the allocation of land use in EXIOBASE, not all HANPP values enter the economy and are internationally redistributed by the input-output table: we attribute HANPP from infrastructure and from private land use (i.e. subsistence farming and forestry) to households and do not reallocate them, as described below.

The F_hh matrix features the direct land use by households for 'other land use', 'infrastructure land', and for 'forest area – marginal use'. We follow the allocation of land use in EXIOBASE and directly allocated 100 % of the HANPP from built-up land (infrastructure) to domestic consumption, which means that HANPP from built-up land was not reallocated via international trade flows. The same holds true for the land use category 'forest area – marginal use', which captures subsistence forestry and is considered to be directly used by households and not entering economic processes. Similarly, the 'other land use' account in the F_hh matrix covers private gardening and subsistence land use. Since HANPP occurring from this type of land use does not enter the market economy, we do not allocate it to industries, but assign it to the appropriating country directly.

The remaining larger share of NPP was appropriated by the market and reallocated to consumers along downstream supply chains. We allocate the HANPP to the EXIOBASE sectors in relation to their land requirements, as documented in the land use satellite accounts. For instance, we assign the HANPP from grassland to all sectors that use grassland inputs in relation to their requirements of permanent pastures. Analogous, the HANPP from cropland is allocated to those sectors requiring cropland, and the HANPP from forestry to those sectors requiring forest area. For the 'other land use' of industries we apply the average HANPP intensity [t C per ha] of each sectors' specific land-use profile. For instance, for a sector with 80 ha cropland and 20 ha grassland use, we assume that the 'other land use' has a HANPP intensity of $HANPP_{cropland} * 0.8 + HANPP_{grassland} * 0.2$.

Re-allocating HANPP with EXIOBASE

We sum up the resulting HANPP vectors (one for each land use category) into one vector giving the total HANPP value for each sector and extend the MRIO table by this vector in order to re-allocate the HANPP along international monetary supply chains. Starting with the technical coefficient matrix (A) of EXIOBASE, which represents the direct input coefficients (i.e. the amount of input a sector requires from other sectors to create one dollar of output)[54], we calculate the Leontief inverse (L):

$$L = (I - A)^{-1}$$

where I is an identity matrix with ones on the main diagonal and zeros in all other cells.

The total output of sectors (x) was calculated as:

$$x = L*y$$

where y equals the row sums of Y.

Finally, we calculate a vector of so-called "HANPP coefficients" (e) by dividing the total HANPP by x (total output) of each sector. By multiplying the diagonalized HANPP coefficient vector (ê) with the Leontief inverse (L) and final demand (Y), i.e. FP = êLY, we get a matrix (FP), which gives the HANPP footprint of each country by country and sector of origin.

Calculating supply chain requirements of land use sectors

We use output-to-output multipliers to quantify the direct and indirect input requirements of the agriculture and forestry sectors. Our focus lies on the requirements of energy, material, and labour, as well as on CO_2 emissions from combustion. In order to reduce double-counting occurring when applying output multipliers (for a discussion see Miller and Blair 2009)[55], we first aggregate the eight crop-producing sectors, seven livestock sectors, and two manure treatment sectors of EXIOBASE into one single "agriculture" sector. The forestry sector remains unchanged.

To calculate the output multipliers we do a column-wise division of the L matrix by the values on its main diagonal[55]:

$$L^* = L\left(\hat{L}\right)^{-1}$$

where $\hat{L}$ is a diagonal matrix created from the on-diagonal elements in L.

We used the following extensions of EXIOBASE: total use of energy carriers; employment hours (aggregate of six different extensions capturing skill level and gender); CO_2 equivalents from combustion to air (CO_2, CH4, and N_2O); and domestic used extraction of metal ores, non-metallic minerals, and fossil fuels (an aggregate of 21 different extensions). We calculate sector footprint by

$$eL^*x$$

where e is the environmental extension in inputs (or emissions) per Million Euros and x is the gross production in Million Euros.

These sector footprints were then reallocated to the country finally demanding the outputs of the land-use sectors, following the same procedure as for the reallocation of HANPP, i.e. applying the final demand-driven Leontief model. We first calculate the footprint coefficient of agriculture and forestry by dividing the total sector footprint by their respective gross production. Second, we diagonalize the footprint coefficient and multiply with the Leontief inverse (L) and the matrix of final demand (Y). The resulting matrix provides the resource requirements of the land-use sectors that were directly and indirectly associated with the demands of other sectors worldwide, e.g. the energy embodied in traded biomass goods.

Cluster analysis

We conduct an agglomerative hierarchical cluster analysis (Ward's cluster)[40] to identify 'connection clusters'. We set the cluster analysis with values for 2015 where each country (or world region) is represented by one case (n=46). Note that in EXIOBASE many poorer countries are lumped together in the five world regions (Rest of the World Latin America; Rest of the World Asia and Pacific; Rest of the World Africa; Rest of the World Europe; Rest of the World Middle East). We excluded the extreme outliers Malta, Luxemburg, and Taiwan, which would not allow for proper group formation.

For the clustering, we use the following nine variables, which are relevant in determining biophysical disconnectedness:

(1) eHANPP exports, (2) imports, and (3) net-imports (all per capita); the (4) HANPP self-supply; (5) total energy embodied in biomass consumption; (6) direct labour, (7) total energy, and (8) total material inputs per biomass used extraction, as well as (9) the CO_2 emissions from combustion of non-renewables per biomass used extraction.

We use these nine variables to identify typologies of countries, i.e. different groups of countries that exhibit similar characteristics concerning biophysical (dis-)connections. We use Ward 's hierarchical cluster analysis with the 'hclust' function and the 'agnes' function (agglomerative nesting) in R[56] to identify groups in our dataset where the cluster criteria follow pairwise distance matrix observations. The cluster analysis follows minimum within-cluster variance and maximum between-cluster variance. It yields five clusters (agglomerative coefficient of 0.90). To identify which variables most strongly characterize the clusters we use the 'indval' function of the 'labdsv' package in R. The defining cluster coefficients are provided in Table 1.

Data availability

The data that support the findings of this study are available in the SI and from the corresponding author upon request.

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Author contributions

CD, HvW, and DA designed the study. CD, HvW, FK, MB, KF, and DA performed the research and carried out the computations. All authors contributed substantially to the analysis and interpretation of results and writing of the manuscript.

Competing interests

The authors declare no competing interests

Additional information

Supplementary Information

Supplementary Table 1 | Table of countries and world regions included in this study.

Country name	ISO3	Country code in EXIOBASE	Cluster
Afghanistan	AFG	WWA	self sufficient
Albania	ALB	WWE	self sufficient
Algeria	DZA	WWF	self sufficient
Angola	AGO	WWF	self sufficient
Argentina	ARG	WWL	intermediate
Armenia	ARM	WWA	self sufficient
Australia	AUS	AUS	exporters
Austria	AUT	AUT	outsourcers
Azerbaijan	AZE	WWA	self sufficient
Bahamas	BHS	WWL	intermediate
Bahrain	BHR	WWM	intensifiers
Bangladesh	BGD	WWA	self sufficient
Belarus	BLR	WWE	self sufficient
Belgium	BEL	BEL	outsourcers
Belize	BLZ	WWL	intermediate
Benin	BEN	WWF	self sufficient
Bhutan	BTN	WWA	self sufficient
Bolivia	BOL	WWL	intermediate
Bosnia and Herzegovina	BIH	WWE	self sufficient
Botswana	BWA	WWF	self sufficient
Brazil	BRA	BRA	intermediate
Brunei Darussalam	BRN	WWA	self sufficient
Bulgaria	BGR	BGR	intermediate
Burkina Faso	BFA	WWF	self sufficient
Burundi	BDI	WWF	self sufficient
Cambodia	KHM	WWA	self sufficient
Cameroon	CMR	WWF	self sufficient
Canada	CAN	CAN	exporters
Cape Verde	CPV	WWF	self sufficient
Central African Republic	CAF	WWF	self sufficient
Chad	TCD	WWF	self sufficient
Chile	CHL	WWL	intermediate
China	CHN	CHN	self sufficient
Colombia	COL	WWL	intermediate
Comoros	COM	WWF	self sufficient
Congo, Dem Republic of	COD	WWF	self sufficient
Congo, Republic of	COG	WWF	self sufficient
Costa Rica	CRI	WWL	intermediate
Côte d'Ivoire	CIV	WWF	self sufficient
Croatia	HRV	HRV	intermediate
Cuba	CUB	WWL	intermediate
Cyprus	CYP	CYP	intensifiers
Czech Republic	CZE	CZE	intermediate
Denmark	DNK	DNK	outsourcers
Djibouti	DJI	WWF	self sufficient
Dominican Republic	DOM	WWL	intermediate
Ecuador	ECU	WWL	intermediate
Egypt	EGY	WWF	self sufficient
El Salvador	SLV	WWL	intermediate
Equatorial Guinea	GNQ	WWF	self sufficient
Estonia	EST	EST	exporters
Ethiopia PDR	ETH	WWF	self sufficient
Fiji Islands	EJI	WWA	self sufficient
Finland	FIN	FIN	outsourcers
France	FRA	FRA	outsourcers
French Guiana	GUF	WWL	intermediate
French Polynesia	PYF	WWA	self sufficient
Gabon	GAB	WWF	self sufficient
Gambia	GMB	WWF	self sufficient
Georgia	GEO	WWA	self sufficient
Germany	DEU	DEU	outsourcers
Ghana	GHA	WWF	self sufficient
Greece	GRC	GRC	outsourcers
Guadeloupe	GLP	WWL	intermediate
Guatemala	GTM	WWL	intermediate
Guinea	GIN	WWF	self sufficient
Guinea-Bissau	GNB	WWF	self sufficient
Guyana	GUY	WWL	intermediate
Haiti	HTI	WWL	intermediate
Honduras	HND	WWL	intermediate
Hungary	HUN	HUN	intermediate
Iceland	ISL	WWE	self sufficient
India	IND	IND	self sufficient
Indonesia	IDN	IDN	self sufficient
Iran, Islamic Rep.	IRN	WWM	intensifiers
Iraq	IRQ	WWM	intensifiers
Ireland	IRL	IRL	exporters
Israel	ISR	WWM	intensifiers
Italy	ITA	ITA	outsourcers
Jamaica	JAM	WWL	intermediate
Japan	JPN	JPN	intensifiers
Jordan	JOR	WWM	intensifiers
Kazakhstan	KAZ	WWA	self sufficient
Kenya	KEN	WWF	self sufficient
Korea, Dem People's Rep	PRK	WWA	self sufficient
Korea, Rep.	KOR	KOR	intensifiers
Kuwait	KWT	WWM	intensifiers
Kyrgyz Republic	KGZ	WWA	self sufficient
Laos	LAO	WWA	self sufficient
Latvia	LVA	LVA	exporters
Lebanon	LBN	WWM	intensifiers
Lesotho	LSO	WWF	self sufficient
Liberia	LBR	WWF	self sufficient
Libyan Arab Jamahiriya	LBY	WWF	self sufficient
Lithuania	LTU	LTU	exporters
Luxembourg	LUX	LUX	not used in cluster
Macedonia, FYR	MKD	WWE	self sufficient
Madagascar	MDG	WWF	self sufficient
Malawi	MWI	WWF	self sufficient
Malaysia	MYS	WWA	self sufficient
Mali	MLI	WWF	self sufficient
Malta	MLT	MLT	not used in cluster
Martinique	MTQ	WWL	intermediate
Mauritania	MRT	WWF	self sufficient
Mauritius	MUS	WWA	self sufficient
Mexico	MEX	MEX	intermediate
Moldova	MDA	WWE	self sufficient
Mongolia	MNG	WWA	self sufficient
Morocco	MAR	WWF	self sufficient
Mozambique	MOZ	WWF	self sufficient
Myanmar	MMR	WWA	self sufficient
Namibia	NAM	WWF	self sufficient
Nepal	NPL	WWA	self sufficient
Netherlands	NLD	NLD	outsourcers
New Caledonia	NCL	WWA	self sufficient
New Zealand	NZL	WWA	self sufficient
Nicaragua	NIC	WWL	intermediate
Niger	NER	WWF	self sufficient
Nigeria	NGA	WWF	self sufficient
Norway	NOR	NOR	outsourcers
Oman	OMN	WWM	intensifiers
Pakistan	PAK	WWA	self sufficient
Panama	PAN	WWL	intermediate
Papua New Guinea	PNG	WWA	self sufficient
Paraguay	PRY	WWL	intermediate
Peru	PER	WWL	intermediate
Philippines	PHL	WWA	self sufficient
Poland	POL	POL	intermediate
Portugal	PRT	PRT	outsourcers
Puerto Rico	PRI	WWL	intermediate
Qatar	QAT	WWM	intensifiers
Réunion	REU	WWA	self sufficient
Romania	ROU	ROU	intermediate
Russian Federation	RUS	RUS	intermediate
Rwanda	RWA	WWF	self sufficient
Samoa	WSM	WWA	self sufficient
Saudi Arabia	SAU	WWM	intensifiers
Senegal	SEN	WWF	self sufficient
Serbia and Montenegro	SRB	WWE	self sufficient
Sierra Leone	SLE	WWF	self sufficient
Slovakia	SVK	SVK	intermediate
Slovenia	SVN	SVN	intermediate
Solomon Islands	SLB	WWA	self sufficient
Somalia	SOM	WWF	self sufficient
South Africa	ZAF	ZAF	intermediate
Spain	ESP	ESP	outsourcers
Sri Lanka	LKA	WWA	self sufficient
Sudan	SUD	WWF	self sufficient
Suriname	SUR	WWL	intermediate
Swaziland	SWZ	WWF	self sufficient
Sweden	SWE	SWE	outsourcers
Switzerland	CHE	CHE	outsourcers
Syrian Arab Republic	SYR	WWM	intensifiers
Taiwan	TWN	TWN	not used in cluster
Tajikistan	TJK	WWA	self sufficient
Tanzania	TZA	WWF	self sufficient
Thailand	THA	WWA	self sufficient
Timor-Leste	TLS	WWA	self sufficient
Togo	TGO	WWF	self sufficient
Trinidad and Tobago	TTO	WWL	intermediate
Tunisia	TUN	WWF	self sufficient
Turkey	TUR	TUR	intermediate
Turkmenistan	TKM	WWA	self sufficient
Uganda	UGA	WWF	self sufficient
Ukraine	UKR	WWE	self sufficient
United Arab Emirates	ARE	WWM	intensifiers
United Kingdom	GBR	GBR	outsourcers
United States	USA	USA	intermediate
Uruguay	URY	WWL	intermediate
Uzbekistan	UZB	WWA	self sufficient
Vanuatu	VUT	WWA	self sufficient
Venezuela, RB	VEN	WWL	intermediate
Vietnam	VNM	WWA	self sufficient
Yemen, Rep.	YEM	WWM	intensifiers
Zambia	ZMB	WWF	self sufficient
Zimbabwe	ZWE	WWF	self sufficient

Supplementary Table 2 Development of indices in world regions, in percent (1/2).

year	LATAM				ME				US_CA		
	Biomass index	HANPP index	Energy input index		Biomass index	HANPP index	Energy input index		Biomass index	HANPP index	Energy input index
1995	-	-	-		-	-	-		-	-	-
1996	0.02	0.01	-0.01		0.00	-0.01	0.08		0.01	-0.00	-0.05
1997	0.04	0.02	-0.02		0.00	-0.01	0.17		0.02	-0.00	-0.10
1998	0.06	0.03	-0.02		0.00	-0.02	0.25		0.02	-0.01	-0.15
1999	0.08	0.04	-0.03		0.00	-0.02	0.34		0.03	-0.01	-0.21
2000	0.10	0.05	-0.04		0.00	-0.03	0.42		0.04	-0.01	-0.26
2001	0.13	0.07	0.03		0.03	-0.03	0.58		0.05	-0.00	-0.25
2002	0.15	0.08	0.09		0.05	-0.03	0.73		0.06	0.01	-0.24
2003	0.18	0.10	0.16		0.08	-0.03	0.89		0.07	0.02	-0.23
2004	0.21	0.11	0.22		0.10	-0.04	1.04		0.08	0.03	-0.23
2005	0.24	0.13	0.29		0.13	-0.04	1.20		0.09	0.04	-0.22
2006	0.29	0.14	0.33		0.15	-0.02	1.27		0.09	0.04	-0.25
2007	0.34	0.15	0.37		0.16	-0.00	1.35		0.09	0.05	-0.28
2008	0.39	0.16	0.41		0.18	0.01	1.43		0.09	0.05	-0.31
2009	0.44	0.17	0.45		0.19	0.03	1.50		0.09	0.06	-0.34
2010	0.49	0.18	0.49		0.21	0.04	1.58		0.09	0.06	-0.37
2011	0.50	0.19	0.53		0.24	0.10	1.56		0.11	0.05	-0.36
2012	0.51	0.21	0.57		0.27	0.15	1.55		0.12	0.04	-0.36
2013	0.52	0.23	0.61		0.30	0.20	1.53		0.14	0.04	-0.36
2014	0.54	0.25	0.65		0.32	0.26	1.51		0.16	0.03	-0.35
2015	0.55	0.26	0.69		0.35	0.31	1.50		0.17	0.02	-0.35

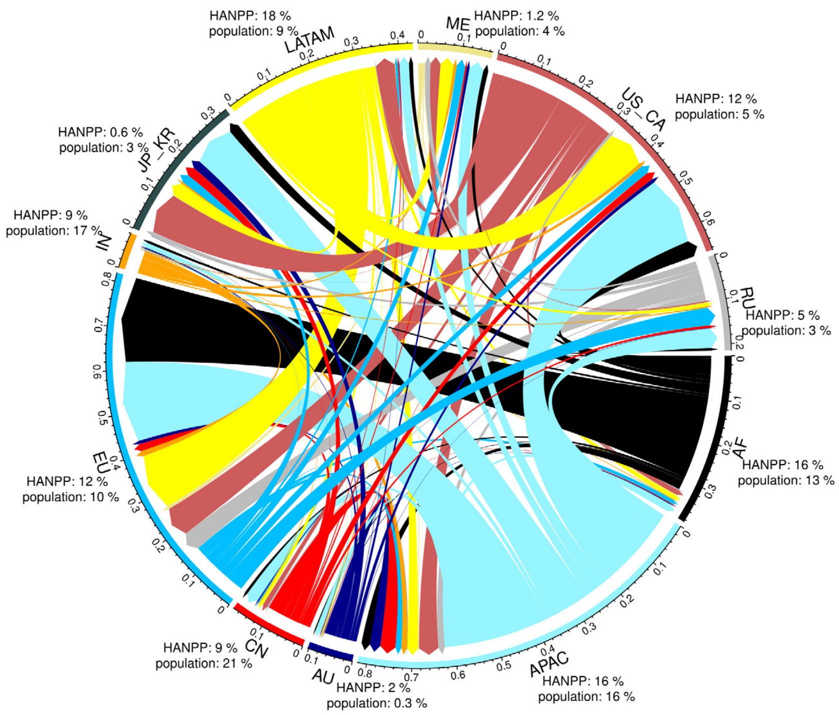
year	RU				AF				APAC		
	Biomass index	HANPP index	Energy input index		Biomass index	HANPP index	Energy input index		Biomass index	HANPP index	Energy input index
1995	-	-	-		-	-	-		-	-	-
1996	-0.06	-0.03	-0.06		0.02	0.02	-0.03		0.01	-0.00	0.03
1997	-0.12	-0.06	-0.12		0.04	0.03	-0.06		0.02	-0.00	0.07
1998	-0.17	-0.10	-0.19		0.06	0.05	-0.08		0.03	-0.00	0.10
1999	-0.23	-0.13	-0.25		0.08	0.06	-0.11		0.04	-0.00	0.14
2000	-0.29	-0.16	-0.31		0.10	0.08	-0.14		0.05	-0.00	0.17
2001	-0.26	-0.16	-0.33		0.12	0.11	-0.10		0.06	-0.00	0.21
2002	-0.24	-0.16	-0.34		0.14	0.14	-0.06		0.08	0.00	0.24
2003	-0.22	-0.16	-0.36		0.16	0.17	-0.02		0.09	0.01	0.28
2004	-0.19	-0.16	-0.37		0.18	0.21	0.03		0.11	0.01	0.32
2005	-0.17	-0.17	-0.39		0.20	0.24	0.07		0.12	0.01	0.35
2006	-0.17	-0.21	-0.40		0.24	0.27	0.16		0.17	0.02	0.43
2007	-0.17	-0.25	-0.41		0.27	0.31	0.25		0.21	0.03	0.51
2008	-0.17	-0.29	-0.42		0.31	0.34	0.34		0.25	0.04	0.59
2009	-0.17	-0.33	-0.44		0.35	0.37	0.43		0.30	0.05	0.67
2010	-0.17	-0.37	-0.45		0.39	0.40	0.51		0.34	0.06	0.75
2011	-0.14	-0.33	-0.45		0.42	0.45	0.53		0.37	0.10	0.78
2012	-0.11	-0.28	-0.46		0.45	0.49	0.54		0.39	0.13	0.81
2013	-0.08	-0.24	-0.46		0.48	0.54	0.55		0.42	0.16	0.85
2014	-0.05	-0.19	-0.47		0.51	0.58	0.57		0.44	0.19	0.88
2015	-0.02	-0.15	-0.47		0.54	0.62	0.58		0.47	0.22	0.91

Supplementary Table 3 Development of indices in world regions, in percent (2/2).

year	AU				CN				EU		
	Biomass index	HANPP index	Energy input index		Biomass index	HANPP index	Energy input index		Biomass index	HANPP index	Energy input index
1995	-	-	-		-	-	-		-	-	-
1996	0.01	0.00	0.01		0.01	0.02	-0.05		-0.01	-0.00	0.01
1997	0.02	0.01	0.03		0.01	0.03	-0.09		-0.02	-0.01	0.01
1998	0.03	0.01	0.04		0.02	0.05	-0.14		-0.03	-0.01	0.02
1999	0.05	0.01	0.06		0.03	0.07	-0.19		-0.04	-0.02	0.03
2000	0.06	0.02	0.07		0.03	0.09	-0.23		-0.05	-0.02	0.03
2001	0.05	0.00	0.19		0.07	0.10	-0.17		-0.04	-0.03	0.00
2002	0.05	-0.01	0.30		0.10	0.12	-0.10		-0.03	-0.04	-0.03
2003	0.04	-0.02	0.42		0.14	0.14	-0.03		-0.02	-0.04	-0.06
2004	0.03	-0.03	0.53		0.17	0.15	0.03		-0.01	-0.05	-0.09
2005	0.03	-0.04	0.65		0.21	0.17	0.10		-0.00	-0.05	-0.12
2006	0.02	-0.05	0.61		0.21	0.15	0.16		-0.00	-0.04	-0.13
2007	0.02	-0.06	0.58		0.21	0.13	0.21		-0.01	-0.02	-0.13
2008	0.01	-0.07	0.55		0.21	0.11	0.26		-0.01	-0.01	-0.13
2009	0.01	-0.08	0.52		0.21	0.09	0.32		-0.01	0.01	-0.14
2010	0.01	-0.09	0.48		0.21	0.07	0.37		-0.01	0.02	-0.14
2011	0.01	-0.09	0.47		0.27	0.08	0.32		0.01	0.01	-0.15
2012	0.02	-0.09	0.45		0.32	0.10	0.28		0.04	0.00	-0.16
2013	0.03	-0.09	0.44		0.37	0.11	0.23		0.06	-0.01	-0.17
2014	0.04	-0.09	0.42		0.42	0.13	0.18		0.09	-0.02	-0.18
2015	0.04	-0.09	0.40		0.47	0.14	0.13		0.12	-0.03	-0.20

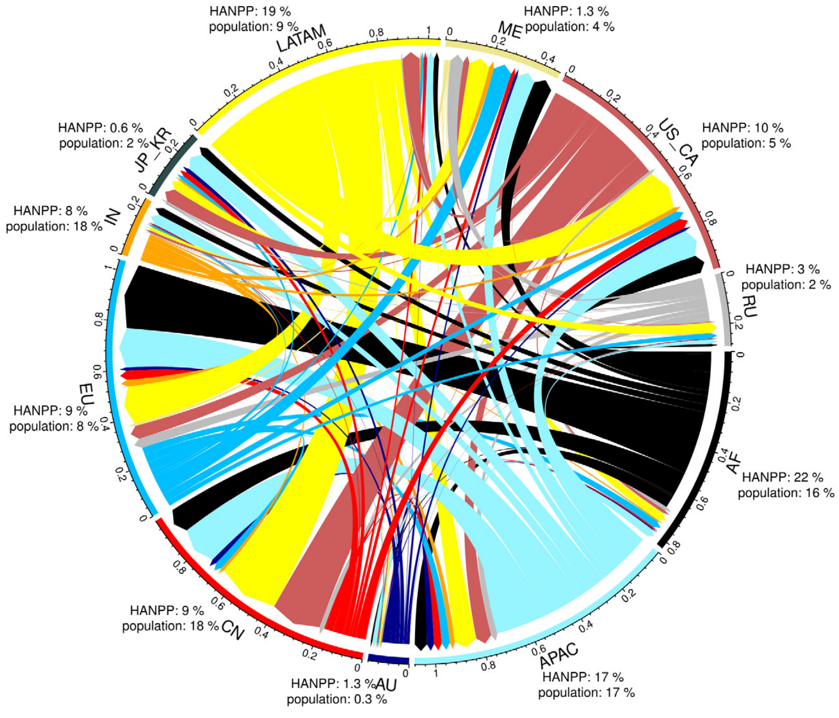
year	IN				JP_KR				global		
	Biomass index	HANPP index	Energy input index		Biomass index	HANPP index	Energy input index		Biomass index	HANPP index	Energy input index
1995	-	-	-		-	-	-		-	-	-
1996	0.01	-0.00	0.02		-0.01	-0.01	0.00		0.01	0.00	-0.01
1997	0.03	-0.00	0.04		-0.03	-0.01	0.00		0.01	0.01	-0.02
1998	0.04	-0.00	0.06		-0.04	-0.02	0.00		0.02	0.01	-0.03
1999	0.05	-0.01	0.09		-0.05	-0.02	0.00		0.03	0.01	-0.04
2000	0.06	-0.01	0.11		-0.06	-0.03	0.00		0.03	0.02	-0.05
2001	0.06	0.00	0.17		-0.08	-0.04	0.02		0.05	0.03	-0.03
2002	0.05	0.01	0.23		-0.09	-0.04	0.04		0.07	0.04	-0.00
2003	0.04	0.02	0.29		-0.10	-0.05	0.06		0.09	0.05	0.02
2004	0.04	0.02	0.35		-0.11	-0.06	0.08		0.10	0.06	0.05
2005	0.03	0.03	0.42		-0.13	-0.07	0.10		0.12	0.07	0.07
2006	0.07	0.03	0.49		-0.11	-0.05	0.14		0.14	0.08	0.10
2007	0.11	0.03	0.57		-0.08	-0.03	0.19		0.17	0.09	0.13
2008	0.15	0.03	0.65		-0.06	-0.01	0.24		0.19	0.09	0.15
2009	0.19	0.03	0.73		-0.04	0.01	0.29		0.21	0.10	0.18
2010	0.23	0.04	0.81		-0.02	0.03	0.34		0.23	0.11	0.20
2011	0.24	0.05	1.15		-0.01	0.04	0.28		0.26	0.13	0.22
2012	0.24	0.06	1.49		-0.01	0.06	0.23		0.28	0.14	0.24
2013	0.24	0.07	1.83		-0.01	0.08	0.17		0.31	0.16	0.26
2014	0.25	0.09	2.18		-0.01	0.09	0.11		0.33	0.18	0.27
2015	0.25	0.10	2.52		-0.00	0.11	0.06		0.35	0.20	0.29

1995

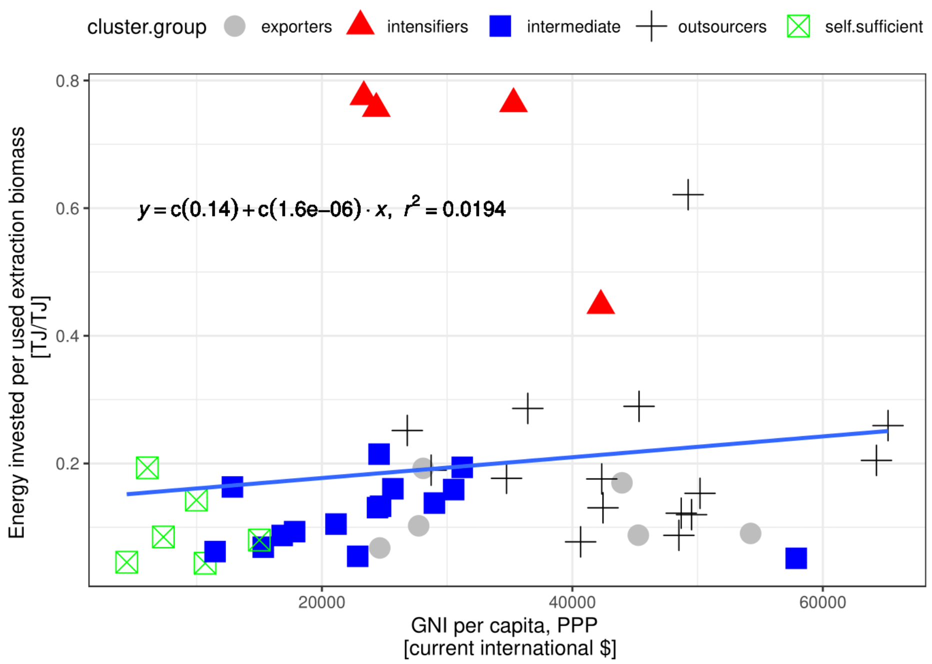


Supplementary Fig. 1 | Embodied HANPP flows between world regions as directed arrows in 1995. Values in the circular network plot are given in gigatons carbon [Gt C]. Annotated text gives shares of global HANPP and population respectively. LATAM = Latin America, ME = Middle East, US_CA = USA and Canada; RU = Russia, AF = Africa, APAC = Asia and Pacific, AU = Australia, CN = China, EU = Europe, IN = India, JP_KR = Japan and South Korea.

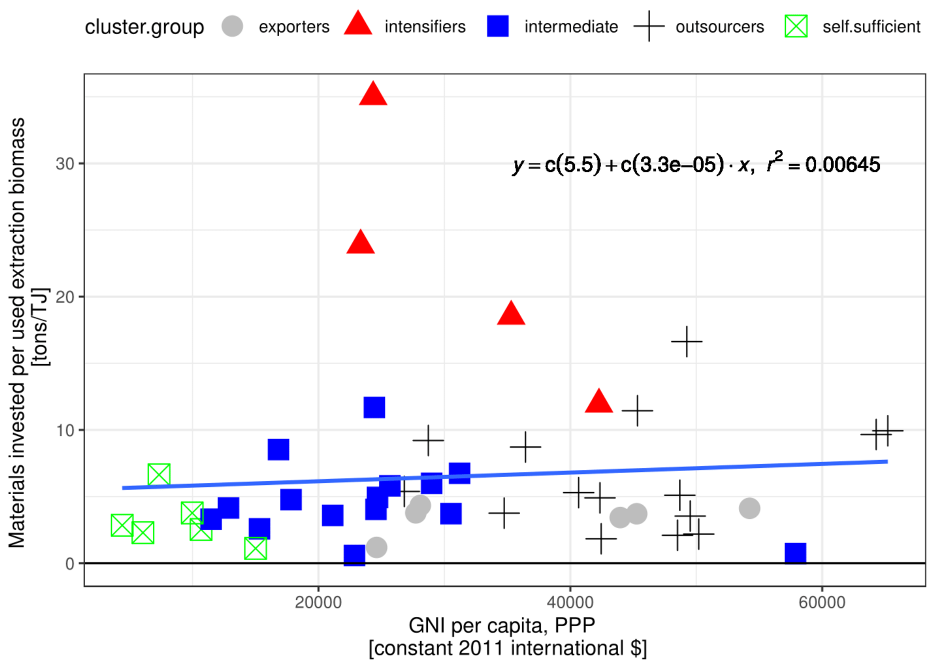
2015



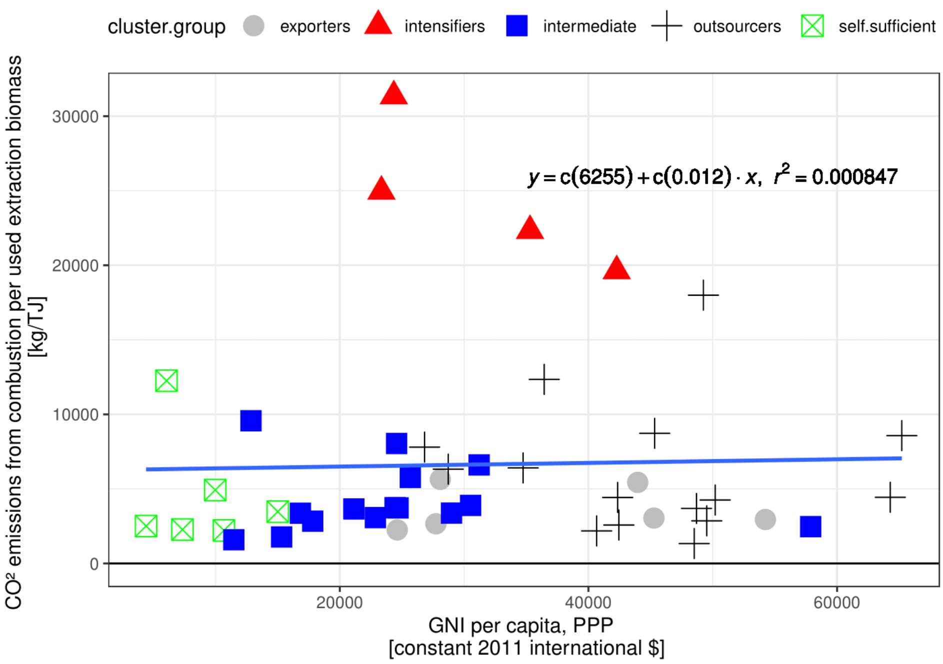
Supplementary Fig. 2 | Embodied HANPP flows between world regions as directed arrows in 2015. Values in the circular network plot are given in gigatons carbon [Gt C]. Annotated text gives shares of global HANPP and population respectively. LATAM = Latin America, ME = Middle East, US_CA = USA and Canada; RU = Russia, AF = Africa, APAC = Asia and Pacific, AU = Australia, CN = China, EU = Europe, IN = India, JP_KR = Japan and South Korea.



Supplementary Fig. 3 | Linear regression analysis with GNI per cap (PPP, current international $) as the predictor and the variable 'energy invested per biomass used extraction' as the response variable. With a p-value of 0.36 the regression is not significant.



Supplementary Fig. 4 | Linear regression analysis with GNI per cap (PPP, current international $) as the predictor and the variable 'materials invested per biomass used extraction' as the response variable. With a p-value of 0.60 the regression is not significant.



Supplementary Fig. 5 | Linear regression analysis with GNI per cap (PPP, current international $) as the predictor and the variable 'CO₂ emissions from combustion per biomass used extraction' as the response variable. With a p-value of 0.85 the regression is not significant.

Chapter V

Global patterns of ecologically unequal exchange: implications for sustainability in the 21st century

Christian Dorninger, Alf Hornborg, David J. Abson, Henrik von Wehrden, Anke Schaffartzik, Stefan Giljum, John-Oliver Engler, Robert L. Feller, Klaus Hubacek, Hanspeter Wieland

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Abstract

Ecologically unequal exchange theory posits asymmetric net flows of biophysical resources from poorer to richer countries. It hypothesizes that, through international trade, wealthier countries are able to satisfy their demand for natural resources through net imports, allowing them to decouple economic growth from domestic resource use. Thereby, high-income countries appropriate a disproportionally large share of the world's resources from the global market. To date, empirical evidence to support this theoretical notion as a systemic aspect of the global economy is underdeveloped. Through environmentally-extended multi-regional input-output modelling, we provide empirical underpinning for ecologically unequal exchange as a structural and persistent feature of the world economy from 1990 to 2015. We identify the regions of origin and final consumption for four resource groups: materials, energy, land, and labor. By comparing the monetary exchange value of resource flows embodied in trade we find significant international disparities in how resources are valued. Value added generated per ton of raw material embodied in exports is 11 times higher in high-income countries compared to those with the lowest income, and even 28 times higher per unit of embodied labor. Apart from China and India for embodied land, all world regions serve as net exporters of all types of embodied resources to high-income countries across the whole time period. Ecologically unequal exchange thus allows high-income countries to simultaneously net appropriate resources and generate a monetary surplus through international trade. This involves far-reaching implications for global sustainability and for the economic growth prospects of nations.

Keywords: ecologically unequal exchange, embodied trade flows, environmentally-extended multi-regional input-output analysis, international trade, structural equation modelling

Significance Statement

This study investigates global patterns of ecologically unequal exchange over the last three decades. We find evidence for ecologically unequal exchange simultaneously resulting from and reinforcing international economic inequality. We show that high resource consumption and economic growth in high-income countries are sustained by asymmetric exchange relationships with poorer regions from which resources are obtained and to which environmental burdens are shifted. High-income countries are persistent net appropriators of materials, energy, land, and labor. The capacity to generate significantly higher levels of value added per unit of exported resource allows high-income countries to appropriate more resources, perpetuating unequal exchange relations. Our results challenge the fundamental assumption purported in orthodox economic thought that international trade benefits all participating parties equally.

Global use of natural resources has reached unprecedented levels and is expected to further rise (1, 2). Simultaneously, international trade volumes have grown rapidly over the last decades (3, 4) as domestic requirements for materials, energy, land, and labor have increasingly been met by drawing on international sources (4, 5).

The advocacy of free trade is largely premised on the notion that such trade is economically beneficial to all parties (6). However, this perspective neglects the material aspects of global trade flows. The theory of ecologically unequal exchange (7, 8) postulates that the exclusive focus on monetary flows implies a disregard for asymmetric transfers of biophysical resources, such as materials, energy, land, and labor, which are embodied in traded commodities and services. Ecologically unequal exchange is defined as the asymmetric net transfer of resources (including labor) from peripheral to core areas of the global economic system (9, 10).

High-income nations depend on resource-intensive industrial technologies and infrastructures whose efficient functioning is contingent on these annual net transfers of resources from distant areas (11, 12). Moreover, high-income nations obtain significantly higher revenues for their resources exported than poorer nations, which is mostly due to the positions occupied in global supply chains and their respective roles in the world economy (13–15). The asymmetry of international trade, i.e. the exchange of unequal resource volumes and nonequivalent monetary values, are crucial determinants of the capacity to accumulate capital and technological infrastructure, i.e. achieve economic growth.

These trade patterns arise from and reproduce global socio-economic inequalities and hamper socio-environmental sustainability through environmental burden-shifting to poorer nations (5, 16). This displacement of extractive frontiers to “elsewhere” (17) is in turn linked to socio-environmental conflicts and the rise of environmental justice movements affecting the agricultural, mining, and manufacturing sectors (16) as well as commodified sinks (18).

To date, empirical evidence to support the theoretical notion of ecologically unequal exchange as a structural feature of the global economy is underdeveloped. The results of the only global assessment for a single year (19) have been called into question (20). This study, therefore, assesses the international exchange of a range of embodied resource flows at the global scale over a 26-year period (1990-2015). We quantify ecologically unequal exchange in four biophysical resources embodied in traded goods and services:

1) raw materials, expressed in 'raw material equivalents' (RMEs): i.e. materials directly traded plus all materials embodied in traded goods and services (measured in Gigatons [Gt]) (21);
2) energy, i.e. primary energy used along the whole supply chain to produce a certain good or service (measured in Exajoules [EJ]) (22);
3) land, i.e. land use that is directly and indirectly required for the production of a good or service (measured in hectares [ha]) (23); and
4) labor, i.e. all the labor expended in the supply chain to produce a certain good or service (measured in person-year equivalents [p-y_{eq}]) (24).

We use consumption-based pressure indicators ('footprints') in order to capture the displacement effects (5, 25), which are often related to the aforementioned environmental conflicts and especially to ecological distribution conflicts (26). A national footprint represents the domestic extraction (materials) or use (energy, land, labor) of biophysical resources within a given nation plus the net trade (i.e. imports minus exports, including embodied flows). For example, the domestic extraction of materials plus the RMEs of imports and minus the RMEs of exports results in a country's material footprint (27).

Our analysis is based on the most recent data available from the environmentally-extended multi-regional input-output (EEMRIO) database Eora (28, 29). In addition to direct international trade flows, EEMRIO models allow calculating embodied resource flows associated with global supply chains, by including the intermediate resources that are used to produce final marketed goods and services (5, 27).

Another branch of multi-regional input-output analysis, in addition to the environment-related assessments, is concerned with global monetary value chains and the analysis of so-called "trade in value added" (TiVA). TiVA, which is sometimes referred to as the 'value footprint' (5), accounts for the monetary value added of a country that is directly and indirectly embodied in the final demand of another country, i.e. TiVA represents the monetary value a nation generates with exports rather than the total export value of the goods exported (30). The TiVA indicator is the financial counterpart to input-output-based resource footprints and it follows the same calculation steps (see methods section).

While the theory of ecologically unequal exchange in itself is much more complex, we only test for a set of specific hypotheses that can be operationalized and assessed with quantitative data and models available. Accordingly, we present the domestic extraction and use of resources and their reallocation through international trade on a global scale and in a temporal perspective. We calculate net appropriation and net provision as well as the differences in monetary valuation (TiVA) of the four different resources around the world. Additionally, we build four structural equation models (SEM), one for each of the examined resources, to statistically assess the causal relationships predicted by the theory.

Our analysis includes 170 countries, 99.2 % of the world population in 2015, and almost the entire global supply chains and economy-wide resource flows. In order to investigate patterns of income inequality, we group countries into four income classes based on GNI per capita. Inspired by the World Bank's income and lending groups (31) we refer to them as high-income (HI), upper-middle income (UMI), lower-middle income (LMI), and low-income (LI). However, in order to maintain relatively evenly sized income groups in terms of total population, our income boundaries deviate from those of the World Bank (the SI contains a detailed description of income boundaries, a full list of countries and a map, **Fig. 5** and **Table 1**.). Due to their large population sizes, we treat China (CHN) and India (IND) as separate cases.

Production and consumption perspectives on resources and TiVA

Across the embodied flows of materials, energy, land, and labor, the group of HI countries used more resources from a consumption perspective than they provided through production in the year 2015 (Fig. 1a-d). Their final demand was associated with raw material requirements (i.e. including embodied resource use) exceeding their domestic extraction by 10 Gt. All regions except for HI countries were net providers of raw materials, with their production exceeding their consumption of resources. The largest net exporter of RMEs is the group of UMI nations (4.3 Gt) (Fig. 1a).

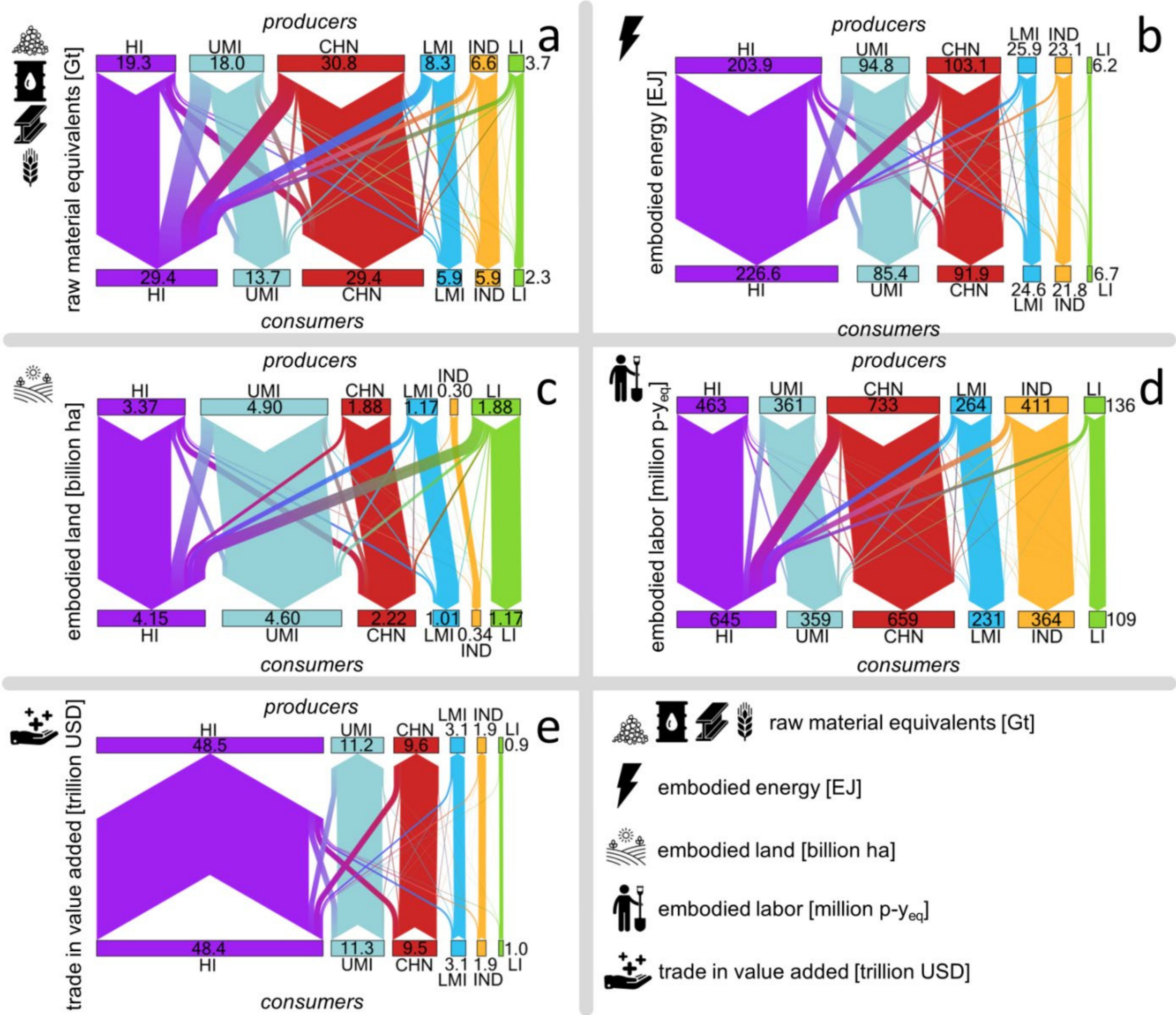

Fig. 1. Sankey diagrams exhibiting production and consumption of resources in each income-based country grouping (high-income HI, upper-middle income UMI, lower-middle income LMI, low-income LI), and China (CHN) and India (IND) in 2015. Flows represent the redistribution of resources through trade. Note that money and resources flow in opposite directions in trade relations, i.e. value added flows from consumers to producers.

HI nations were both the largest domestic producers of primary energy (203.9 EJ) and the main net appropriators of energy embodied in traded goods (22.7 EJ), resulting in a very high energy footprint (226.6 EJ). Energy – that is, almost exclusively fossil energy – appropriated by HI countries mainly stemmed from the UMI countries and China (Fig. 1b). Next to the HI countries, the only other net-appropriation occurred in the LI countries, although at a very low level of about 0.5 EJ.

The HI countries were also the largest net appropriators of land (of approximately 0.8 billion hectares), their land footprint corresponded to 31% of total global land used (Fig. 1c). Together with the HI countries, China and, to a lesser extent, India were net appropriators of embodied land, while the UMI, LMI and LI countries were net providers. Nonetheless, the UMI countries maintained the largest land footprint.

All income groups but the HI countries were net providers of labor (Fig. 1d). China, with a high level of domestic labor use, exhibited the largest international net provision of embodied labor (74 p-yeq), followed by India with net exports of 47 million p-yeq in 2015. In comparison, the HI countries net appropriated approximately 182 million p-yeq.

In 2015, HI countries achieved a monetary trade surplus and with 48.5 trillion USD not only by far the highest value added (TiVA), but more than all other income groups, China and India combined (26.7 trillion USD) (Fig. 1e). Only HI countries and China achieved a monetary trade surplus (in terms of value added) in 2015. However, while China exhibited a trade deficit in terms of natural resources (except for embodied land), the HI countries were a net importer of all resources assessed. In 2015, well over half of global TiVA was between high-income countries while, as we have demonstrated in Fig. 1a-d, materials, energy, land, and labor notably flowed from all other country groupings to the HI countries.

Temporal persistence: annual net trade and accumulated appropriation and provision

Compared to their population, HI countries net appropriate a disproportionately large share of materials, energy, land, and labor through international trade (Fig. 2). This disproportional distribution grew from 1990 until the 2007/8 global financial crisis, requiring ever-larger net provisions from the rest of the world. The financial crisis was associated with reductions in the net appropriation of all four resources by HI countries. However, they remained the only significant net appropriators. Rising appropriation by HI countries was mirrored by rising provision by, i.e. exports from, China. The expansion of net exports of RMEs and embodied energy was especially pronounced in the UMI countries and coincided with relatively stagnant net provisions of embodied land and labor. LI countries were the primary net providers of embodied land, with rapid increases during the 1990s.

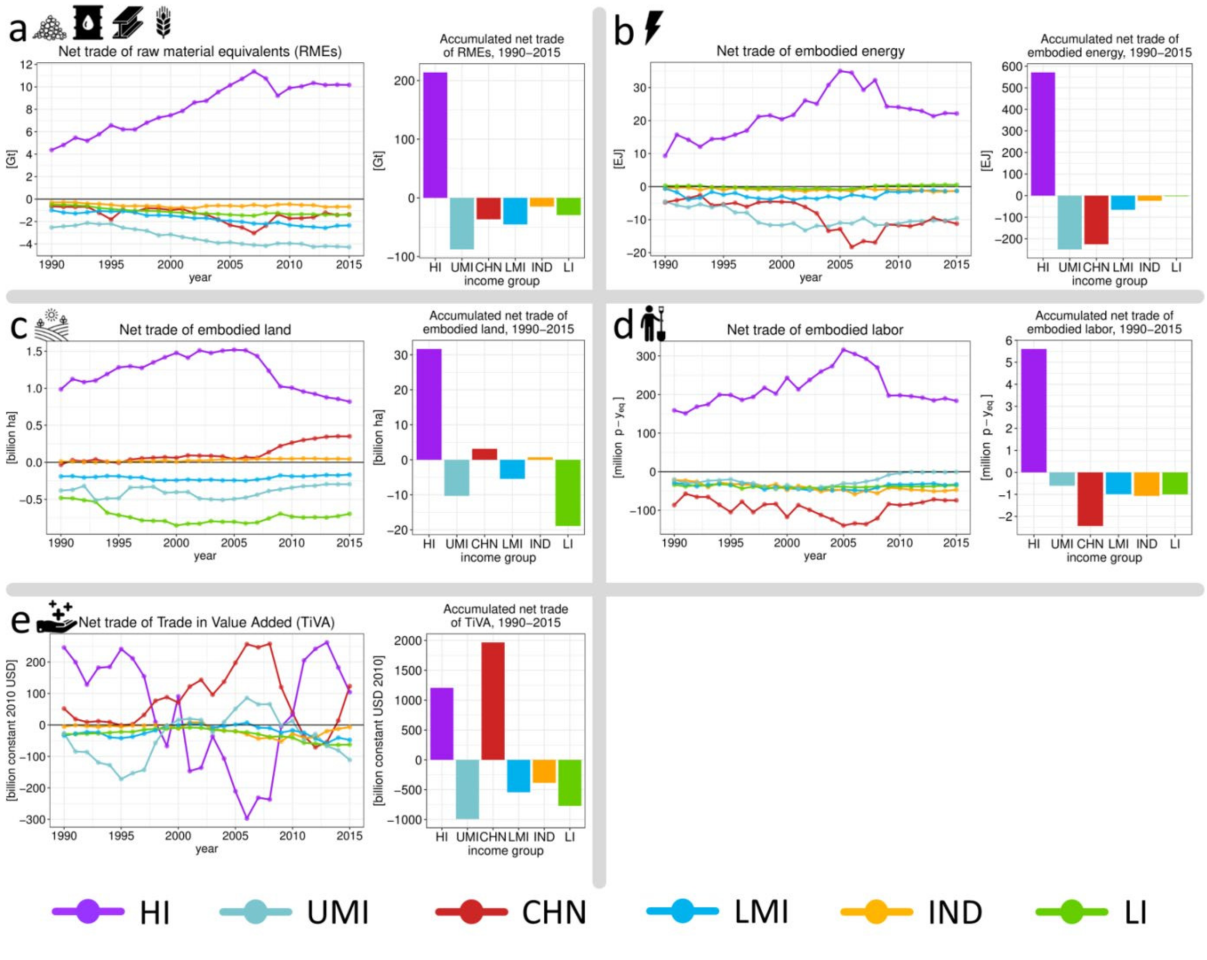

Fig. 2. Net trade of resources over time and accumulated appropriation and supply as bar plots, 1990-2015. a: raw material equivalents (RMEs) [Gt]; b: embodied energy [EJ]; c: embodied land [billion ha]; d: embodied labor [million p-y_{eq}]; and e: trade in value added (TiVA) [bn constant 2010 USD]. Positive values represent a net appropriation of resources.

While cumulatively acting as a net appropriator of embodied resources, the group of HI countries was able to generate a monetary trade surplus (positive TiVA) of approximately 1,200 trillion USD during this phase. China achieved an even higher monetary trade surplus (approximately 1,900 trillion USD). However, unlike the HI countries, China acted as a net provider of embodied materials, energy, and labor. In general, the temporal patterns of the net trade of TiVA exhibited considerably less stability than the trade of resources and there was a less marked difference between high and low-income country groups.

Monetary valuation of embodied resources

The asymmetry in the distribution of monetary value added is especially apparent in the direct comparison between embodied resource flows and TiVA which we present in Fig. 3. With lower per capita income, value added per unit of exported embodied resource is generally lower. This inequality was found for all four resources assessed and particularly pronounced for embodied labor time. However, China often obtained more TiVA per unit of exports than the UMI group and, for land also more than the HI group since 2010.

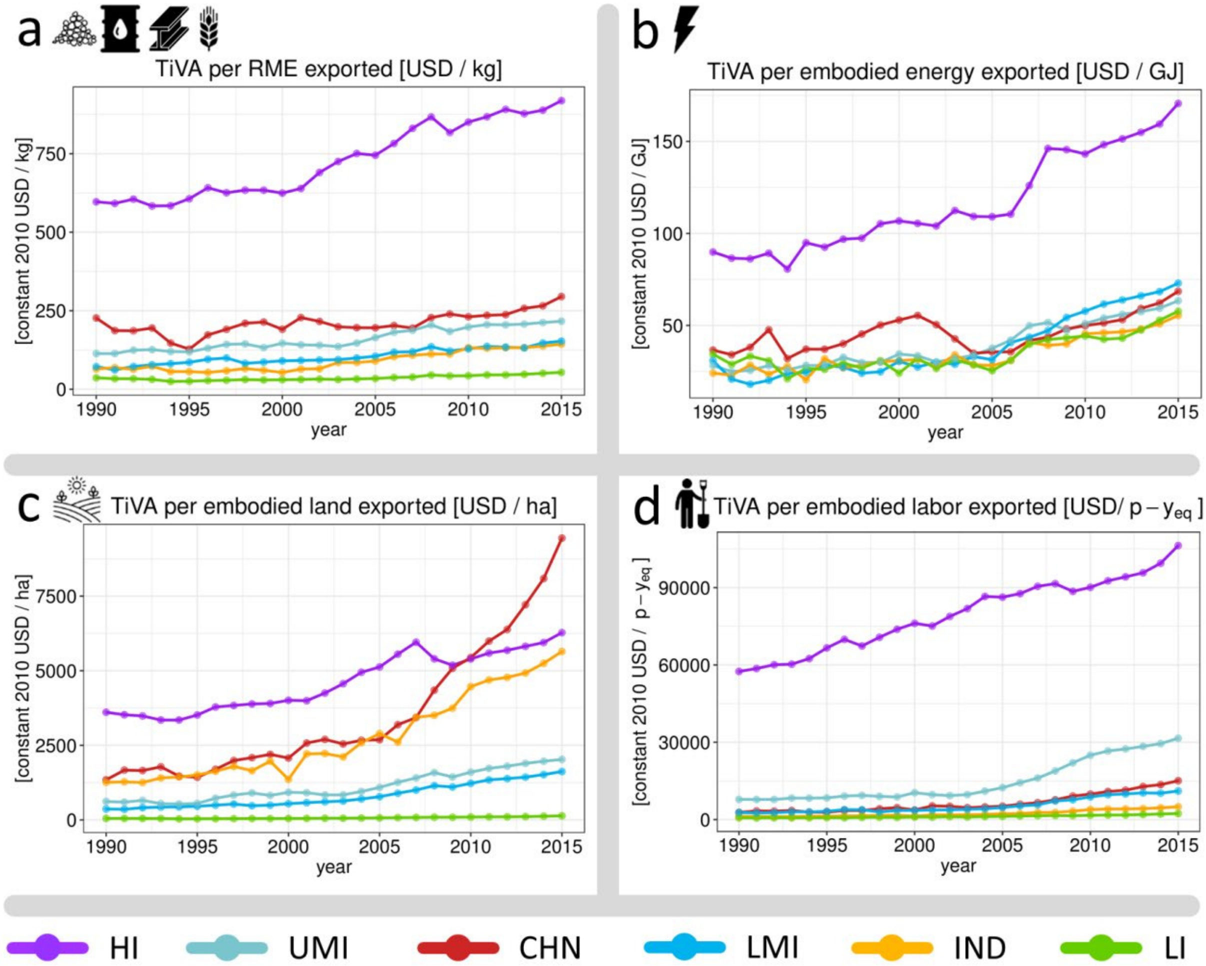

Fig. 3. Trade in value added (TiVA) of resources embodied in exports, 1990-2015, in constant international 2010 USD. Top left: value added per raw material equivalent (RME) exported [USD per kg]; top right: value added per unit of embodied energy exported [USD per GJ]; bottom left: value added per hectare embodied in exports [USD per ha]; bottom right: value added per labor equivalent embodied in exports [USD per p-y_{eq}].

The HI countries generated significantly higher levels of TiVA per unit of exported RMEs than all other income groups. This trend is apparent throughout the analyzed period and does not decrease over time. HI countries tend to receive more than double the TiVA per embodied energy exported than the poorer countries.

For land, the HI countries are not the only group with high TiVA per unit of land embodied in exports. Because of low export flows of embodied land (making them net-importers of embodied land overall, Fig. 1c and Fig. 2c), the high TiVA in China's case and even India's stagnating TiVA give these countries comparatively high TiVA/ha of embodied land (Fig. 3c). For the other income groups, and especially for the LI nations, the TiVA from exports of embodied land remained very low compared to HI countries, China, or India (this is the result of the LI countries acting as major providers of land while receiving far less TiVA than any of the other country groups).

In terms of compensation for embodied labor, there are, again, tremendous differences between HI countries and the rest of the world. During this 26-year period, HI countries gained on average 12 times more TiVA per labor unit (p-yeq) embodied in exports than the rest of the world.

Structural Equation Models (SEMs)

Fig. 4 shows four structural equation models (SEMs) which test hypotheses in form of causal relationships between dependent and independent variables: We used income (GNI), a technology adaptation index (32), military expenditure (33), and biophysical reserves, i.e. the total fossil fuels (34) and metal ores reserves (35), plus the national actual terrestrial net primary productivity (NPPact) expressing biomass reserves (36), as independent variables (representing economic, technological, and military power, as well as natural resource endowment) and net imports of resources and the TiVA generated per resource unit embodied in exports as dependent variables. All data for the SEMs are available in the SI.

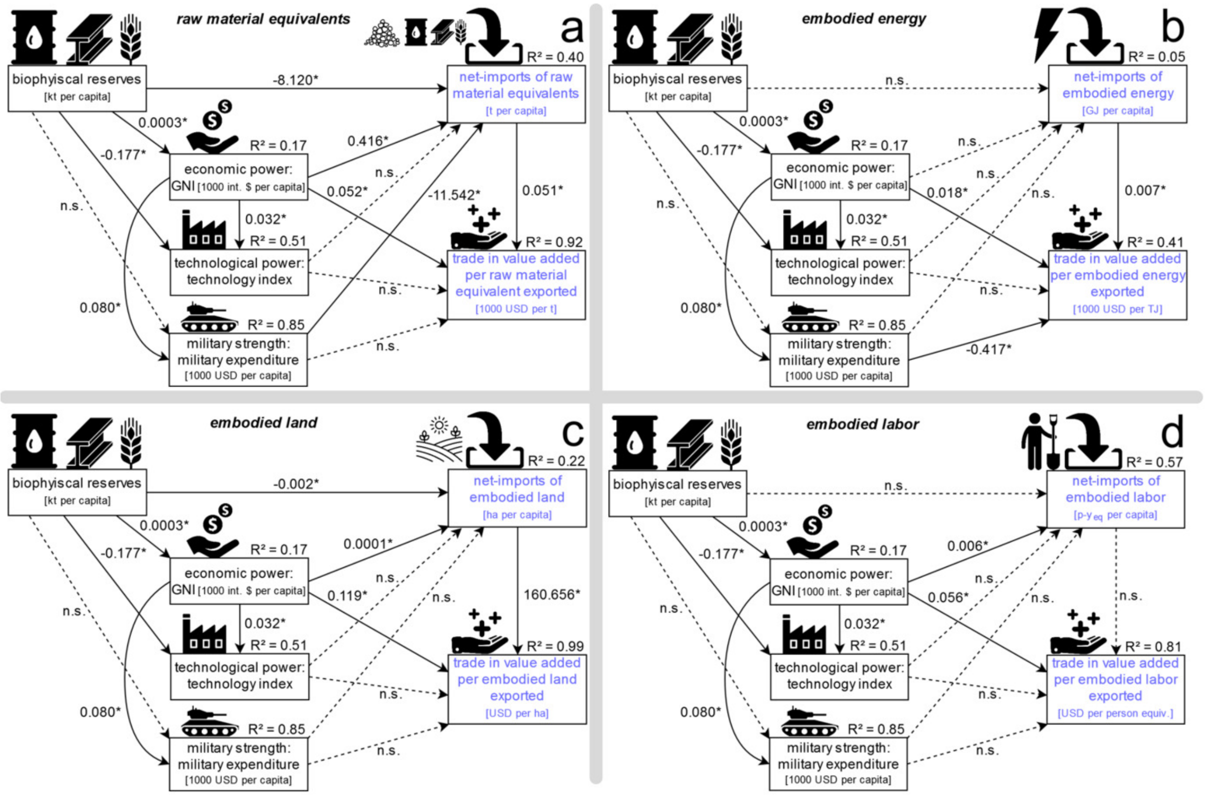

Fig. 4. Piecewise structural equation model quantifying hypothesized relationships between economic and technological power, military strength, biophysical reserves and net imports of resources as well as trade in value added per exported resource item in global trade in 2015 (n = 170). Each of our final SEMs contains 13 relationships, indicated as directed arrows. Path coefficients are not standardized to allow for a direct interpretation of effects in ratios between a rise in the value of the predictor and its effect on the value of the response variable. The four predictor variables on the left of each SEM (reserves, GNI, technology, military) remain unaltered throughout, and only the response variables (net trade and trade in value added) are replaced for each of the four resource types (indicated in blue). The asterisk indicates that the 95 % confidence interval around the estimate does not include zero. Non-significant path coefficients are indicated by a dotted line and labeled “n.s.”.

Fit statistics indicate that the hypothesized model provides an adequate description of the data, both with respect to overall model fit ($p = 0.63$, Fisher’s $C = 2.57$) as well as variance in the data explained in individual model regressions (as indicated by R^2 values). Of the 13 directed relationships, ten were found to be likely non-zero. The fit of our model to the data suggests that nations tend to become net importers of raw material equivalents (RMEs) with growing income. For each additional 1,000 $ GNI per capita, we estimate an increase in net imports of RMEs of 0.4 tons per capita. Conversely, for each kiloton of resources available (as reserves) per capita, a country’s net RME imports decline by 8.1 tons per capita. With regards to exports, income has a positive effect on the TiVA per RME exported. We find that for an additional GNI of 1,000 $ per capita, a country increases the value added per ton of RME exported by 52 USD. Military strength, as measured by the annual governmental military expenditure per capita (33), had a negative effect on net imports of RMEs. Technological power, as represented by a country’s technological adoption index of the World Economic Forum (32), did neither have a significant effect on per-capita net imports of RMEs, nor on value added per RME exported (Fig. 4a).

The SEM for embodied energy ($p = 0.3$, Fisher’s $C = 4.88$) does not exhibit significant effects of biophysical reserves and GNI on the net import of embodied energy, and only 5 % of the variability in the data on net imports of embodied energy was explained by the model. However, higher income and net imports of embodied energy both had a positive effect on TiVA per exported unit of energy. Our model indicates that higher military expenditure implied on average lower TiVA per embodied energy unit exported (Fig. 4b).

The SEM for embodied land ($p = 0.52$, Fisher's $C = 3.21$) shows a positive impact of per-capita GNI on net imports of embodied land, albeit a rather small one (0.0001 ha per capita per 1000 $/cap increase). A one ha/cap increase in net imports of embodied land implies an increase in value added by 160 USD per ha of embodied land exported (Fig. 4c).

The SEM for embodied labor and its TiVA ($p = 0.78$, Fisher's $C = 1.78$) is the only one of our models which does not yield a positive relationship between net imports and value added (Fig. 4d). For each 1000 $/cap increase in GNI, net imports of embodied labor tend to rise by 0.006 p-yeq. With the same increase in GNI, the TiVA per embodied labor [p-yeq] exported increases by 56 USD. The richer a country, the greater its net appropriation of embodied labor and the more it received for the embodied labor it exported. Conversely, the poorer a country, the larger is its net exports of embodied labor, but the less it receives per unit of embodied labor exported.

In sum, from the 4 SEMs we conclude that the crucial variable determining access to resources and trade in value added for exports was economic power, i.e. per-capita GNI. By contrast, military power did not play a role or even had a negative effect. However, per-capita GNI had a positive impact on both military expenditure and technological adaptation. The effect of income thus outweighs other potentially significant effects of technological or military capacity.

Discussion: implications of ecologically unequal exchange

The theory of ecologically unequal exchange posits the disproportionate access to resources of high-income countries. Our analysis shows how the creation of value added in HI nations depends on the annual net inflow of resources from relatively poorer regions. This observation holds true for the entire period observed, suggesting that this asymmetric exchange is a structural feature of trade relations and that economic growth in HI nations has not shown a decoupling from such unequal exchange relations.

There were significant differences in the monetary valuation of materials, energy, land, and labor embodied in traded goods. These differences were mostly determined by the countries' income level, implying that poorer countries hold positions in global supply chains that determine low monetary compensation for resources and products they sell. Conversely, the export of high value added products in the richer countries enables them to produce a higher gross national income to maintain high and import-dependent resource throughputs.

The asymmetries in biophysical exchange flows and the disparity in how embodied flows are being valued, generate a remarkable phenomenon: In standardized accountings of international trade, money and materials flow in opposite directions (6, 37). However, when embodied resources are considered, net flows of money and resources are aligned in the same direction. That means HI nations accomplish a net appropriation of materials, energy, land, and labor, while simultaneously generating the globally largest monetary surplus from those net appropriations.

Against the backdrop of the global extent and temporal persistence of ecologically unequal exchange presented in this study, we find that the unequal exchange is not coincidental or transitional, but systemic and pervasive in the current structure of the global economy. Its temporal persistence, global validity, and applicability to all four primary resources assessed underscore its systemic character. And while it enables biophysical and economic growth in the benefitting regions, it entails continued inequalities between countries and shifting of socio-environmental burdens to extractive regions (5).

Our analysis suggests that relationships of ecologically unequal exchange are a prerequisite for the seamless functioning of modern technology (e.g. the automobile industry and its infrastructure, energy production, but also industrial livestock production systems, textiles, or electronics). We argue that economic growth and technological progress in core areas of the world-system occurs at the expense of their peripheries (38, 39), i.e. that growth is fundamentally a matter of appropriation (9). In fact, modern technological systems may, in part, be driven by differences in how human time and natural space are valued in different parts of the world. High resource consumption is enabled by globally prolonged supply chains, favoring countries with high-value added processes (15).

In view of the empirical evidence provided in this study, a "catch-up" development has failed to materialize across a wide range of countries and needs to be scrutinized much more critically (see Fig. 1 and Fig. 2). Our study suggests that, because catching-up requires an appropriation of resources from poorer regions, it seems illusory to hope for the poorest regions to catch up and adopt the HI-country mode of industrialization. For these reasons, industrialization as experienced by the world's wealthiest countries, and some emerging economies like China, cannot become universal. Rather, the conditions of sustainable development must be fundamentally re-conceptualized. Economic theory must better acknowledge the material aspects of economic flows in order to be able to understand the holistic relationship between economic growth, international trade, and today's global sustainability challenges (40). The inequality observed is functional and systemic and not a mere side-effect.

Conclusions

We have shown that the consideration of asymmetric global flows of embodied materials, energy, land, and labor are key to understanding how market exchange can obscure inequalities. This fundamental observation is crucial in accounting for the limited political acceptance of the ecologically unequal exchange perspective. What is arguably one of the main sources of inequalities in our modern world is, thereby, kept outside the mainstream field of vision in economics and politics. Policy instruments for mitigating the deleterious global consequences of ecologically unequal exchange are thus non-existent. We argue that any national attempt that seriously aims at sustainability inevitably must include considerations of unequal exchange as a structural outcome of the current globalized economic system.

Materials and Methods

Environmental Input-Output Analysis

Input-output analysis (IOA), originally conceived by Nobel Prize Laureate Wassily Leontief (41), is based on monetary input–output tables (IOT), which describe interdependencies in the economy by recording transactions among industries (Z), supply of final demand (y) and value added in production (v)[1]. The core principle in IOTs are monetary industry balances, where total output must be equal to total input per industry. Henceforth, capital and minor letters respectively denote matrix and column-vector, while prime indicates transposition. Total output (x) equals all sales for intermediate production plus final demand, that is, $\mathrm{x} = \mathrm{Zi} + \mathrm{y}$, whereas gross input ($\mathrm{x}'$) equals all inter-industry purchases plus value added, $\mathrm{x}' = \mathrm{iZ} + \mathrm{v}$. Note that i is a summation-vector of ones, hence Zi sums the transaction matrix across rows and iZ across columns. On the basis of input–output tables, the demand-driven IO model can be estimated by

[1] Value added in production accounts for the compensation of employees, depreciation of fixed capital, profits plus taxes minus subsidies.

$$x = (I - A)^{-1}y = Ly,$$

where $A = Z\hat{x}^{-1}$ is the direct input coefficients i.e. technology matrix, whose element $a_{ij} = z_{ij}/x_j$ expresses direct inputs from industry i per unit of gross output of sector j. I is the identity matrix. Hats (^) indicate diagonalization of vectors, and $\hat{x}^{-1}$ denotes matrix inversion of $\hat{x}$. $L = (I - A)^{-1}$ is the 'Leontief inverse', whose element l_{ij} quantifies the total upstream i.e. direct and indirect inputs from sector i that are required to produce a unit of industry output j for final demand.

Multi-regional input-output analysis

Multi-regional input-output (MRIO) tables integrate national IO tables and bilateral trade accounts and thereby contain data for hundreds of countries. MRIO analysis evolved into an IOA branch that is especially concerned with the assessment of environmental pressures embodied in international trade (5). A number of global multi-regional input-output (MRIO) databases have been developed over the last decade. The present study uses the MRIO database Eora (28, 29)2, for three reasons: its high country resolution (189 countries), the availability of time series data (from 1990 to 2015), and the high level of disaggregation of products and industries (between 26 and 500).

Trade in value added (TiVA)

To compare the value added from international trade over time we use TiVA (42, 43) in constant international 2010 USD. Calculating monetary bilateral trade flows on the basis of TiVA is fully consistent with the IO-based footprint concept because both indicators follow the same system boundaries, i.e. they quantify two properties (financial vs. physical) of the same object (all supply chains between production and final consumption of two countries including all direct and indirect interlinkages). In contrast to global bilateral monetary trade flows, TiVA is globally balanced, meaning that national exports and imports globally sum up to zero. From a conceptual point of view, monetary bilateral gross trade flows, as reported by UN-Comtrade, IMF and WTO, should be used mainly for assessments of apparent, direct physical trade flows.

Using a demand-driven IO model as described before, a value added footprint i.e. TiVA indicator (B) is calculated by $B = \hat{p}L\hat{y}$, where $\hat{p} = v\hat{x}^{-1}$ is a diagonalized vector showing the amount of value added (v) per unit of industries' gross output (x). The column sum of B adds up to final demand (y) and the row sum to value added (v), no double-counts involved. Note that global value added (v) sums up to global final demand (y), in 2015 this was approximately 75 trillion USD. Consequently, element b_{ij} quantifies how much value added (v) is embodied in the total upstream inputs from industry i required to satisfy the final demand for industry output j. In other words, we can interpret element b_{ij} as an indicator showing how much of the expenditures of final demand for industry output j is directly and indirectly captured by the production activity of industry i.

Structural equation model (SEM)

We used piecewise structural equation modeling (SEM) to put the hypotheses from the theory of ecologically unequal exchange to a rigorous quantitative test. SEMs are networks of variables connected through paths, which represent causal relationships (44, 45). The main feature of SEM is that variables can simultaneously take the roles of predictors and responses. The SEM approach is also able to model indirect effects between two variables that are mediated by other variables.

[2] Version v.199.82 (available at http://www.worldmrio.com/).

We construct our SEM from a set of linear and generalized linear regression models. Linear models were possible for all net import variables and the technological power model. For all value added models as well as for per-capita GNI and military expenditure, we used generalized linear models with a Gamma error structure and log-link function. All statistical analyses were performed within the R environment (46), making use of the 'piecewiseSEM' package (45). All diagrams were drawn using the web-based visualizing tool 'draw.io' (www.draw.io).

Income groups

Countries with a GNI per capita (constant 2011 $ in purchasing power parity; PPP) (33) higher than 23,905 in 2015 are part of the high-income (HI) cluster (n=41; 1.14 billion people; 15.5 % of world population); countries with GNI per capita between 10,218 and 23,905 international $ are part of the upper-middle income (UMI) cluster (n=41; 1.19 billion people; 16.1 % of world population); countries with per capita incomes between 4,956 and 10,128 are in the lower-middle income (LMI) cluster (n=36; 1.15 billion people; 15.7 % of world population); and countries with a GNI per capita below or equal to 4,956 $ in 2015 formed the low-income (LI) country cluster (n=50; 1.13 billion people; 15.3 % of world population). China (CHN; GNI of 10,288 international $; 1.38 billion people; 18.7 % of world population) and India (IND, GNI of 5,688 international $; 1.31 billion people; 17.8 % of world population) were treated as separate cases due to their large populations and importance in terms of international trade.

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Supporting Information

Additional method and data description:

Environmentally-extended multi-regional input-output tables

Monetary IO tables are complemented by extension tables (e) recording non-monetary flows that are associated with economic activities, such as raw material extraction (measured in metric tons), direct energy (Joule) and land use (hectares) and labor requirements (working hours). Extension tables are sometimes referred to as the production-based account. Consumption-based accounts (F) are calculated by $F = \hat{q}L\hat{y}$, where $\hat{q} = e\hat{x}^{-1}$ is a diagonalized intensity vector showing the direct use of non-monetary flows (e) per unit of industries' gross output (x). Element f_{ij} quantifies the amount of non-monetary flows (e) that are embodied in the total upstream inputs from industry i required to satisfy the final demand for industry output j (for further details see Miller and Blair, 2009 (1). It is important to note that consumption-based accounts (F), when calculated in an IOA framework, always add up to the total production-based account (e). In other words, non-monetary flows are allocated to final demand without double-counting.

Physical data on raw material extraction has been gathered from the UNEP International Resource Panel database (2), one of the most detailed and comprehensive global raw material extraction database available. It covers 44 aggregated raw material categories for all countries worldwide, compiled following standardized principles of 'economy-wide material flow accounting' (3).

Trade in Value Added (TiVA)

The TiVA concept is motivated by the fact that monetary databases on bilateral gross trade flows, for example as reported by WTO, IMF, or UN-Comtrade, do not accurately measure the amount of value added exchanged between countries, i.e. the value of the traded products. In monetary terms, trade in intermediates account for approximately two thirds of international trade (43). In the era of globalized supply chains, imports (of intermediates) are used to produce exports and hence bilateral gross exports may include inputs – i.e. value added – from third party countries. TiVA reveals where (e.g. which country or industry) and how (e.g. by capital or labor) value is added, i.e. captured or created, along global supply chains (4). A report published by UNCTAD (5) also uses the Eora database to calculate global TiVA. The most comprehensive online database on TiVA is maintained by the OECD (6), which is calculated from the OECD ICIO (Inter-Country Input-Output) MRIO database (7).

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Fig. 5 also includes boxplots indicating the distribution of material footprint values per capita within the income groups and the significant difference between the groups, which was also confirmed by an ANOVA conducted. Here we can see that the income clusters explain the metabolic rate very well (boxplots etc.).

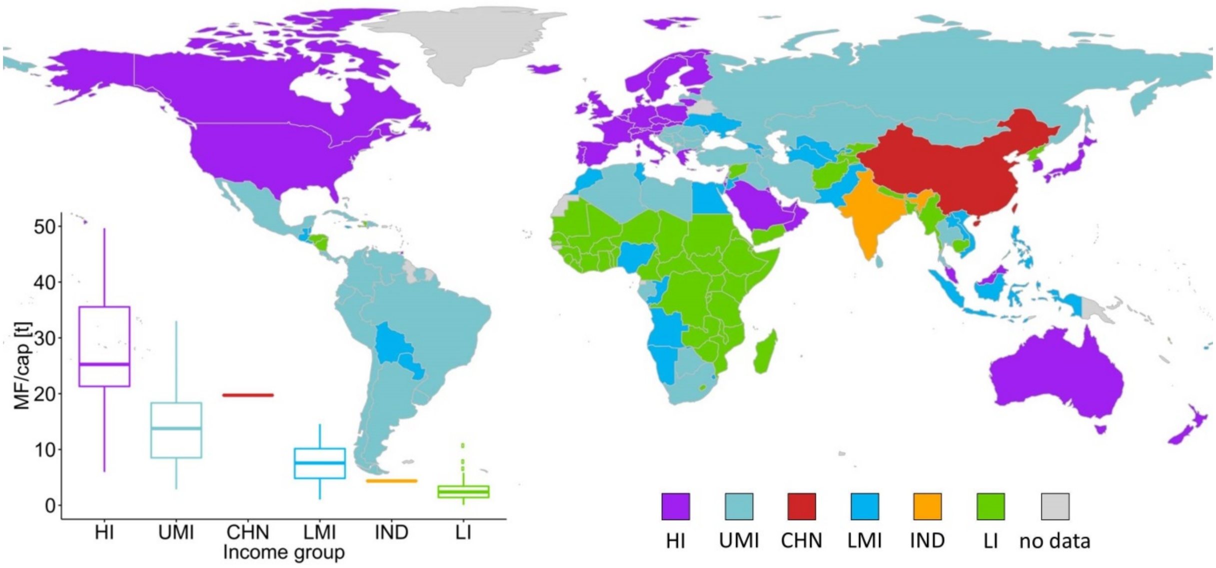

Fig. 5. The global distribution of income clusters in a map and a boxplot of the distribution of the material footprint in each income-group.

List of countries:

Table 1. List of countries.

Low-income (LI)	India (IND)	Lower-middle income (LMI)	China (CHN)	Upper-middle income (UMI)	High-income (HI)
n = 50	*n = 1*	*n = 36*	*n = 1*	*n = 41*	*n = 41*
Afghanistan	India	Albania	China (incl. Taiwan, Macao, and Hong Kong)	Algeria	Australia
Bangladesh		Angola		Antigua	Austria
Benin		Armenia		Argentina	Bahrain
Burkina Faso		Belize		Azerbaijan	Belgium
Burundi		Bhutan		Bahamas	British Virgin
Cambodia		Bolivia		Barbados	Brunei
Cameroon		Bosnia and Herzegovina		Botswana	Canada
Central African Republic		Cape Verde		Brazil	Cyprus
Chad		Congo		Bulgaria	Czech Republic
Cote dIvoire		Ecuador		Chile	Denmark
Djibouti		Egypt		Colombia	Estonia
DR Congo		El Salvador		Costa Rica	Finland
Eritrea		Fiji		Croatia	France
Ethiopia		Georgia		Cuba	Germany
Gambia		Guatemala		Dominican	Iceland
Ghana		Indonesia		Gabon	Ireland
Guinea		Jamaica		Greece	Israel
Haiti		Jordan		Hungary	Italy
Honduras		Maldives		Iran	Japan
Kenya		Moldova		Iraq	Kuwait
Kyrgyzstan		Mongolia		Kazakhstan	Lithuania
Laos		Morocco		Latvia	Luxembourg
Lesotho		Namibia		Lebanon	Malta
Liberia		Nigeria		Libya	Netherlands
Madagascar		Pakistan		Malaysia	New Zealand
Malawi		Paraguay		Mauritius	Norway
Mali		Peru		Mexico	Oman
Mauritania		Philippines		Montenegro	Portugal
Mozambique		Samoa		Panama	Qatar
Myanmar		Sri Lanka		Poland	Saudi Arabia
Nepal		Swaziland		Romania	Singapore
Nicaragua		Tunisia		Russia	Slovakia
Niger		Turkmenistan		Serbia	Slovenia
North Korea		Ukraine		Seychelles	South Korea
Rwanda		Uzbekistan		South Africa	Spain
Sao Tome and Principe		Viet Nam		Suriname	Sweden
Senegal				TFYR Macedonia	Switzerland
Sierra Leone				Thailand	Trinidad and
Somalia				Turkey	United Arab
South Sudan				Uruguay	United Kingdom
Sudan				Venezuela	United States of
Syria					
Tajikistan					
Tanzania					
Togo					
Uganda					
Vanuatu					
Yemen					
Zambia					
Zimbabwe					

Section C

Sustainability interventions for re-connecting humans to nature

Chapter VI

Leverage points for sustainability transformation: a review on interventions in food and energy systems

Christian Dorninger, David J. Abson, Cristina I. Apetrei, Pim Derwort, Christopher D. Ives, Kathleen Klaniecki, David P. M. Lam, Maria Langsenlehner, Maraja Riechers, Nathalie Spittler, Henrik von Wehrden

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Abstract

There is increasing recognition that sustainability science should be solutions orientated and that such solutions will often require transformative change. However, the concrete sustainability interventions are often not clearly communicated, especially when it comes to the transformative change being created. Using food and energy systems as illustrative examples we performed a quantitative systematic review of empirical research addressing sustainability interventions. We use a modified version of Donella Meadows' notion of 'leverage points' – places in complex systems where relatively small changes can lead to potentially transformative systemic changes – to classify different interventions according to their potential for system wide change and sustainability transformation. Our results indicate that the type of interventions studied in the literature are partially driven by research methods and problem framings and that 'deep leverage points' related to changing the system's rules, values and paradigms are rarely addressed. We propose that for initiating system wide transformative change, deep leverage points – the goals of a system, its intent, and rules – need to be addressed more directly. This, in turn, requires an explicit consideration of how scientific approaches shape and constrain our understanding of where we can intervene in complex systems.

Highlights

- Scientific approaches are biased towards specific types of interventions.
- Technological approaches most often focus on rather shallow leverage points.
- Interdisciplinary approaches address deeper, more effective, leverage points.
- System characteristics most often targeted are parameters and information flows.
- Deep system properties are rarely addressed in empirical studies.

Keywords: Energy system; Food system; Leverage points; Sustainability interventions; Sustainability transformation

1. Introduction

In the face of multiple global sustainability crises (Hoekstra and Wiedmann, 2014; Steffen et al., 2018, 2015) there are increasing calls for sustainability transformation (Elmqvist et al., 2019; Kallis and March, 2015; Lucas and Horton, 2019) and increasing recognition that sustainability science needs to shift from a problem to solutions orientation (Komiyama and Takeuchi, 2006; Miller et al., 2014; Washington, 2015). While the sustainability agenda entered the academic and political arena in the 1980s (Clark and Dickson, 2003; Kates, 2015), the transformation towards sustainability remains, seemingly, a distant prospect. Unsolved severe sustainability issues include climate change, biodiversity loss, the exhaustion of non-renewables, and social-ecological and economic inequalities (Dorninger and Hornborg, 2015; FAO, 2019; Pachauri et al., 2014; Torres et al., 2017). One contributing factor to the lack of progress towards sustainability may be the way in which sustainability interventions – defined as deliberate human actions targeting sustainability in a given system of interest – are identified and studied. It has been argued that most scientific attention has been given to 'shallow' interventions that are rather simple to envision, but have a limited potential for triggering systemic change (Abson et al., 2017; Fischer et al., 2007). Such 'shallow' interventions stand in contrast to less tangible interventions, which are the underpinning, ultimate drivers of current trajectories. Yet, such potentially more powerful interventions (Meadows, 1999) that address 'deeper' systems properties, and which are the underpinning, ultimate drivers of current trajectories, are under researched.

In this article we adopt a 'leverage points perspective' to review sustainability interventions in food and energy systems in order to understand which types of interventions are most often in focus and the potential of these interventions to achieve transformative change. We here define 'transformative change' of systems as a radical alteration of systemic interconnections and systems behaviour with fundamentally different sustainability outcomes. A sustainability transformation genuinely disrupts previous pathway dependencies and entails large scale non-linear shifts for more desirable social-ecological system states (Blythe et al., 2018; Hölscher et al., 2018).

In this regard, it has been argued that sustainability related literature is largely focused on symptoms treating of very specific adverse outcomes, but generally fails to address root causes of unsustainable systems behaviour (Ehrenfeld, 2004). We hypothesize that this may, at least in part, be related to (1) the type of system studied and how it is bounded, (2) to the way in which researchers frame sustainability challenges, and (3) the scientific approaches they use to study possible interventions to address the identified problems. We relate the interventions to the problem framing, scientific disciplines, and scientific methods employed in empirical research on sustainability interventions. We also explore if the investigated intervention, and its corresponding leverage point, is proposed to have transformative potential – and if so, which tool or actor is described to possess this potential? Finally, we are interested in the implementation of the intervention: who is the intervener and what is the outcome?

The leverage points concept was introduced by Donella Meadows (1999a) and developed further by Abson et al. (2017). A leverage point is a point of intervention in a system of interest to alter its behaviour, trajectories, and outcomes. Meadows defined a leverage point as "a place in the system where a small change could lead to a large shift in behaviour (2008: 145)." She suggested a hierarchy of 12 intervention points ranging from relatively ineffective intervention points with limited transformational potential to more effective places to intervene which entail higher systemic resistance to changing it (Meadows, 1999). Abson et al. (2017) synthesized Meadows' original 12 leverage points into four broad system characteristics on which sustainability interventions can be focused: systems parameters, systems feedbacks, system design, and system intent. System parameters are understood as a system's mechanistic characters (taxes, standards) and physical structure (buffers, flows). System feedbacks are the interconnections between the elements of the system which steer reinforcing (positive) or dampening (negative) feedback loops. A system's design is made of the structure of information flows, its rules, and power characteristics. Finally, the system intent is concerned with the goal of the system and with the paradigm or mindset out of which it arises (Abson et al., 2017). The four system characteristics are ranked from shallow to deep and each capture three of Meadows' original leverage points (Fig. 1). The leverage points concept provides a conceptual tool and epistemological lens through which diverging sustainability problem framings, derived interventions, and resulting outcomes can be analysed. The scale represents a hierarchy of intervention points for leveraging change in systems (Abson et al., 2017).

Meadows (1999) Places to intervene in a System (in increasing order of effectiveness)	**Abson et al. (2017) System characteristics (nested hierarchy – increasingly constraining order)**
12. Constants, parameters, numbers (such as subsidies, taxes, standards)	
11. The sizes of buffers and other stabilizing stocks, relative to their flows	***parameters***
10. The structure of material stocks and flows (such as transport networks, population age structures)	
9. The lengths of delays, relative to the rate of system change	
8. The strength of negative feedback loops, relative to the impacts they are trying to correct against	***feedback***
7. The gain around driving positive feedback loops	
6. The structure of information flows (who does and does not have access to what kinds of information)	
5. The rules of the system (such as incentives, punishments, constraints)	***design***
4. The power to add, change, evolve, or self-organize system structure	
3. The goals of the system	
2. The mindset or paradigm out of which the system – its goals, structure, rules, delays, parameters – arises	***intent***
1. The power to transcend paradigms	

Fig. 1.: The leverage points 12- and 4- scale. On the left the 12 leverage points by Meadows (1999a) in their hierarchical scale from shallow (top) to deep (bottom), and on the right the synthesized version of Abson et al. (2017) as four broad system characteristics.

We focus on interventions in food and energy systems as two types of social-ecological systems that are crucial for global sustainability (GEA, 2012; Godfray et al., 2010), currently on relatively unsustainable pathways (Dangerman and Schellnhuber, 2013; Lucas and Horton, 2019), and have received substantive research attention in the academic literature (Fig. 8 in the appendix shows the temporal development of studies included in this review). Using two different types of social-ecological systems is intended to shed additional light on how the 'systems of interest' – the subjective delineation of boundaries and characteristics of a system based on the interests and preanalytic assumptions of the researcher (Costanza, 2001; Ison, 2008) — may shape understandings of transformative change. As we are interested in empirically observable interventions in real-world systems that have already been carried out or proposed to be implemented based on empirical observations, we chose to work with sustainability-focused, empirical research only.

2. Method

Our systematic quantitative review follows the guidelines for the "Preferred reporting items for systematic reviews and meta-analyses" (PRISMA) framework as described by Moher et al. (2009). We developed a search string which we applied to academic literature databases to identify potentially relevant articles. We then screened the abstracts according to our inclusion criteria, applied a full-text analysis for final eligibility, and applied a coding scheme to the remaining articles to be included, which finally provided us with a set of variables for statistical analysis (Fig. 2).

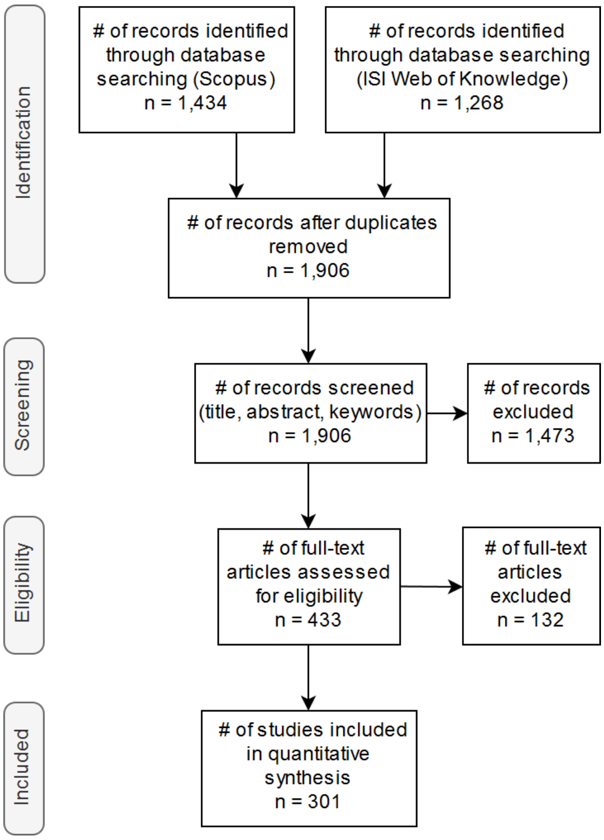

Fig. 2: Systematic case selection process as PRISMA flow diagram (Moher et al., 2009).

On 30 October 2017 we applied our search string (see appendix) to the databases of Scopus (www.scopus.com) and the ISI Web of Science (www.webofknowledge.com). Our search string includes publications from 1990-2017. One single publication was captured by the databases as to be published only in 2018. The search string was restricted to empirical academic English articles that include the term "food system "or "energy system", plus "sustainability" or "sustainable" and a term of 'change' or 'intervention' in their title, abstract or keywords. After removing duplicates the search string yielded in a total result of 1,906 articles.

We screened the title, abstract and keywords of these 1,906 papers based on specific inclusion and exclusion criteria respectively: We specifically looked for empirical papers that research and report on an explicit intervention that targets sustainability change in the respective food or energy system of interest or that formulates possible interventions based on the empirical observation. Thus, the papers to be included had to describe a specific and intentional human intervention targeting sustainability in the system, either analysed or proposed based on the empirical observation. Purely descriptive or evaluative empirical studies without any intervention proposed or described were excluded from the review.

After the abstract, title, and keywords screening, we downloaded 433 papers and once again applied our inclusion and exclusion criteria, this time via a full-text eligibility assessment, resulting in 301 articles included in the review (the full list of included articles is provided in the appendix). The coding scheme used in the systematic review was tested and refined on 12 randomly selected papers before being applied to the 301 review articles. We compared the results of each reviewer to refine the coding scheme and to improve common understandings to ensure the inter-coder-reliability. The latter was additionally secured by continuous and final cross-checking the results between different reviewers for consistency in the application of the coding scheme. We coded for 16 variables – each representing one question that was applied to the reviewed articles – that can be summarized into seven groups of variables:

Table 1

The 16 variables of the coding scheme grouped in seven categories.

1. System	**4. Scientific problem**	**7. Implementation**
1. System (food or energy)	9. Problem framing	15. Primary intervener/executer
2. System aspect	10. Focal issue	16. Outcome of the intervention
3. Spatial scale		
2. Method	**5. Intervention**	
4. Datatype	11. Leverage point 4-scale (Abson et al., 2017)	
5. Analysis		
6. Evaluation	12. Leverage point 12-scale (Meadows, 1999)	
3. Discipline	**6. Transformation**	
7. Principal discipline	13. Transformative potential (yes or no)	
8. Disciplinary approach (single-, inter-, or transdisciplinary)	14. Transformative tool	

Most variables were coded in terms of exhaustive and mutually exclusive categories (variables number 1, 3, 4, 7, 8, 10, 13, 14, 15, and 16). However, for some variables multiple possible categories applied (2, 5, 6, 9, 11, and 12)[1]. For example, the problem framing of a paper could include multiple dimensions (i.e., it could be framed as an economic, technical, and ecological problem). Most importantly, a particular intervention could relate to multiple leverage points (on both the 12 point leverage point scale and the four system characteristics scale) which resulted in multiple possible entries per intervention. Table 3 in the appendix provides details of all variables and categories including how often each variable was coded for in the articles.

After coding we applied mostly descriptive analysis of the resulting variables. Subsequently, we conducted an agglomerative hierarchical cluster analysis (Ward's hierarchical cluster) to identify groups of papers that are similar in regards to their overall scientific approach (i.e., similar in their disciplinary approach, methods, problem framing, focal issue etc.) It is important to note that we excluded the intervention variables (leverage points 12-scale and 4-scale) from the cluster analysis, because we aimed to understand whether certain scientific approaches are significantly related to the type of leverage point associated with the intervention investigated. We used a hierarchical cluster analysis (Ward) with the *hclust* function and the *agnes* function (agglomerative nesting) in R (R Core Team, 2018) to identify groups in our dataset where the cluster criteria follow pairwise distance matrix observations. This approach is suitable for our large dataset to identify groups in the data according to dissimilarity (minimum within-cluster

[1] Note that the allowance of multiple entries also affects the proportions within the variable (compare Fig. 3 below and Table 3 in the appendix), i.e. each entry counts separately and one single paper can have multiple entries which affects the proportion within the variable.

variance). The Ward's hierarchical clustering does not require pre-specified number of clusters (Ward, 1963). To identify which variables characterize the resulting clusters we used the *indval* function of the *labdsv* package in R.

We used the resulting cluster groups and other significant variables to create a flow chart and barplots to analyse the connections of variables to one another (e.g. which problem framing is more or less strongly connected to a specific leverage point). Lastly, we analysed correlations (Chi² tests of independence) between the leverage point(s) and the cluster, problem framing, or stated outcome of the intervention. All analyses were carried out in R (R Core Team, 2018).

3. Results

3.1. Overview

Out of the 301 articles included in this review 129 papers were concerned with food systems and 172 with energy systems (Fig. 3).[2] The system aspects studied were mostly energy generation (23 %), consumption of food or energy (18 %), general system structure (17 %) and the production of food (16 %). Supply and transportation (14 %) as well as emissions (6 %) were studied to a lesser extent. Regarding the spatial scale of the system investigated, we found strong representations of national (31 %), local (26 %), and regional (21 %) studies. Systems on the lab scale (10 %) or on the global scale (6 %) were studied less often (Fig. 3).

Studies used mostly quantitative data (49 %), some qualitative (23 %), and fewer mixed data (21 %). The methods of data analysis were mostly statistics (24 %) and modelling (17 %), but also qualitative (23 %) and content (12 %) analysis. The data were often evaluated via a monitoring of flows (26 %), a technical performance analysis (19 %), with institutional (13 %) and behavioural change (13 %) evaluation, or with a cost-benefit analysis (12 %) (Fig. 3).

The key disciplines for the intervention were (in decreasing order of magnitude): policy (food or energy policy) (30 %), engineering (28 %), social-ecological studies (20 %), sociology (14 %), economics (5 %), and physics and chemistry (4 %). For the disciplinary approach we differed between single disciplinary approach (63 %), interdisciplinary studies (29 %), and transdisciplinary approaches (8 %) (Fig. 3).

[2] A temporal development of publication numbers split by food and energy is included in the appendix (Fig. 8).

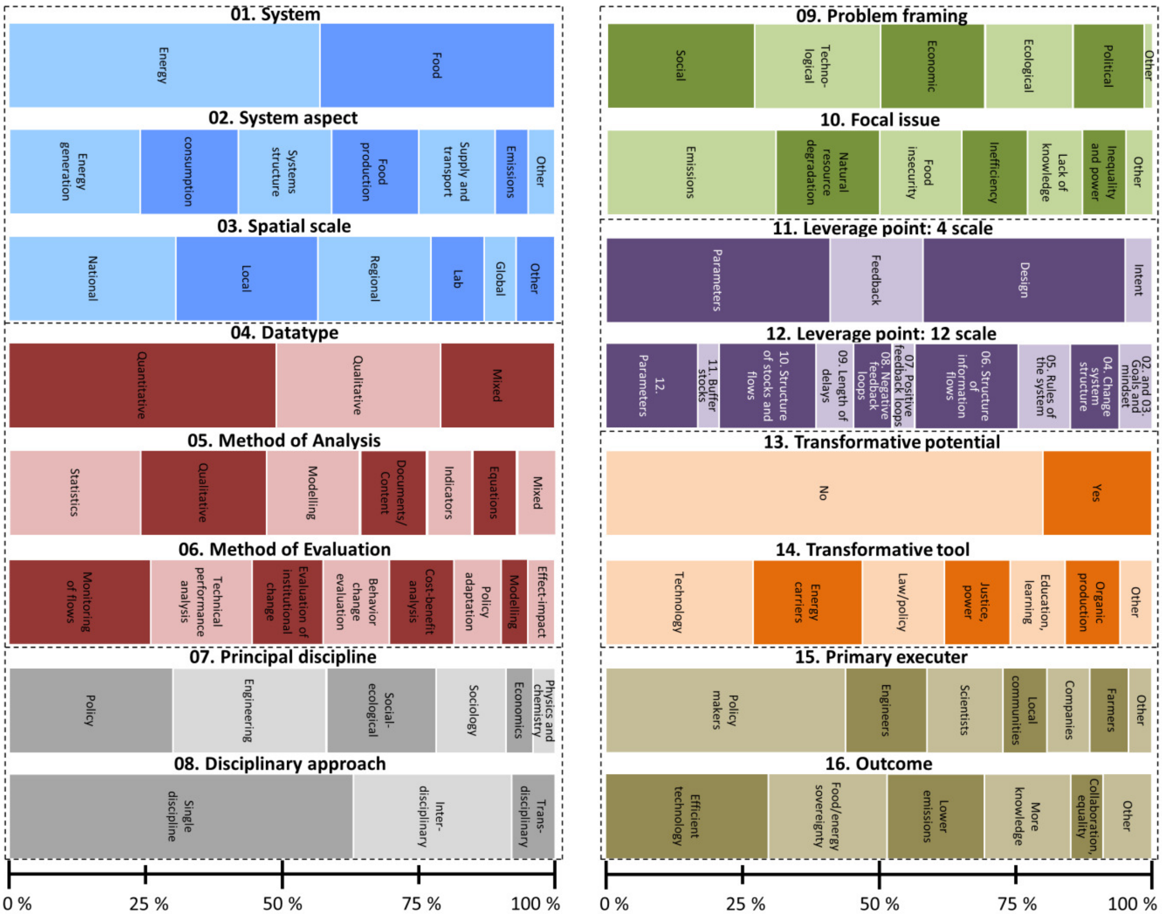

Fig. 3: The proportions of all categories within their variable. Each group of variables is indicated with same shades of colour and with a dotted box. The stacked barplots present the results of both food and energy system papers combined.

The problem framing on the reviewed articles was relatively balanced between social (27 %), technological (23 %), economic (19 %), ecological (16 %), and/or political (13 %) framings. The focal issue was often described as emissions (31 %), followed by natural resource degradation (19 %), food insecurity (15 %) and inefficiency (12 %). The lack of knowledge (10 %) and inequality and power (8 %) were less often focused on.

The application of the leverage point 4-scale (based on Abson et al., 2017), revealed that 41 % of the reviewed papers studied interventions on the system's parameter characteristics, 17 % were concerned with feedbacks, 37 % with the design characterises of the system, and 5 % with the system's intent (note that multiple entries were possible for this variable). The use of the leverage point 12-scale (from Meadows, 1999a) opens up the four system characteristics into more specific intervention points. Note that the proportional divergence compared to the leverage point 4-scale is due to the possibility of multiple classifications in either scale.

The majority of interventions were not explicitly described as to be of transformative character (80 %). Of the remaining fifth, 27 % envision transformation by a new technology, 20 % by new energy carriers, 15 % by new laws and policy, 12 % via justice and power redistribution, 10 % via education and learning, and 10 % by implementing organic production.

The primary interveners were described to be policy makers (44 %), followed by engineers (15 %) and scientists (14 %). 24 % of the interventions were to be undertaken by local communities, cooperatives, and farmers. The outcome of the intervention was described to be either more efficient technology (30

%), food or energy security (22 %), lower emissions (18 %), more knowledge (16 %), more collaboration (6 %) or a shift in norms and paradigms (5 %).

3.2. Clustering scientific approaches

The cluster analysis resulted in four clusters (agglomerative coefficient of 0.87), each representing one scientific approach (Fig. 4). Based on results of the analysis of the defining variables for each cluster group (Table 2) we labelled the clusters accordingly:

1. The 'engineering' cluster (n = 52) was characterized by a focus on energy generation in labs, using mathematical equations and technical performance analysis, by engineering approaches, a technological problem framing around inefficiencies, a transformative potential via new energy carriers, and engineering interventions targeting efficient technology and flows.
2. The 'technocratic' cluster (n = 125) focused on the national energy policy, a political problem framing, a focus on emissions, and policy makers as primary interveners.
3. The 'sociopolitical' cluster (n = 88) featured a focus on local systems, a mixed and qualitative data analysis and evaluation of changed behaviours, with a social problem framing, a focus on food insecurity and health, organic production as proposed to have transformative potential, local communities as primary executers of the intervention, and an envisioned outcome of higher food security.
4. The 'social-ecological' cluster (n = 36) featured a particular focus on global food production, a quantitative analysis of flow indicators, operates from an interdisciplinary social-ecological perspective, applies an ecological problem framing on natural resource degradation, does not explicitly suggest to be of transformative character, and is mostly implemented by spatial and urban planners.

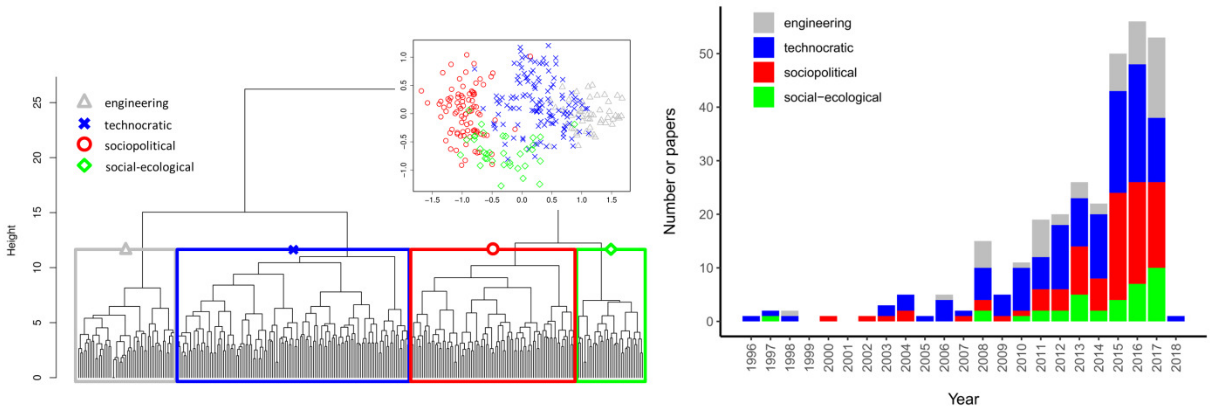

Fig. 4: Results of the cluster analysis visualized in a dendrogram and an ordination (left), and the temporal development of the clusters as in papers included in the review.

The right-hand part of Fig. 4 shows the rapid increase over time in literature addressing sustainability interventions in food and energy systems. While there was some kind of general take off in 2015, it is hard to judge if any specific approach gained more importance than others over time. The proportions of the 4 clusters seem to develop rather proportionally.

Table 2

Results of the cluster analysis and the cluster's determining variables. The value in parenthesis indicates the strength of the coefficient in distinguishing the cluster from others. Note that the variable group on interventions (no. 5 – leverage points) are not included in the cluster analysis. All coefficients are shown, but not more than one for each variable category, only the strongest one. All coefficients shown are significant at p < 0.05.

	Scientific approach			
Variable	Engineering (n=52)	Technocratic (n=125)	Sociopolitical (n=88)	Social-ecological (n=36)
(1) System	Energy (0.51)	-	-	Food (0.49)
System aspect	Energy generation (0.38)	-	-	Food production (0.30)
Spatial scale	Lab (0.44)	National (0.22)	Local (0.19)	Global (0.09)
(2) Methods				
Datatype	-	-	Mixed (0.30)	Quantitative (0.37)
Analysis	Mathematical equations (0.20)	-	Qualitative analysis (0.29)	Indicators (0.12)
Evaluation	Technical performance analysis (0.25)	-	Behaviour change evaluation (0.09)	Monitoring of flows (0.24)
(3) Discipline				
Principal discipline	Engineering (0.40)	Policy energy (0.37)	Sociology (0.26)	Social-ecological (0.34)
Disciplinary approach	Single disciplinary approach (0.36)	-	Transdisciplinary (0.11)	Interdisciplinary (0.25)
(4) Scientific Problem				
Problem framing	Technological (0.57)	Political (0.12)	Social (0.34)	Ecological (0.26)
Focal issue	Inefficiency (0.26)	Emissions (0.26)	Food insecurity and health (0.24)	Natural degradation (0.25)
(6) Transformation				
Transformative potential	Energy carriers (0.08)	-	Organic production (0.07)	No (0.29)
(7) Implementation				
Primary executers	Engineers (0.65)	Policy makers (0.27)	Local communities (0.14)	Urban/spatial planners (0.07)
Outcome	Efficient technology and flows (0.33)	-	Food security (0.29)	-

3.3. Connectivity within scientific approaches

We used a Sankey diagram (Fig. 5) to illustrate the connections between the different variable categories, including the modelled variable of the 'scientific approach'. Technocratic and engineering approaches almost exclusively prevailed in the scientific literature on energy systems. The literature on food systems were mostly based on a social-ecological or sociopolitical approach.

The scientific approaches were strongly related to the problem framing. Engineering approaches implied either an economic or technological problem framing. The technocratic approach was relatively evenly spread among the entire possible problem framing categories. Sociopolitical approaches had a strong tendency framing their research problem as social, political, or economic. And the social-ecological studies most often came with an ecological, social, or economic problem framing.

The interventions concerned with system parameters (leverage points 10-12) often had a technological or economic problem framing. The feedback system characteristics (leverage points 7-9) were frequently related to social or technological problem framings. The design related interventions (leverage points 4-6) were primarily rooted in an ecological, social, or political problem framing. And lastly, the deepest, intent related, system characteristics (Leverage points 1-3) were rarely addressed, but evolved out of multiple problem framings.

The four outcomes most often ascribed to the single interventions (in decreasing order) were efficient technology and flows, food and energy security, more knowledge, and lower emissions and environmental protection. Deeper system properties, like norms and equality, were less often targeted by the interventions. The self-attribution of transformative potential was relatively evenly distributed among the possible intervention outcomes. Nevertheless, the majority of cases do not explicitly link their research to sustainability transformation.

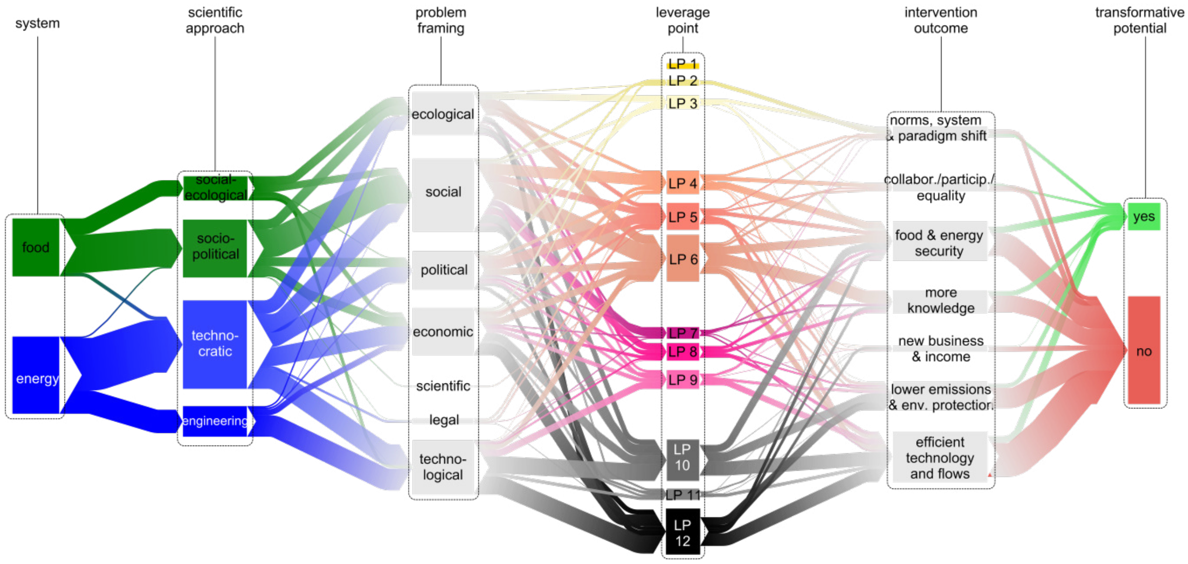

Fig. 5: Sankey diagram showing connections between variables and categories. Colours were selected for ease of visualization. Due to the multiple possible categories in the variables 'problem framing' and 'leverage point', there is an imbalance in in- and outflows for various variable categories.

3.4. The leverage potential of interventions

In the following, we relate the scientific approach, problem framing and outcome to the 'depth' of intervention (i.e. which system characteristics were being intervened in, see Fig. 6). The engineering approach largely targeted system parameters. The technocratic approach very rarely involved interventions on system intent, but addressed parameter, feedback, and design type of interventions in relatively equal proportions. In contrast, the sociopolitical approach features a noticeable focus on system intent and system design. The social-ecological approach exhibited the most balanced proportion of system interventions, including the most pronounced focus on system feedbacks and a considerable share of interventions challenging the intent of the system (Fig. 6).

Our analysis showed that the leverage points approached varied according to the problem framing applied. While the framing of a sustainability problem as a social, ecological, political or economic problem results in a relatively larger share of system intent and system design related interventions, the technological problem framing yielded mostly interventions targeting the system parameters. An economic, ecological, or political problem framing involves similar leverage points as the social problem framing, with partially stronger emphases on system parameter interventions.

With regards to the interventions' proposed (or observed) outcomes, efficient technology, lower emissions, and new business and income largely stemmed from interventions on the system's parameter level. Interventions concerned with feedbacks, design, or the system intent much less often resulted in efficient technology, lower emissions or new business and income. For outcomes related to norms and paradigm shift more than half of the interventions targeted system intent. Outcomes that resulted in more collaboration and equality were largely related to interventions in system design (system goals, rules, flow of information).

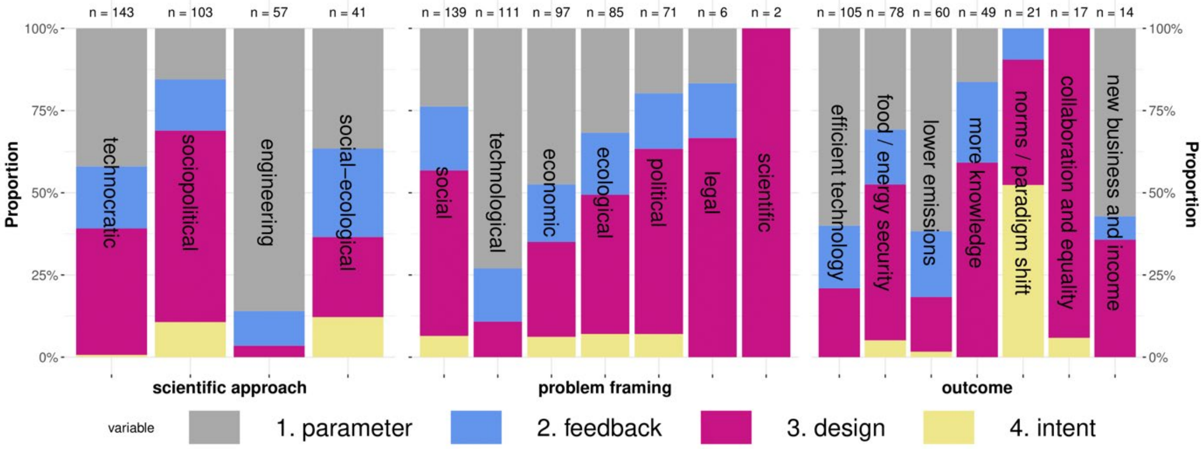

Fig. 6: Stacked bar plots showing the distribution of leverage points within variable categories. The categories of three variables (scientific approach, problem framing, and outcome) are contrasted with the associated system characteristics being intervened on (parameters, feedback, design and intent).

For each Chi² test (scientific approach vs. leverage point; problem framing vs. leverage point; outcome vs. leverage point) we found a highly significant relation ($p < 0.01$) indicating statistical non-independence (see Fig. 7 below and Table 4Table 5 and Table 6 in the appendix and for detailed results of the tests, including the observed, expected, and residual values). Fig. 7 reveals that sociopolitical approaches had a significantly stronger than average focus on deeper leverage points (design and intent interventions) but miss parameter type of interventions. System parameters were much more abundant in the engineering approach. In comparison to the total average over all four approaches, the social-ecological approach lacks design type of interventions but is overrepresented regarding interventions on system feedback and system intent. Technological problem framings are more abundant in shallow leverage points, i.e. parameters, and significantly less abundant in applying deeper leverage points (design and intent). Social and political problem framings involve an emphasis on design and intent characteristics of a system, but lack parameter type of interventions.

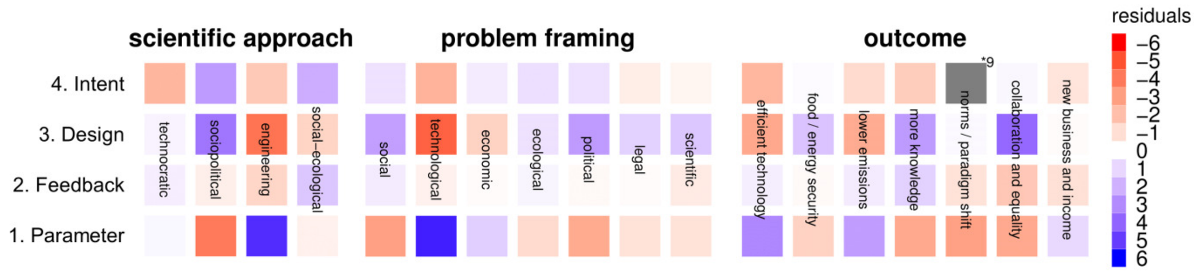

Fig. 7: Coloured rectangles representing the residuals of Chi² tests. Red rectangles indicate negative residuals (underrepresentation) and blue rectangles positive residual values (overrepresentation) compared to the average.

4. Discussion

There is a wide variety of different research investigating interventions that target sustainability in food and energy systems, ranging from qualitative in-depth interview studies on the personal values of individual actors (e.g., Lautenschlager and Smith, 2007) to quantitative assessments of the steel industry to reduce GHG emissions with hydrogen as an auxiliary reducing agent in the blast furnace (e.g., Yilmaz et al., 2017). A leverage points lens provides a common heuristic framework for classifying these diverse interventions in relation to the broad system characteristics that the interventions address.

Within the empirical literature on sustainability interventions in food and energy issues, there was a strong focus on intervening in the more tangible and relatively easy to conceive system parameters (taxes, incentives, flows of physical inputs etc.) – with a similar level of focus on intervening in the system design (structure of information flows, rules, power structures etc.) that shape the management of these institutions. However, the largest fraction of design type of interventions stemmed from new forms of knowledge production (coded as leverage points 6: structure of information flows) – which is an almost natural response of science to suggest the creation of more knowledge. However, sustainability transformation requires not only more knowledge but different values (Chan et al., 2016; Horcea-Milcu et al., 2019; Kohler et al., 2019). Yet, there was considerably less emphasis on interventions related to shortening or strengthening feedback loops within these systems, like the reconnection of human activities to natural cycles (Dorninger et al., 2017; Ives et al., 2018), and even less focus on attempts to intervene in the underpinning values, worldviews and paradigms that ultimately shape those systems (see Fig. 3). This despite the fact that, particularly for a normative research agenda like sustainability (Schmieg et al., 2018), the intent characteristics of a system, i.e. the goal of the system and the paradigm out of which a system arises, are of crucial importance (Fischer and Riechers, 2019; Gladkykh et al., 2018).

This gap in the literature matters because the four broad system characteristics can be considered as hierarchically nested and constraining (Abson et al., 2017). In other words, the system intent (the goal to which the system is oriented) shapes the physical and institutional design of the system, which in turn determines the feedback that the system provides regarding (un)sustainable functioning and therefore the type of parameter that can, or should be, adjusted to shift systems towards sustainability.

This is in no way to suggest that addressing interventions seeking to alter system parameters is not valuable. Indeed, parameter focused interventions may be vital in terms of concrete changes in system sustainability. Research investigating the parameters of a system and the concrete sustainability outcomes in terms of emissions, biodiversity indices, measures of inequality etc., are extremely valuable and, in fact, indispensable for sustainability informed policies. However, we would argue that the scope of changes to such parameters by actors through processes from within the system is constrained by 'deeper' system characteristics. Therefore, attempts to close the 'sustainability gap' – the discrepancy between sustainability targets and ability of current interventions to generate transformative change (Fischer et al., 2007) — may require changes in system intent and design for radical changes in system parameters to be enabled. This sustainability gap is also highlighted by the small number of articles which identified the interventions they studied as transformative (Fig. 5).

Similarly, sociopolitical approaches concerned with system norms and paradigms would benefit from bridging the gap to changing system parameters. For example, how does a paradigm shift play out in terms of sustainability outcomes, given that not all changes in norms and values necessarily result in favourable sustainability outcomes (see for example the environmental awareness – action gap: Kollmuss and Agyeman, 2002; O'Brien, 2013)?

A focus on neglected system feedbacks in relation to transformative change, particularly in the context of complex social-ecological systems (Lambin and Meyfroidt, 2010), may be crucial in motivating transformative change, by shortening or strengthening feedbacks between behaviour and impacts (Dorninger et al., 2017; Sundkvist et al., 2005).

In addition to a need for more focus on system feedbacks and system intent, our results suggest that there is a need for greater emphasis on the interactions between interventions on different system characteristics. We find that different scientific approaches tend to focus on specific system characteristics (for example, the field of engineering approaches on parameters and sociopolitical approaches on system design). This is perhaps unsurprising given the traditional expertise and focus of different scientific approaches, but does highlight the need for genuinely interdisciplinary approaches in sustainability science (Bammer, 2013). The lack of overlap between the four broad scientific approaches (engineering, technocratic, social-ecological and sociopolitical) used to study sustainability interventions in food and energy systems (Fig. 4) can be problematic, for several reasons. Firstly, it limits opportunities for studying interactions between interventions at different leverage points (Abson et al., 2017; Meadows, 1999). Secondly, it potentially leads to policy incoherence (Grabel, 2011; Peters and Savoie, 1996) due to the siloed expertise associated with interventions into different system characteristics that are, in practice, tightly interdependent. Sustainability science would greatly benefit from not only interdisciplinary work, but work that integrates expertise and foci on both ends of the leverage points scale.

Moreover, we find there is a clear and significant tendency to favour specific intervention points depending on the problem framing. The difference is especially pronounced between social and technological problem framings. While we have acknowledged possible multiple problem framings for each reviewed case, i.e. a paper could have a social and technological problem framing combined, the relation to the leverage points was still significantly dependent on the problem framing. What is identified as sustainability problem will influence the range of possible interventions a study will address. The leverage points scale can be used as a conceptual tool to explore how problem framing constrains or enables the investigation or identification of interventions for changing a system's behaviour based on the 'depth' of the intervention.

In terms of individual leverage points, there was a large proportion of interventions around leverage point 6 (the structure of information flows). As the proposition of new models and methods to gain better and more knowledge about a system was coded as an intervention in the structure of information flows (leverage point 6), we reason that this strong emphasis on information flow is almost a natural bias in science. As academic research is very self-reflective and focused on the production of new knowledge the gravitation towards this leverage point is no coincidence. It is likely that scientists focus on the idea that knowledge needs to be shared and that we need greater understandings of systems, how systems work, and how we can do better research.

To this end, when thinking about leverage points and sustainability transformation, there is a need to reflect on the role of academic science in relation to such kind of change. There is an increasing call for sciences directly informing policy making via science-policy interfaces (Hinkel, 2011; Perrings et al., 2011), but also via stakeholder-involving transdisciplinary research (Brandt et al., 2013; Lang et al., 2012). Nonetheless, before aiming to directly influence policy making for sustainability, it will be of importance to change discourses within academic debates towards the embracement of systemic interconnections and complex systems behaviour, deep constraining system properties, and system wide change (Fischer and Riechers, 2019). The leverage points concept provides a potentially useful heuristic tool to rethink transformative research by considering the 'opportunity space' afforded by scientific approaches to studying sustainability interventions.

We do not suggest that sustainability transformation is an end in itself or that it is an inevitable apolitical process (Blythe et al., 2018). One relevant area that this paper does not touch on is who is doing (or is proposed to do) the intervening for transformation. This opens up some challenging normative and ethical questions regarding transformation. While we do not have space to go into this here, it is certainly an important an area for future research.

5. Conclusion

Sustainability research that addresses interventions in complex systems needs to better understand interconnections, and feedbacks between different system characteristics. Adopting a leverage points perspective on sustainability interventions implies taking a systems perspective on how transformation might happen, where structural or ideological system properties constrain one another. System transformation can be triggered via a broad range of possible interventions, at various places in the system (i.e. the 12 leverage points, Meadows, 1999a), all of which have their own contribution to make. However, our findings suggest that empirical studies on interventions at deep leverage points are scarce and that research approaches encompassing both deep and shallow leverage points are largely missing.

If the academic research community aims to play an important role in initiating system wide transformative change, deep leverage points – the goals of a system, its intent, and rules – need to be addressed much more directly. For this, scientific discourses will have to change, hence we suggest the need to shift from disciplinary focus on optimization of (sub)systems of interest, to interdisciplinary approaches spanning systems parameters, feedbacks, design, and intent.

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Appendix

Appendix A. Search string

Scopus:

TITLE-ABS-KEY ("food* system*" OR "energy* system*") AND TITLE-ABS-KEY(*sustain*) AND TITLE-ABS-KEY(lever* OR intervention* OR systemic OR change* OR transform* OR transition* OR shift* OR innovation*) AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"ip")) AND (LIMIT-TO(LANGUAGE,"English")) AND (LIMIT-TO(PUBYEAR,2017) OR LIMIT-TO(PUBYEAR,2016) OR LIMIT-TO(PUBYEAR,2015) OR LIMIT-TO(PUBYEAR,2014) OR LIMIT-TO(PUBYEAR,2013) OR LIMIT-TO(PUBYEAR,2012) OR LIMIT-TO(PUBYEAR,2011) OR LIMIT-TO(PUBYEAR,2010) OR LIMIT-TO(PUBYEAR,2009) OR LIMIT-TO(PUBYEAR,2008) OR LIMIT-TO(PUBYEAR,2007) OR LIMIT-TO(PUBYEAR,2006) OR LIMIT-TO(PUBYEAR,2005) OR LIMIT-TO(PUBYEAR,2004) OR LIMIT-TO(PUBYEAR,2003) OR LIMIT-TO(PUBYEAR,2002) OR LIMIT-TO(PUBYEAR,2001) OR LIMIT-TO(PUBYEAR,2000) OR LIMIT-TO(PUBYEAR,1999) OR LIMIT-TO(PUBYEAR,1998) OR LIMIT-TO(PUBYEAR,1997) OR LIMIT-TO(PUBYEAR,1996) OR LIMIT-TO(PUBYEAR,1995) OR LIMIT-TO(PUBYEAR,1994) OR LIMIT-TO(PUBYEAR,1993) OR LIMIT-TO(PUBYEAR,1992) OR LIMIT-TO(PUBYEAR,1991) OR LIMIT-TO(PUBYEAR,1990))

Results = 1.489

ISI web of knowledge:

((TS=(("food system*" OR "energ* system*") AND (*sustain*) AND (lever* OR intervention* OR systemic OR change* OR transform* OR transition* OR shift* OR innovation*))))

AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article OR Book Chapter)

Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan=1990-2017

Results = 1.276

Appendix B. Coding results

Table 3

Results of the coding scheme application to the 301 reviewed papers in total and percentage values.

	variable	*n*	*%*	*variable*	*n*	*%*	*variable*	*n*	*%*
(1) System	**System**	301	100	**System aspect**	432	100	**Spatial scale**	301	100
	Energy	172	57	Energy generation	100	23	National	94	31
	Food	129	43	Consumption	77	18	Local	77	26
				Systems structure	73	17	Regional	62	21
				Food production	71	16	Lab	31	10
				Supply and transport	61	14	Global	17	6
				Emissions	27	6	International	15	5
				Storage	13	3	No scale	5	2
				Recycling, disposal	10	2			
(2) Method	**Datatype**	301	100	**Analysis**	323	100	**Evaluation**	175	100
	Quantitative	148	49	Statistics	79	24	Flow monitoring	46	26
	Qualitative	91	30	Qualitative	73	23	Technical performance	33	19
	Mixed	62	21	Modelling	56	17	Institutional change	22	13
				Documents/Content	39	12	Behaviour change	22	13
				Indicators	27	8	Cost-benefit	21	12
				Equations	26	8	Policy adaptation	15	9
				Mixed	23	7	Modelling	8	5
							Effect-impact	8	5
(3) Discipline	**Principal discipline**	301	100	**Disciplinary approach**	301	100			
	Policy	89	30	Single discipline	191	63			
	Engineering	83	28	Interdisciplinary	87	29			
	Social-ecological	60	20	Transdisciplinary	23	8			
	Sociology	41	14						
	Economics	15	5						
	Physics and chemistry	13	4						
(4) Scientific problem	**Problem framing**	448	100	**Focal issue**	301	100			
	Social	121	27	Emissions	93	31			
	Technological	102	23	Natural degradation	57	19			
	Economic	85	19	Food insecurity	46	15			
	Ecological	73	16	Inefficiency	35	12			
	Political	59	13	Lack of knowledge	31	10			
	Legal	6	1	Inequality and power	24	8			
	Scientific	2	0	Energy insecurity	14	5			
				Animal welfare	1	0			
(5) Intervention	**LP 4 scale**	344	100	**LP 12 scale**				378	100
	Parameter	140	41	12. Parameters				65	17
	Feedback	60	17	11. Buffer stocks				14	4
	Design	127	37	10. Structure of stocks and flows				68	18
	Intent	17	5	09. Length of delays				26	7
				08. Negative feedback loops				26	7
				07. Positive feedback loops				14	4
				06. Structure of information flows				70	19
				05. Rules of the system				38	10
				04. Change system structure				35	9
				03. Goals of the system				14	4
				02. Underlying system mindset				8	2
				01. Transcend paradigms				0	0
(6) Trans-formation	**Transformative potential**	301	100	**Transformation by**	60	100			
	No	240	80	Technology	16	27			
	Yes	61	20	Energy carriers	12	20			
				Law/policy	9	15			
				Justice, power	7	12			
				Education, learning	6	10			
				Organic production	6	10			
				Collaboration	2	3			
				Food sovereignty	2	3			
(7) Implemen-tation	**Primary executers**	301	100	**Outcome**				301	100
	Policy makers	131	44	Efficient technology				90	30
	Engineers	46	15	Food/energy sovereignty				65	22
	Scientists	42	14	Lower emissions				54	18
	Local communities	25	8	More knowledge				47	16
	Companies	24	8	Collaboration, equality				17	6
	Farmers	23	8	Norms and paradigm shift				16	5
	Spatial planners	5	2	New business				12	4
	Consumers	3	1						
	Teacher	2	1						

Appendix C. Temporal development of food system and energy system papers.

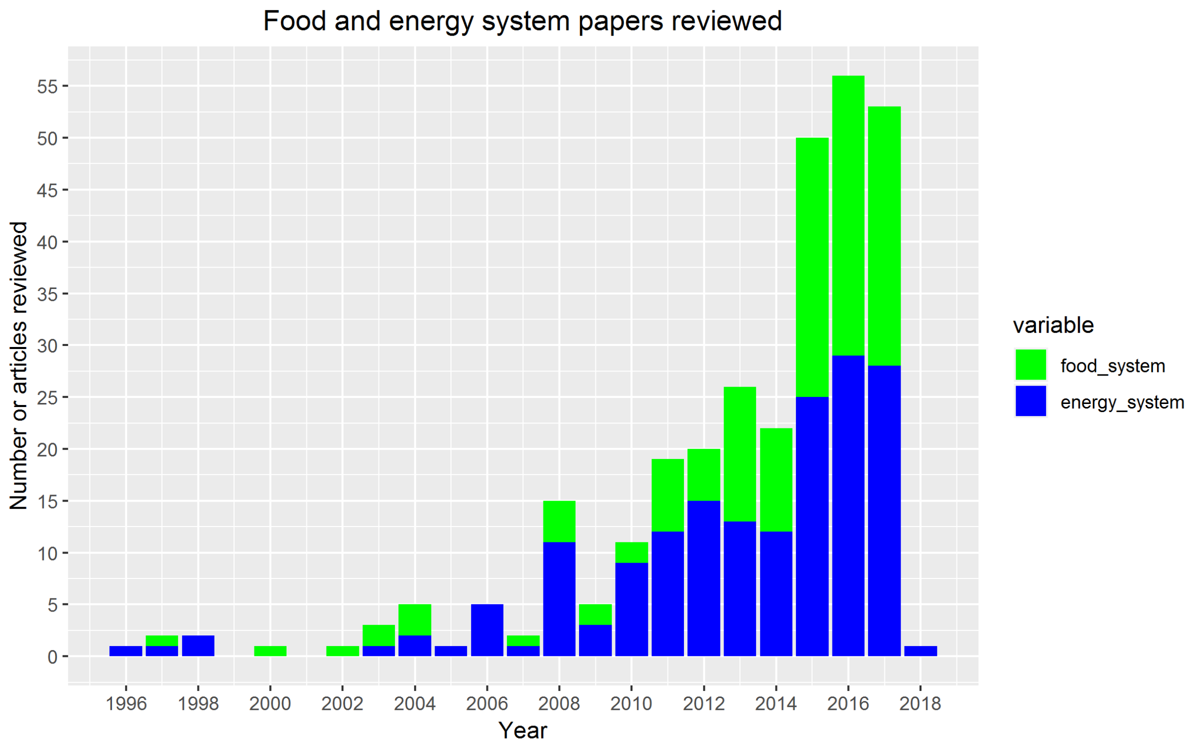

Fig. 8: Temporal development of food system and energy system papers captured in the review (1996-2018).

Appendix D. Chi²-tests results

Table 4

Results of a Pearson's Chi-squared test of the variables: 'Scientific approach' and 'Leverage points 4-scale'. P-value < 2.2e-16. Expected and residual values are rounded.

Scientific approach vs. leverage points				
Observed values	Engineering	Technocratic	Sociopolitical	Social-ecological
1. Parameter	49	60	16	15
2. Feedback	6	27	16	11
3. Design	2	55	60	10
4. Intent	0	1	11	5
Expected values	Engineering	Technocratic	Sociopolitical	Social-ecological
1. Parameter	23	58	42	17
2. Feedback	10	25	18	7
3. Design	21	53	38	15
4. Intent	3	7	5	2
Residual values	Engineering	Technocratic	Sociopolitical	Social-ecological
5. Parameter	5	0	-4	-0
1. Feedback	-1	0	-0	1
2. Design	-4	0	4	-1
3. Intent	-2	-2	3	2

Table 5

Results of a Pearson's Chi-squared test of the variables: 'Problem framing' and 'Leverage points 4-scale'. P-value = 2.0432e-13. Expected and residual values are rounded.

Problem framing vs. leverage points							
Observed values	Technological	Social	Ecological	Economic	Political	Legal	Scientific
5. Parameter	81	33	27	46	14	1	0
6. Feedback	18	27	16	17	12	1	0
7. Design	12	70	36	28	40	4	2
8. Intent	0	9	6	6	5	0	0
Expected values	Technological	Social	Ecological	Economic	Political	Legal	Scientific
6. Parameter	44	55	34	38	28	2	1
7. Feedback	20	25	15	17	12	1	0
8. Design	42	52	32	36	27	2	1
9. Intent	6	7	4	5	4	0	0
Residual values	Technological	Social	Ecological	Economic	Political	Legal	Scientific
10. Parameter	6	-3	-1	1	-3	-1	-1
4. Feedback	-0	0	0	-0	-0	-0	-1
5. Design	-5	2	1	-1	3	1	1
6. Intent	-2	1	1	0	1	-1	-0

Table 6

Results of a Pearson's Chi-squared test of the variables: 'Outcome' and 'Leverage points 4-scale'. P-value < 2.2e-16. Expected and residual values are rounded.

Outcome vs. leverage points							
Observed values	Collaboration, participation, equality	Efficient technology and flows	Food or energy security	Lower emissions and environmental protection	More knowledge	New business and income	Norms, system or paradigm shift
1. Parameter	0	63	24	37	8	8	0
2. Feedback	0	20	13	12	12	1	2
3. Design	16	22	37	10	29	5	8
4. Intent	1	0	4	1	0	0	11
Expected values	Collaboration, participation, equality	Efficient technology and flows	Food or energy security	Lower emissions and environmental protection	More knowledge	New business and income	Norms, system or paradigm shift
1. Parameter	7	43	32	24	20	6	9
2. Feedback	3	18	14	10	9	2	4
3. Design	6	39	29	22	18	5	8
4. Intent	1	5	4	3	2	1	1
Residual values	Collaboration, participation, equality	Efficient technology and flows	Food or energy security	Lower emissions and environmental protection	More knowledge	New business and income	Norms, system or paradigm shift
1. Parameter	-3	3	-1	3	-3	1	-3
2. Feedback	-2	0	-0	0	1	-1	-1
3. Design	4	-3	2	-3	3	-0	0
4. Intent	0	-2	0	-1	-2	-1	10

Chapter VII

Reconnecting with nature for sustainability

Christopher D. Ives, David J. Abson, Henrik von Wehrden, Christian Dorninger, Kathleen Klaniecki, Joern Fischer

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Abstract

Calls for humanity to 'reconnect to nature' have grown increasingly louder from both scholars and civil society. Yet, there is relatively little coherence about what reconnecting to nature means, why it should happen and how it can be achieved. We present a conceptual framework to organise existing literature and direct future research on human–nature connections. Five types of connections to nature are identified: material, experiential, cognitive, emotional, and philosophical. These various types have been presented as causes, consequences, or treatments of social and environmental problems. From this conceptual base, we discuss how reconnecting people with nature can function as a treatment for the global environmental crisis. Adopting a social–ecological systems perspective, we draw upon the emerging concept of 'leverage points'—places in complex systems to intervene to generate change—and explore examples of how actions to reconnect people with nature can help transform society towards sustainability.

Keywords: Human–nature relationship, Social–ecological systems, Sustainability, Transformation

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ORIGINAL ARTICLE

Reconnecting with nature for sustainability

Christopher D. Ives[1,2] · David J. Abson[2] · Henrik von Wehrden[2] · Christian Dorninger[2] · Kathleen Klaniecki[2] · Joern Fischer[2]

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Abstract

Calls for humanity to 'reconnect to nature' have grown increasingly louder from both scholars and civil society. Yet, there is relatively little coherence about what reconnecting to nature means, why it should happen and how it can be achieved. We present a conceptual framework to organise existing literature and direct future research on human–nature connections. Five types of connections to nature are identified: material, experiential, cognitive, emotional, and philosophical. These various types have been presented as causes, consequences, or treatments of social and environmental problems. From this conceptual base, we discuss how reconnecting people with nature can function as a treatment for the global environmental crisis. Adopting a social–ecological systems perspective, we draw upon the emerging concept of 'leverage points'—places in complex systems to intervene to generate change—and explore examples of how actions to reconnect people with nature can help transform society towards sustainability.

Keywords Human–nature relationship · Social–ecological systems · Sustainability · Transformation

Introduction

Humanity's relationship to the natural world has been a topic of scholarship since ancient times, yet with growing recognition of environmental crises over the past decades, society's disconnection from nature has been proposed as a root cause of unsustainability (e.g., Pyle 1993; Folke et al. 2011; Dorninger et al. 2017). Recently, calls for society to 'reconnect with nature' have grown louder (Zylstra et al. 2014), with new research emerging in sustainability science, conservation biology, environmental psychology, and environmental education (Nisbet et al. 2009; Folke et al. 2011; Fischer et al. 2012a; Frantz and Mayer 2014). Yet, most calls for 'reconnection' have remained speculative and vague, with relatively few concrete insights regarding the characteristics of a connected society or how to achieve this goal. The literature is fragmented across disciplinary boundaries, resulting in low coherence in the ways central concepts are understood and applied (Ives et al. 2017). For example, there is confusion around the concept of connection to nature and whether a state of disconnection is a response to or a driver of social–ecological change, or both. On this basis, it is timely to assess together the disparate strands of scholarship to scrutinise if pursuing an agenda of reconnecting people with nature is worthwhile, and if so, how this aim ought to be pursued.

In this article, we lay a conceptual platform to better understand human–nature connectedness. First, we argue that human–nature connectedness is a multifaceted concept incorporating (1) material connections such as resource extraction and use; (2) experiential connections such as recreational activities in green environments; (3) cognitive connections such as knowledge, beliefs and attitudes; (4) emotional attachments and affective responses; and (5) philosophical perspectives on humanity's relationship to the natural world. Second, we show that existing literature frames connection to nature as either the cause of some outcome (such as human health or environmentally-responsible behaviour), the consequence of some driver (such as shifting societal values or technological change), or the treatment for social or environmental problems. Finally, having laid

Handled by Carolyn Lundquist, University of Auckland, New Zealand.

✉ Christopher D. Ives
chris.ives@nottingham.ac.uk

1 School of Geography, University of Nottingham, University Park, Nottingham NG7 2RD, UK

2 Faculty of Sustainability, Leuphana University Lüneburg, Universitätsallee 1, 21335 Lüneburg, Germany

this conceptual platform, we outline ways in which people's connections with nature can be strengthened. We argue that stronger connections—in several of the above-mentioned dimensions—have potential to help leverage deep societal change for sustainability (Meadows 1999; see; Abson et al. 2017). In particular, we discuss the need for 'reconnection strategies' that work to change not only the behaviour of individuals, but also address the systemic structures and paradigms that underpin the actions and behaviours contributing to the current global environmental crisis.

Conceptualising human–nature connections

Many terms related to connections to nature have arisen from various disciplinary schools and normative agendas. One of the earliest concepts is the "biophilia hypothesis" (Wilson 1984), which asserts that humans have an innate desire to connect with nature. The biophilia paradigm underpins much scholarly and practical work to promote interactions with green environments (Kahn and Kellert 2002). "Nature deficit disorder" is a related, more recent concept, which sees children's reduced contact with outdoor environments as having negative results for their development (Louv 2005). Similarly, "extinction of experience" (Pyle 1993; Soga and Gaston 2016) refers to the phenomenon of urbanisation reducing everyday nature experiences, with implications for health, emotions, attitudes, and behaviour.

From a global sustainability perspective, phrases such as "reconnecting to the biosphere" (Folke et al. 2011), "teleconnections" between local consumption and global land use (Yu et al. 2013) or "telecoupling" of socioeconomic and environmental systems over geographic distance (Liu et al. 2013) are used to emphasise the dependence of human society on natural systems and processes. The literature from a social–ecological systems perspective calls for "recoupling social and ecological systems" (Fischer et al. 2012b) to foster sustainability. Other literature has introduced the term "distance from nature". Seppelt and Cumming (2016) suggest that humanity must decrease its distance from the natural world in terms of knowledge of contact with nature while increasing 'distance' in the sense of direct impacts of human activities on ecosystems to maintain the earth's life support system.

Similarly, environmental psychologists have amassed a voluminous literature on the concept of "connectedness to nature", addressing the cognitive and affective domains of individuals' psyches (see Restall and Conrad 2015 for a review). Key literature from this perspective includes Wesley Schultz' (2001) work on the notion of "inclusion of nature in self, Mayer and Frantz's (2004) "Connectedness to Nature Scale", and Nisbet's (2009) work on individual "nature relatedness". These measures typically consider emotional connections, beliefs, and attitudes, and often correlate with other psychological constructs such as value orientations and pro-environmental behaviour (Tam 2013).

The current diversity of approaches to conceptualising and measuring connections with nature has led to a fragmentation of the literature. This is partly due to the term 'connection' being applied to qualitatively different concepts. In some instances, connection to nature refers to a cognitive appreciation of being embedded within nature, in others to an emotional attachment, while still others focus on material dependence on nature. Although this diversity of meanings is being addressed by psychologists through ever more expansive psychometric scales of nature connectedness (e.g., Nisbet et al. 2009), these remain focused on the individual scale and cannot integrate society-scale phenomena of connection or disconnection.

In their recent review, Ives et al. (2017) called for more integrated research on human–nature connectedness. To facilitate this and to clarify why and how to reconnect people with nature, we develop our discussion around the five categories of nature connections Ives et al. (2017) proposed: (1) material, (2) experiential, (3) cognitive, (4) emotional, and (5) philosophical connections (Fig. 1.). These can be considered to operate along a spectrum from external connections to nature (e.g., physical appropriation or interaction) through to internal connections to nature (e.g., emotions or worldviews). An additional dimension to consider is the scale at which these connections operate and can be analysed: some connections are understood primarily at the individual scale, while others can be readily aggregated to the societal scale. Descriptions of these dimensions of nature connections are provided in Table 1.

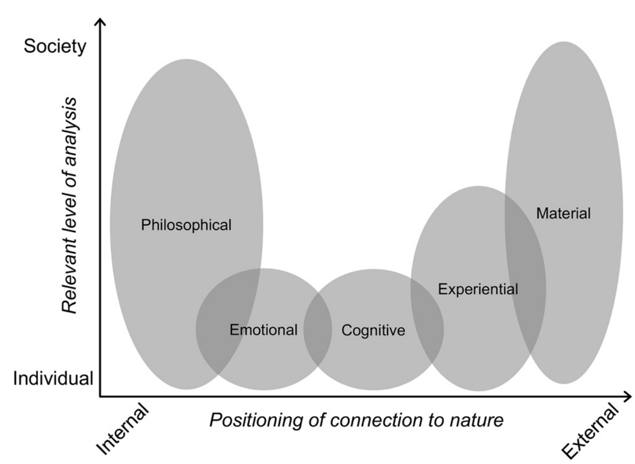

Fig. 1 Conceptualisation of different types of human–nature connections, along a spectrum from people's inner to outer worlds (*x*-axis), and their relevance at different scales of social aggregation (*y*-axis). While presented as independent categories here in this figure, in reality, each type of human–nature connection may interact with the others

Table 1 Descriptions of different types of nature connection

Connection	Description	Analytical scale	Key literature
Material	Consumption of goods/materials from nature (e.g., food, fibre)	Can be analysed for individuals or societies. Often connected to system characteristics. Needs to be spatially explicit (e.g., material flows within or between focal landscapes)	Material flow analysis (Haberl et al. 2004) Human Appropriation of Net Primary Productivity (HANPP) (Haberl et al. 2009) Teleconnections (Yu et al. 2013) Ecological Footprint (Wackernagel et al. 1999)
Experiential	Direct interaction with natural environments (e.g., parks, forests). Note that qualities of connections may vary substantially	Normally measured for individuals, but can be aggregated to the societal scale	Soga and Gaston (2016) Keniger et al. (2013)
Cognitive	Knowledge or awareness of the environment and attitudes/values towards nature	Individual	Bradley et al. (1999) Schultz (2001)
Emotional	Feelings of attachment to or empathy towards nature	Individual	Emotional affinity towards nature scale (Kals et al. 1999) Place attachment to natural areas (Stedman 2003)
Philosophical	Perspective or world view on what nature is, why it matters, and how humans ought to interact with it (e.g., master, participant, steward)	Relevant to individuals, as well as to dominant views at the societal scale	Van den Born (2008) Raymond et al. (2013)

These various dimensions of connection to nature do not operate in isolation—in reality, they interact with and are influenced by one another. For example, physical interactions with natural environments (experiential connections) can shape environmental knowledge and positive attitudes towards the environment (cognitive connections) (Collado et al. 2013). Conversely, people with positive psychological orientations towards nature (emotional and cognitive connections) have been shown to be more likely to visit parks and reserves (experiential connections) (Lin et al. 2014). Ewert et al. (2005) also found that early-life outdoor activities (experiential connections) were related to environmental beliefs (cognitive connections) in adulthood, and Lumber et al. (2017) showed that direct contact with nature along with emotional engagement and contemplation of meaning are associated with a psychological measure of nature relatedness. Many other interactions are likely to exist, but have yet to be examined in depth.

The concept of human–nature connections as outlined above might be considered a theoretical perspective that integrates different relationships between social and natural systems. Other frameworks have been proposed that derive from different applied or theoretical perspectives (see Muhar et al. 2017 for a synthesis of concepts). One of the most commonly applied concepts in environmental management and sustainability is ecosystem services (Millenium Ecosystem Assessment 2003). While related, we consider ecosystem services to be a separate but complementary framework to connection to nature. First, ecosystem services is commonly understood as anthropocentric in focus, since it emphasises the benefits people derive from nature (Schroeter et al. 2014; Silvertown 2015). In contrast, connection to nature is not inherently normative, but describes interactions that may be positive, negative, or benign. Second, ecosystem services have its roots in economic thought, as highlighted by the emphasis on quantifying the 'value' of different goods and services that are derived from ecosystems (Silvertown 2015). Human–nature connection represents a broader approach, as highlighted by the 'philosophical' dimension which explicitly considers different forms of conceptualising human–nature relationships. Therefore, human–nature connection as a concept is likely to be better positioned to describe and address environmental and sustainability challenges across different socio-cultural contexts.

Causes, consequences, and treatments

Literature on connection to nature is fragmented beyond differences in the types of connection and scale of analysis. Research also varies according to whether it emphasises (1) the *causes* of nature disconnection, (2) the *consequences* of disconnection, or (3) reconnecting to nature as a *treatment* for some problem. Soga and Gaston (2016) reviewed the literature on the causes and consequences of experiential connections to nature. Yet, similar work to separate causes, consequences, and treatments will be equally important for other dimensions of nature connection.

Causes of disconnection from nature

Disconnection from nature is often considered as a symptom of broader-scale societal changes (Pyle 2003; Seppelt and Cumming 2016). However, the literature varies according to whether immediate or more fundamental causes of disconnection from nature are considered. Claims about the fundamental causes underpinning disconnection from nature are largely speculative, particularly when considered at the societal scale. Some scholars have argued that disconnection is symptomatic of underlying philosophical or functional shifts such as the dominance of materialism and over-consumption (Pyle 2003). While this may have intuitive appeal, there is little concrete evidence for this assertion. The notion of 'reconnecting to the biosphere' proposed by Folke et al. (2011) also implies a historical separation of people from nature, namely, a cognitive disconnection between people's understanding of the impacts of their activities and biophysical reality. Evidence for such cognitive disconnection is stronger, and can be traced to the increased complexity of global resource systems (see Steffen et al. 2011). Other studies have considered more immediate causes of nature disconnection, and are generally more firmly grounded in empirical evidence. Examples of variables contributing to nature disconnection include urbanisation (Cumming et al. 2014), reduced access to green spaces (Lin et al. 2014), changing social norms and perceptions (Valentine and McKendrck 1997), and rise in electronic media (Pergams and Zaradic 2006).

Consequences of disconnection from nature

Other studies focus on consequences of being disconnected from nature. Research has spanned fields from child development to sustainability and has addressed matters such as health benefits of outdoor experiences, and individual behaviours associated with emotional or cognitive attachments to nature. One widely publicised consequence of connecting to nature is that of learning and development benefits for children (e.g., Taniguchi et al. 2005). Recent research has pointed to benefits of interactions with natural environments for happiness and general wellbeing (Capaldi et al. 2014) and mental and physical health (Keniger et al. 2013). Furthermore, other literature has demonstrated links between individual nature connectedness and sustainable behaviours (Geng et al. 2015).

At a broader scale, it is commonly asserted in disciplines such as conservation science, environmental psychology, and sustainability science that humanity's growing disconnection from the natural world is contributing to the global environmental crisis (Nisbet et al. 2009; Zylstra et al. 2014). Kareiva (2008) argued that an experiential separation from nature, as demonstrated through a decline in visitation rates to national parks, "may well be the world's greatest environmental threat". While it is difficult to prove empirically that such experiential disconnection poses a threat to biodiversity and sustainability, some evidence has emerged that shows experiences of nature are correlated with willingness to donate to conservation causes (Zaradic et al. 2009) and that psychological connectedness to nature is positively correlated with vegetation protection behaviours by farmers (Gosling and Williams 2010).

Reconnecting to nature as a treatment

Finally, studies have considered reconnecting people to nature as a treatment, often focused at the individual scale. For example, nature experiences have been explored as treatments for psychological illness such as depression and anxiety (Townsend 2006). Proven health benefits of nature interaction have also led to research modeled on medical approaches such as exploring the nature 'dose' necessary to achieve health outcomes (Shanahan et al. 2016). In education, programs that focus on nature experiences as ways of fostering curiosity and resourcefulness are being developed to counteract the dominance of indoor-only play (Mainella et al. 2011). Citizen science has also been explored as a mechanism by which people can connect experientially with nature so as to foster environmental knowledge, concern, and pro-conservation behaviour (Conrad and Hilchey 2011).

Beyond the scale of individuals, a growing body of the literature asserts a need for society to reconnect with nature to facilitate societal transformation towards sustainability (Folke et al. 2011; Abson et al. 2017). Yet, despite the high stakes, nature reconnection as a treatment for society-scale system change has received scant empirical attention to date. We consider that framing human–nature connections as a treatment for social and environmental problems has great merit in the context of myriad challenges facing contemporary society. Yet, researchers must be clear about the motivation for these studies and the mechanisms by which reconnecting people with nature might address the problem at hand, as well as clarifying the overarching narrative they are speaking to (i.e., disconnection from nature as a cause or a symptom).

While some have argued for a reconnection between people and nature, others have called for society to be decoupled from the environment to ensure planetary sustainability. Two aspects of decoupling are often conceptualised: (i) resource decoupling, which denotes a separation of economic activity from resource use, and (ii) impact decoupling, which conceptualises a separation of economic activity from environmental impacts (UNEP 2011). We consider that disconnections from nature and eco-economic decoupling are related, but distinct terms, and are compatible in different contexts. The typology of nature connections we present can help demonstrate this. Reconnection with nature in a cognitive sense might be necessary for a decoupling of economic growth from environmental impacts. Furthermore, issues of scale are critical, since decoupling of economic activity from natural resources almost always conceptualises human–nature connections at the societal scale. By reconnecting people materially to *local* ecosystems and reducing global teleconnections, any impacts to the environment will be recognised more easily, thus decoupling human economic activity from degradation elsewhere.

Reconnecting people with nature for sustainability?

The preceding sections sought to bring clarity to the multidimensionality of concepts and perspectives that characterise the literature on human–nature connections. Specifically, we distinguished five types of nature connections and the societal scales at which they operate, and found that the existing literature can be characterised as framing nature connectedness as a cause, consequence, or treatment to a problem. Here, we explore how reconnecting people with nature can act as a treatment for key sustainability challenges by looking at the five types of nature connectedness from social–ecological systems perspective. Social–ecological systems (or coupled human and natural systems) are complex systems, characterised by multiple interactions and feedbacks between human and natural elements (Fischer et al. 2015). Such a framing is therefore important when addressing sustainability problems, because these problems arise from a complex interplay between environmental and socio-political factors (Fischer et al. 2015). While social–ecological system thinking has been critiqued for subjective definitions of systems boundaries (e.g., Epstein et al. 2013) and under-theorising political and economic dynamics in environmental management (Cote and Nightingale 2012), the framework outlined below provides a useful heuristic way of organising actions for reconnecting people with nature.

Leverage points

Assuming that "reconnecting" people with nature could be a treatment for the global sustainability crisis, how exactly might an agenda of reconnecting people and nature bring about systemic change? In this section, we draw on the notion of "leverage points" to scrutinise the logic underpinning a possible reconnection agenda. Following Meadows (1999), leverage points are places within complex systems, where interventions can be directed to bring about change in overall system behaviour.

Leverage points can be shallow or deep according to the type of influence they have on a system. Changes to shallow leverage points are relatively ineffective, whereas even minor changes to deep leverage points can alter overall system behaviour. Shallow leverage points relate to (1) system parameters and (2) feedbacks between variables. In contrast, deep leverage points relate to (3) the system design or architecture and (4) the goals or intents pursued through the system. In a sustainability context, this means that changing certain parameters in a system (e.g., the proportion of protected land) is likely to be a less effective leverage point than changing its design (e.g., the rights of biodiversity to persist) or overarching goal (e.g., respect for rather than exploitation of nature). Here, it is important to note that shallow leverage points, such as increasing the amount of protected land, are crucial. However, our ability to increase this parameter is fundamentally constrained by the design of the system and the goals to which the system is oriented. Therefore, focusing only on shallow interventions is unlikely to bring about major changes in system behaviour (Abson et al. 2017).

This framing around deep versus shallow leverage points provides a working hypothesis regarding how different types of "reconnection" may be more or less effective in fostering sustainability (Fig. 2). Particularly, we propose that connections to nature related to the design or goal implicit in a given system are more likely to have a strong effect on sustainability outcomes than connections related to parameters or feedbacks. It follows that addressing "inner" connections (such as philosophical and cognitive connections) is necessary to bring about sustainability transformation. Strengthened "outer" connections (such as experiential and material connections) can potentially play supporting roles, but,

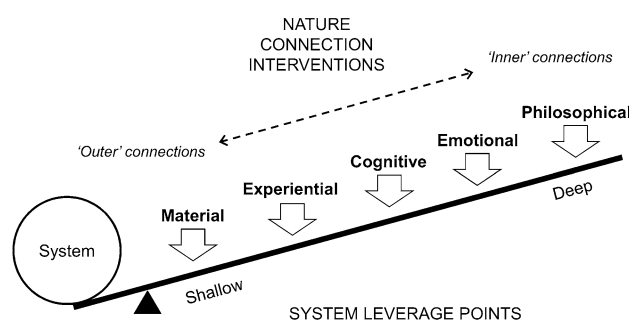

Fig. 2 Hypothesised mechanisms by which interventions for reconnecting people with nature can bring about system change. More externally-defined connections to nature (e.g., material and experiential connections) are more likely to influence system parameters (such as resource stocks and flows), while internally-defined connections (such as philosophical perspectives and emotional responses to nature) are more likely to influence the underlying goals and values embodied in a system. We note that connections to nature may affect system properties in more complex ways than are represented here, and system attributes and different types of interventions are likely to interact

by themselves, are unlikely to bring about transformative change. In reality, many interventions relating to strengthened connections to nature need to occur in concert, because they can be expected to interact.

From theory to practice

Numerous practical examples exist for how types of connections between people and nature can be strengthened. Materially reconnecting people to local ecosystems can influence the parameters of a system to enhance sustainability. On a fundamental level, humanity is connected to the biosphere through the consumption of energy, goods, and other resources, but increased consumption of these is not ecologically desirable. Thus, the type of material reconnection that we advocate is a local strengthening of ties to nearby ecosystems to decouple consumption of wealthy, urban populations from impacts elsewhere in the world and increase regional self-sufficiency. Specific interventions could include restaurants serving locally grown produce, urban dwellers growing food in community gardens, or houses being built with locally sourced timber. Shortening food chains in these ways can reduce food miles with resulting benefits for CO_2 emissions (Smith et al. 2005). Materially reconnecting to local ecosystems can also relate to other nature connections and system attributes. For example, food mile or source country labelling on products can enhance cognitive feedbacks between consumers and production landscapes. Alternatively, growing food for personal consumption can simultaneously promote sustainability, enable experiences of nature, enhance knowledge of natural processes and ecosystem functions, and contribute to emotional attachment to place (Hawkes and Acott 2013).

Many of the aforementioned material connections are closely tied to direct sustainability outcomes such as reducing carbon emissions and reducing biodiversity loss. However, these parameter changes may depend upon more fundamental systemic change. Wholesale sustainability transformation may require interventions at deep leverage points, since sustainability solutions ultimately hinge upon "value and belief systems, at levels ranging from individuals to societies" (Fischer et al. 2012a). Interventions that connect people to nature emotionally and philosophically have the greatest potential here. For example, art has the capacity to transcend the cognitive mind and convey meaning through visceral experience, and thus has considerable potential to influence the goals people pursue in life (Thomsen 2015). There is also increasing recognition of the importance of worldviews for sustainable lifestyles (Hedlund-de Witt et al. 2014). Here, the role of spirituality and religion in reorienting people towards nature is one under-researched area that has potential to function as a deep leverage point (Hitzhusen and Tucker 2013). Formal religious faiths contain teachings that promote environmental stewardship and challenge prevailing paradigms of consumption and growth (Gottlieb 2006) and can motivate action for sustainability (The Alliance of Religions and Conservation 2015). Furthermore, their spiritual practices can be powerful in shaping the deep values and beliefs people hold. Contemplative practices, such as mindfulness, even outside of a religious context are indeed powerful levers that have been found to relate to psychological nature connectedness (Howell et al. 2011) and can help promote sustainability (Wamsler et al. 2017).

Some activities that connect people with nature may simultaneously impact shallow and deep leverage points. A good example of this is community gardening. Research has shown that in addition to growing food (materially connecting to nature), allotment gardening can promote environmental learning (Bendt et al. 2013), offer therapeutic benefits (Pitt 2014), and build social cohesion and resilience (Firth et al. 2011). Similarly, nature-based education such as forest kindergartens (Waldkindergarten), popular in Germany, Sweden, and Denmark, may help Children develop deep empathy for nature in addition to developmental benefits (Kane and Kane 2011). Furthermore, interactions among forms of nature connectedness—as evident in allotment gardening or outdoor education—can offer potentially stronger leverage potential. For example, one recent study demonstrated relationships among exposure to urban nature, tree planting behaviour, and psychological connectedness to nature (Whitburn et al. 2018). Many of these initiatives are likely to be particularly powerful in urban contexts, where populations are often disconnected from experiences of nature (Miller 2005; Soga and Gaston 2016). Relating research and practice on urban greening concepts such as green infrastructure (Andersson et al. 2014), biophilic cities (Beatley 2011), and nature-based solutions (Lafortezza et al. 2017) to scholarship on sustainability transformations is, therefore, an important area for future attention in sustainability science.

Structural change may often be necessary to enable interventions for connecting people with nature to be implemented or benefits realised. For example, educational policy may need revising to allow school students' greater interaction with nature as part of curricula, planning law may need reform to increase biological diversity within cities, and transport networks may need modification to enable people to access natural areas easily. Thus, reconnecting people with nature may both effect and depend upon deep structural change.

How interventions at deep leverage points can be scaled up is a question that sustainability scientists should actively pursue. For example, which "shallow leverage points" must be addressed in tandem for interventions at "deep leverage points" to achieve their full potential? Similarly, it is important to consider which kinds of shifts are appropriate and necessary in different social, economic, and environmental contexts. Arguably, application of the leverage point framework coupled with the typology of human–nature connections could be an effective heuristic for directing research along these lines.

Conclusion

It is evident that reconnecting people with nature can play a useful role in addressing many of today's ecological and sustainability challenges. To meaningfully progress a "reconnection agenda", tangible actions must be directed towards specific changes, whether in health, education, or conservation. To this end, specifying particular types of nature connections to be enhanced is a key first step. A second step is to couch these within the literature of demonstrated causes and consequences of nature connections and a plausible theory of change (such as the concept of leverage points for sustainability transformation). Building on this theoretical foundation will enable research to move past vague speculation about the need to reconnect people with nature, and instead build an evidence base that can support research and practice.

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Appendix I

Human–nature connection: a multidisciplinary review

Christopher D. Ives, Matteo Giusti, Joern Fischer, David J. Abson, Kathleen Klaniecki, Christian Dorninger, Josefine Laudan, Stephan Barthel, Paivi Abernethy, Berta Martin-Lopez, Christopher M. Raymond, Dave Kendal, Henrik von Wehrden

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Abstract

In sustainability science calls are increasing for humanity to (re-)connect with nature, yet no systematic synthesis of the empirical literature on human–nature connection (HNC) exists. We reviewed 475 publications on HNC and found that most research has concentrated on individuals at local scales, often leaving 'nature' undefined. Cluster analysis identified three subgroups of publications: first, HNC as mind, dominated by the use of psychometric scales, second, HNC as experience, characterised by observation and qualitative analysis; and third, HNC as place, emphasising place attachment and reserve visitation. To address the challenge of connecting humanity with nature, future HNC scholarship must pursue cross-fertilization of methods and approaches, extend research beyond individuals, local scales, and Western societies, and increase guidance for sustainability transformations.

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Human–nature connection: a multidisciplinary review

Christopher D Ives [1,2], Matteo Giusti[3], Joern Fischer[2], David J Abson[2], Kathleen Klaniecki[2], Christian Dorninger[2], Josefine Laudan[2], Stephan Barthel[3,4], Paivi Abernethy[2,5], Berta Martín-López[2], Christopher M Raymond[6], Dave Kendal[7] and Henrik von Wehrden[2]

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Addresses
[1] School of Geography, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom
[2] Faculty of Sustainability, Leuphana University, Lueneburg, Germany
[3] Stockholm Resilience Centre, Sweden
[4] University of Gävle, Sweden
[5] Royal Roads University, Victoria, BC, Canada
[6] Department of Landscape Architecture, Planning and Management, Swedish University of Agricultural Sciences, Sweden
[7] School of Ecosystem and Forest Sciences & Melbourne School of Design, The University of Melbourne, Australia

Corresponding author: Ives, Christopher D (chris.ives@nottingham.ac.uk)

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Introduction

The relationship between people and nature has attracted rising interest among scientists, given evidence of health and well-being benefits from human interaction with nature [1,2,3••] and its contribution to addressing sustainability challenges [4,5•,6]. Indeed, while humanity is ultimately dependent on natural resources, the urgent need for human populations (particularly those in the West) to be reconnected to nature or embedded within ecological limits has been recently emphasised by many sustainability scientists [7,8•,9–12]. These calls for (re)-connection to and embeddedness within nature have implied more than physical dependence, but active development of cognitive, emotional and biophysical linkages that positively shape human–nature interactions. Research on this topic has been characterised by a plurality of disciplinary and conceptual perspectives, language, methods and research approaches. With this heterogeneity, the literature has become fragmented, compromising the consolidation of ideas and their application to practice. A first step towards consolidation is to generate a coherent overview of existing scholarship.

In reviewing this literature, clear terminology is critical. We adopt the term 'human-nature' connection (HNC) as an umbrella concept, encompassing a broad range of terms from different disciplines and applications [13•], for instance connectedness with nature [14] or nature relatedness [6] in environmental psychology and (re-)connection to the biosphere [7,11] in sustainability science. Some reviews of HNC have emerged recently [3••,5•,15], but they are couched within particular disciplinary perspectives and use narrow definitions of 'connection'. In this study we elected not to prescribe a strict definition of 'nature', but were guided by the perspective of articles reviewed. Reviewed literature reported on places, landscapes and ecosystems that are not completely dominated by people, but also include non-human organisms, species and habitats. With this review we intend to provide a multidisciplinary space for academic and cultural integration, extension and cross-fertilization.

We report the findings of systematic review of scholarly publications from a range of disciplinary backgrounds that have empirically investigated HNC. We sought to first, assess the diversity of subjects, methods and motivations of research on HNC; second, identify clusters of papers and their distinguishing characteristics; and third, consider how future research on HNC can better inform sustainability science.

Methods

The Scopus database was queried with a search string comprised of 41 components that combined a variety of terms related to 'nature', 'people' and 'connection' (see Supplementary appendix 1a for full search string). The search was applied to Abstract, Title and Keywords on 16 November 2015 and returned 3849 papers, which was reduced to 2649 after restricting results to articles in English. Only English literature was selected because of the difficulties in systematically reviewing literature across multiple languages (e.g. the necessity of reviewers subjectively translating concepts into a common language, and the loss of meaning or misinterpretation this would likely entail). Articles were screened to ensure they were peer reviewed and published in an academic journal, reported on empirical data (i.e. excluding reviews, conceptual papers or critical commentary), and studied a type of relationship people have with green or natural environments (full inclusion criteria provided in Supplementary appendix 1b). We note that since the review focussed on articles studying connections between people and nature, literature that assumed this connection but did not address it explicitly (e.g. some research in forestry or agriculture) was not included. Screening returned a final set of 475 papers published between 1984 and 2015 (Supplementary appendix 2).

Each paper was coded for: (i) descriptive information about the article (e.g. country, journal and discipline); (ii) conception of 'nature'; (iii) social group analysed (e.g. individuals versus communities); (iv) class of HNC(s) studied; (v) methodological details; and (vi) the purpose of the study. Response categories for all questions were developed iteratively by the author team. The final typology distinguished between five classes of HNC: material (e.g. resource extraction), experiential (e.g. activities), cognitive (e.g. attitudes, values), emotional (e.g. fear, joy) and philosophical (e.g. ontological frameworks) (see Supplementary appendix 1c for full details and definitions). The first 10% of papers were coded by multiple authors, and response categories were clarified where inconsistencies were found.

Data on all reviewed publications were analysed in R [16] to generate descriptive statistics, multivariate clusters, and an ordination. Agglomerative hierarchical clustering was performed using the 'agnes' function in the 'cluster' package using a Euclidian measure of dissimilarity and Ward's clustering method. 'Indicator species analysis' was used to identify which variables most influenced these groups using the 'indval' function within the 'labdsv' package. Ordination of data was performed via Detrended Correspondence Analysis using the 'decorana' function in the 'vegan' package.

Results

Overview

Research on HNC is increasing (Figure 1), with 345 papers (72.6%) published from 2010 onwards. Nondescript or 'unspecified' forms of nature were most commonly studied (30.9%), followed studies on human connections to urban nature (14.1%), and protected areas (11.9%) (Figure 2). Most HNC research targeted individuals (76%), especially local people (24.3%). Most research has studied cognitive (35.9%), experiential (22.0%), emotional (21.8%), and philosophical (13.9%) connections to nature, whereas material connections (6.5%) have received less attention (Figure 2). Most studies addressed one (161 papers; 33.9%) or two (169 papers; 35.6%) types of HNC, 97 papers (20.4%) studied three types of connections, 38 papers (8.0%) four types, and 10 papers (2.1%) studied five types of connection.

Methodological patterns

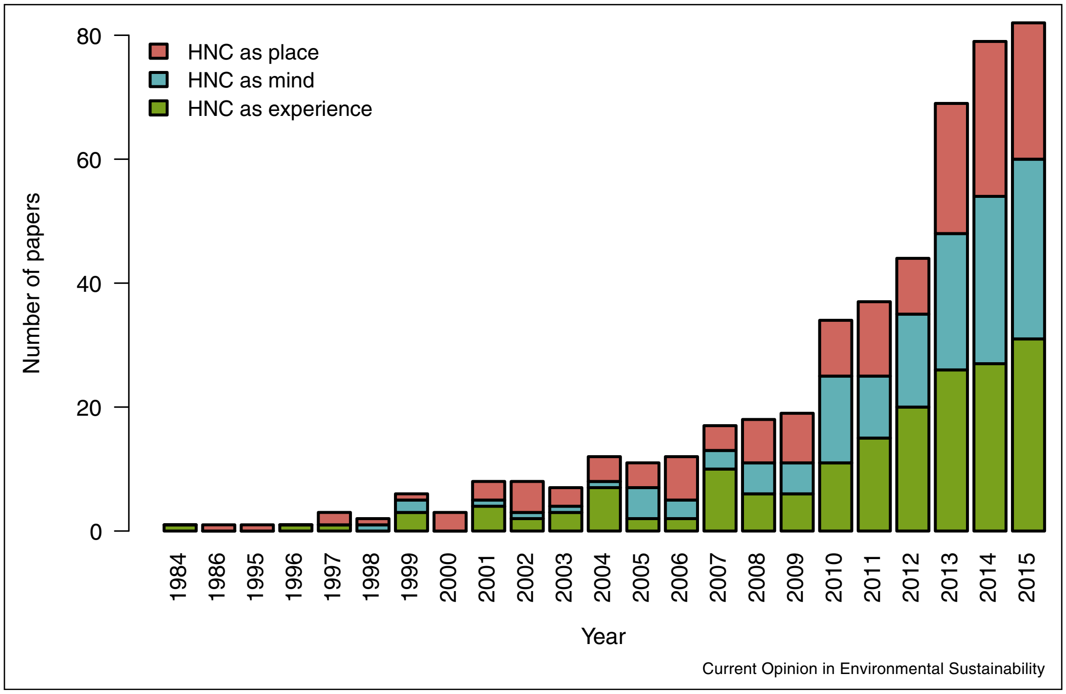
Empirical research on HNC has been biased towards western countries. The top five countries represented were USA (152 papers; 32.0%), Australia (54 papers; 11.4%), Canada (42 papers; 8.8%), United Kingdom (27 papers; 5.9%) and The Netherlands (22 papers; 4.6%). HNC has been mostly observed (87.8%), rather than experimentally tested (12.2%), using quantitative (48.8%), qualitative (32.0%), or mixed datasets (19.2%) (Figure 2).

Similar numbers of studies explored HNC as a predictor variable (31.2%), response variable (26.7%), or both a predictor and response (17.3%), suggesting that scholars have been equally interested in the drivers and effects of HNC. However, 24.8% of papers studied HNC as a variable in itself (i.e. neither as a predictor nor response). Substantial proportions of studies used psychometric scales (24.6%) or assessed place attachment (28.6%). Psychology was the most represented discipline in the literature (29.4%), followed by the social sciences (21.4%), environmental disciplines (15.2%), tourism (10.4%), education (10.3%), planning (7.0%), and health (6.4%).

Multivariate analysis

Cluster analysis revealed three distinct subgroups of publications (Figure 3), characterised by different indicator variables (Table 1). We labelled the clusters as follows: *HNC as mind* (145 papers), *HNC as experience* (178 papers), and *HNC as place* (152 papers). The fastest growth in research over time occurred in publications in the *HNC as mind* cluster (Figure 1), characterised by studies that address cognitive and philosophical aspects of HNC at the individual level. These studies commonly investigated

Figure 1



Increase in the number of published studies on human–nature connection (HNC) by year. Colours within bars relate to the three groups as identified by the cluster analysis: HNC as mind, HNC as experience, and HNC as place.

students using quantitative research methods to explain, describe, and predict psychological dynamics and pro-environmental behaviours. However, in this cluster the concept of nature was generally undefined, and policy guidance was less common than in other clusters. In contrast to *HNC as mind*, both *HNC as experience* and *HNC as place* focussed on relationships between specific peoples and places. *HNC as experience* described qualitatively people's experiences of particular local areas and were characterised by an observational research approach. An example of this is Cosquer et al.'s study of people's interactions with everyday nature as part of a butterfly citizen science programme in France [17]. In contrast, research in the *HNC as place* cluster typically used quantitative questionnaires to study emotional connections to specific natural spaces, often at the landscape scale. These studies often also provided policy guidance to address sustainability issues. For example, Tonge et al. [18] applied place attachment concepts to explore how visitors related to the Ningaloo Marine Park in Australia and how this influenced conservation actions.

Discussion

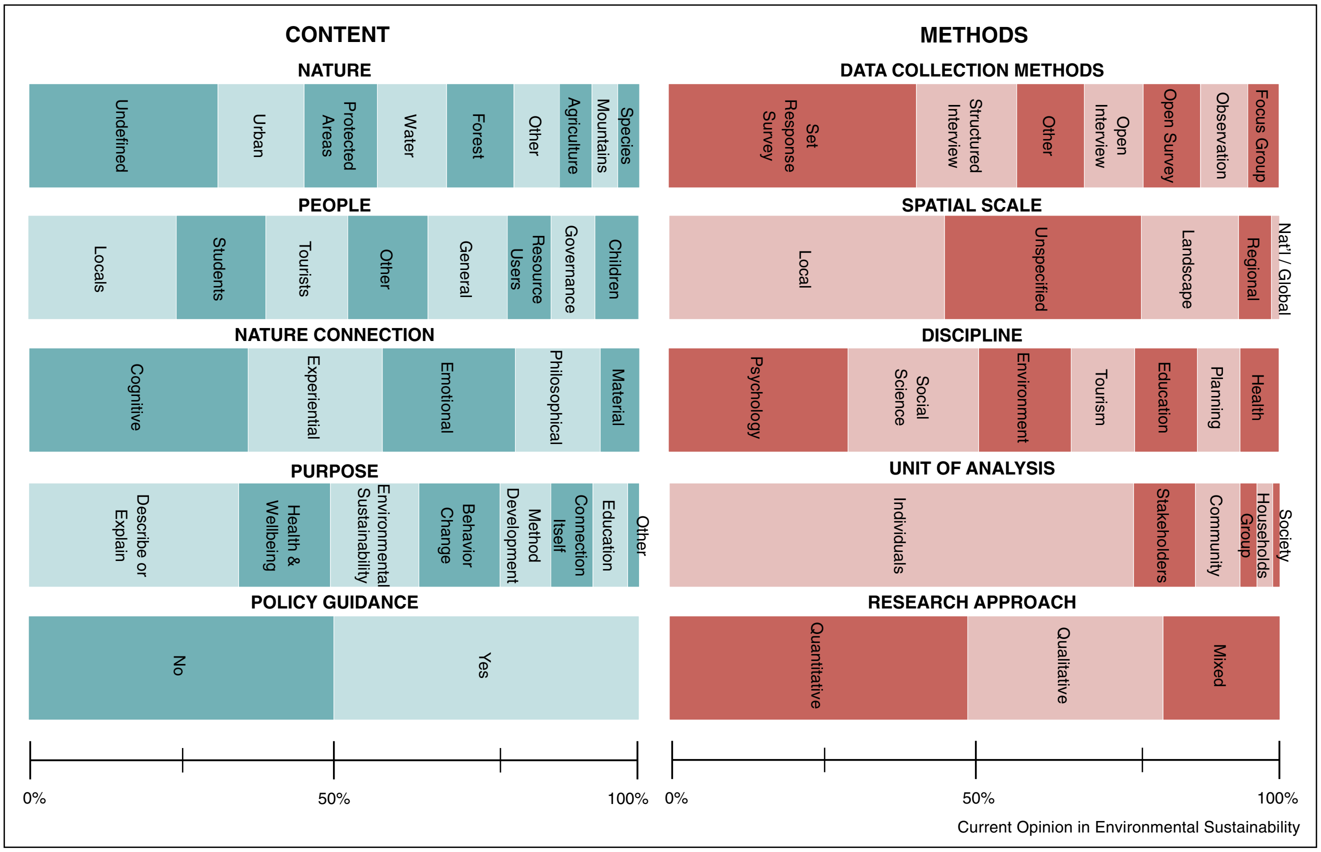
Our findings suggest that research on HNC is receiving increasing interest, but, being highly heterogeneous, has yet to reach its full potential in supporting humanity on a pathway towards sustainability. To this end, we propose three key priorities: first, greater integration of complementary perspectives in HNC research; second, further extension of HNC research; and third, more targeted application of insights to foster sustainability transformation.

Complementarity and integration

The research clusters identified highlighted disciplinary, methodological and contextual differences (Table 1), which seem to represent co-existing epistemological positions in HNC research. The *HNC as mind* cluster typically encapsulates an objectivist epistemology. These publications draw upon theory and methods from psychology to understand nature connection as a real psychological entity that affects behaviour [see 6,14]. In contrast, the *HNC as place* cluster largely operates within a constructionist epistemology, with knowledge of nature connection derived through exploring relational interactions between people and specific places (see also [19••]). The *HNC as experience* cluster often adopts a subjectivist epistemology, observing and describing the uniqueness of individuals' experiences of nature. These epistemological differences suggest that resolving the longstanding challenge of defining nature (and non-nature) [see 20] in a way that unifies disciplines is likely to be difficult.

These perspectives are fundamentally different but they contribute complementary insights that may be integrated in future research. First, since *HNC as mind* rarely

Figure 2



Overview of the proportions of studies focusing on particular content or using particular methods. Each bar represents a question that was applied to reviewed papers.

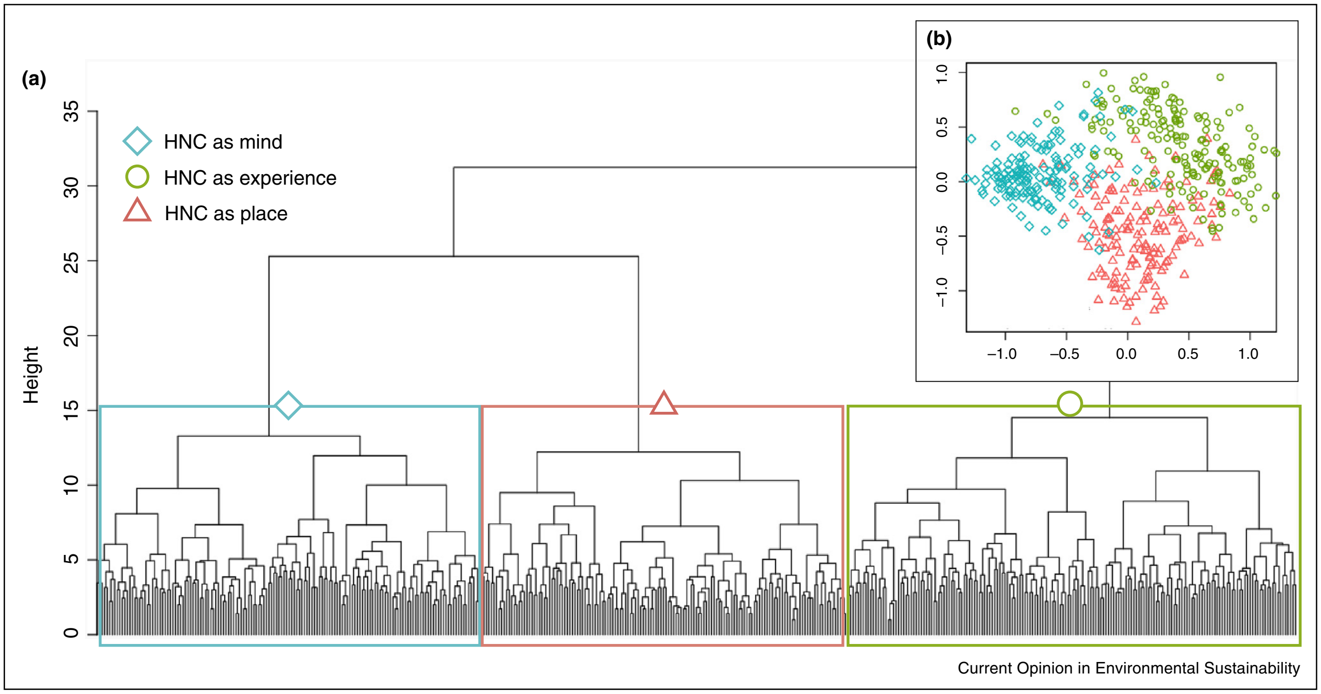
specifies the type of nature that people are connected to and focuses predominantly on individuals, *HNC as place* can contribute to this literature with an understanding of how HNC of communities is situated in geographical locations, while *HNC as experience* may offer deeper understandings via qualitative descriptions. Second, research on *HNC as place* could be enhanced by the quantitative and more generalisable perspectives of *HNC as mind*, along with the deep and nuanced insights offered by *HNC as experience*. Finally, the *HNC as experience* literature could benefit from the statistical rigour of *HNC as mind* and the applied focus of *HNC as place*. Full integration of these perspectives is likely to be difficult [21] and may not be feasible or even appropriate in every case. However, it would be worth exploring how sustainability science could facilitate cross-fertilization of HNC knowledge in order to pursue 'theoretically and empirically rich solutions-oriented research' [22].

Extension

An integrated HNC research agenda for sustainability must address key gaps in the current literature. Of particular concern for sustainability is the relatively minor focus on material connections to nature (Figure 2). While there are many fields that study material connections to nature (e.g. natural resource management), our study focussed on the specific subset that explores human connections. Material HNC must be better understood as it shapes patterns of resource consumption, which in turn drive environmental sustainability outcomes [12,23,24]. Moreover, understanding the relationships between material connections and other 'internal' connections to nature (e.g. cognitive, emotional) will help to explore potential feedbacks and points of intervention for sustainability transformation [see [20]].

Second, HNC should be studied in and communicated across a greater diversity of cultural contexts. Of the published articles included in this review, the vast majority have largely been undertaken in post-industrial, Anglo-Saxon countries. However, this result may be biased due to restricting our review to articles in English. Relevant literature in non-western cultures might be published in other languages and express conceptualisations of HNC that are altogether different from those dominant in Anglo-Saxon cultures [26]. Thus, given the

Figure 3



(a) Dendrogram of the papers on human–nature connection (HNC) coded in this review. Each coded paper is represented by a vertical line at the bottom of the chart. The similarity between papers is indicated by their distance from one another along the lines of the 'tree'. **(b)** Ordination of reviewed papers highlighting three distinct clusters of articles: *HNC as mind* (blue diamonds), *HNC as experience* (green circles), and *HNC as place* (red triangles).

key sustainability challenges at play in the Global South [27], there is an urgent need for more research from these countries, increased support for publication of these studies in international journals, and extending HNC research beyond western cultural framings.

Third, future research (particularly in psychology) must specify the characteristics of nature that people are connected to. Without such information, it is difficult to know how policies and decisions for sustainability should be formulated. For example, there is scant evidence on whether interactions with forests, rivers, grasslands or urban parks are more effective in promoting health and well-being, or pro-environmental attitudes and behaviours.

Fourth, our review revealed an underrepresentation of research at the community or society level. Theories of sustainability transformation highlight the critical importance of action and change at this level [28–30,31•]. Therefore, we encourage future exploration of how groups of people, initiatives and organisations within society are connected to nature as a way of moving beyond the current focus on individuals.

Finally, there is a need to more strongly relate HNC to specific sustainability issues. Only a small portion of the literature addressed the importance of HNC for sustainability. Most literature simply described or explained people's connection to nature, and only publications within the *HNC as place* cluster regularly offered policy guidance. Directing future research to pressing sustainability challenges and explicitly offering practical recommendations appears important.

Application

There are increasing calls in the literature for a 'biosphere-based sustainability science' [8•] whereby human development progress is intimately connected with stewardship of the planet. We affirm these calls, and suggest that such an integrated sustainability science could greatly benefit from incorporating the diverse insights from literature on HNC. These insights are critical for identifying which social–ecological settings can allow people to enhance their connection with nature, establishing how the multiple types of HNC can foster pro-environmental behaviours, and defining both the characteristics of a sustainable future and the pathways by which it can be reached.

A strong connection between people and nature is emphasised in key global sustainability agreements. For example, one target under Goal 12 (responsible consumption and production) of the Sustainable Development Goals is to

Table 1

Results of the 'indicator species analysis' showing the most pertinent distinguishing characteristics of three clusters of papers on human–nature connection (HNC). The coded variables are listed as relating to either the content of the study, or methodological aspects for all of three clusters identified: *HNC as mind*, *HNC as experience*, *HNC as place*. Indicator value coefficients are listed (only those ≥0.2 reported), and denoted as follows: ***if coefficient ≥ 0.4; **if 0.4 > coefficient ≥ 0.3; *0.3 > coefficient ≥ 0.2.

Variable	HNC as mind	HNC as experience	HNC as place
Content			
Type of nature	*** Undefined (0.45)		
People studied	*** Students (0.44)	* Other (0.21)	** Locals (0.31) * Tourists (0.27)
Type of connection	* Cognitive (0.29)	* Experiential (0.21)	* Emotional (0.22)
Purpose		* Other (0.22)	
HNC related to other variables		* HNC as a variable in itself (0.23)	
Research on place attachment	*** No (0.46)		*** Yes (0.47)
Spatial scale	*** Unspecified (0.52)	* Local (0.28)	* Landscape (0.22)
Policy guidance	* No policy guidance (0.28)		* Provides policy guidance (0.22)
Methods			
Discipline	*** Psychology (0.50)	* Social sciences (0.26)	* Environmental studies (0.22)
Research approach	* Experimental research (0.28)	** Observational research (0.37)	
Data type	*** Quantitative (0.45)	*** Qualitative (0.81)	
Data collection		** Structured interviews (0.36) * Open interviews (0.21)	*** Set response survey (0.45)
Unit of analysis	** Individual (0.38)		
Type of analysis	*** Quantitative analysis (0.47)	*** Qualitative analysis (0.56)	
Use of psychometric scales	*** Yes (0.54)	*** No (0.44)	

'ensure that people everywhere have...awareness for...lifestyles in harmony with nature'. Similarly, Goal 11 (sustainable cities) includes a target to provide 'universal access to safe, inclusive and accessible, green and public spaces'. The recent UN New Urban Agenda also seeks to promote 'healthy lifestyles in harmony with nature' [(32,s 14c)]. The implementation of these goals should draw on HNC research.

Finally, HNC research can help inform transformative or transitional pathways towards sustainability. Scholars have highlighted that the scale of change needed to reach a sustainable future is beyond what can be achieved via incremental adjustments to current systems [25•,33]. Accordingly, theories of social change have considered socio-technological transitions [34] and social–ecological transformations [35]. In this context, incorporating knowledge of how HNC influences environmental worldviews, values, attitudes and behaviours may help identify effective 'seeds' of change [29], 'protected niches' [36] and 'deep leverage points' [25•] for sustainability transformation. For example, insights from HNC research could inform the Smart Cities (IT-based sustainable cities) discourse, which has inadequately considered how technological solutions may affect people's interactions with nature. This is especially important for children, as deep seated environment-related attitudes are acquired during childhood [37] and persist through adulthood [38]. Furthermore, rapid land conversion for urbanisation, combined with increased internet access, population density and new technologies challenge people's direct sensory experience of nature, and will likely have negative implications for human health and well-being [39,40].

Conclusion

The importance of HNC for sustainability is increasingly recognized. The task of sustainability scientists now is to establish how different types of nature connections may contribute to positive change for sustainability. This review has provided a foundation for this agenda. It has shown that a substantial body of empirical research has accrued, yet has remained disparate. We call for researchers and practitioners to take stock of this existing evidence, integrate insights across methodological, epistemological and geographic boundaries, and pursue novel interdisciplinary research that can generate knowledge for a sustainable future characterised by strong connections between humanity and the biosphere.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cosust.2017.05.005.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Keniger LE, Gaston KJ, Irvine KN, Fuller RA: **What are the benefits of interacting with nature?** *Int J Environ Res Public Health* 2013, **10**:913-935.

2. Bratman GN, Hamilton JP, Daily GC: **The impacts of nature experience on human cognitive function and mental health**. *Ann N Y Acad Sci* 2012, **1249**:118-136.

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Appendix II

Values in transformational sustainability science: four perspectives for change

Andra‑Ioana Horcea‑Milcu, David J. Abson, Cristina I. Apetrei, Ioana Alexandra Duse, Rebecca Freeth, Maraja Riechers, David P. M. Lam, Christian Dorninger, Daniel J. Lang

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Abstract

In sustainability science calls are increasing for humanity to (re-)connect with nature, yet no systematic synthesis of the empirical literature on human–nature connection (HNC) exists. We reviewed 475 publications on HNC and found that most research has concentrated on individuals at local scales, often leaving 'nature' undefined. Cluster analysis identified three subgroups of publications: first, HNC as mind, dominated by the use of psychometric scales, second, HNC as experience, characterised by observation and qualitative analysis; and third, HNC as place, emphasising place attachment and reserve visitation. To address the challenge of connecting humanity with nature, future HNC scholarship must pursue cross-fertilization of methods and approaches, extend research beyond individuals, local scales, and Western societies, and increase guidance for sustainability transformations.

Keywords: Sustainability transformation, Transdisciplinarity, Value negotiation, Eliciting values, Value shift

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SPECIAL FEATURE: ORIGINAL ARTICLE

Theoretical traditions in social values for sustainability

Values in transformational sustainability science: four perspectives for change

Andra-Ioana Horcea-Milcu[1] · David J. Abson[1] · Cristina I. Apetrei[1] · Ioana Alexandra Duse[1] · Rebecca Freeth[1] · Maraja Riechers[1] · David P. M. Lam[1] · Christian Dorninger[1] · Daniel J. Lang[1]

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Abstract
Despite the normative nature of sustainability, values and their role in sustainability transformations are often discussed in vague terms, and when concrete conceptualizations exist, they widely differ across fields of application. To provide guidance for navigating the complexity arising from the various conceptualizations and operationalization of values, here, we differentiate four general perspectives of how and where values are important for transformation related sustainability science. The first perspective, surfacing implicit values, revolves around critical reflection on normative assumptions in scientific practices. Sustainability transformations concern fundamental ethical questions and are unavoidably influenced by assumptions sustainability scientists hold in their interactions with society. The second perspective, negotiating values, is related to the values held by different actors in group decision processes. Developing and implementing solution options to sustainability problems requires multiple values to be accounted for in order to increase civic participation and social legitimacy. The third perspective, eliciting values, focuses on the ascription of values to particular objects or choices related to specific sustainability challenges, for example, valuations of nature. The fourth perspective, transforming through values, highlights the dynamic nature and transformational potential of values. Value change is complex but possible, and may generate systemic shifts in patterns of human behaviours. Explicit recognition of these four interconnected values perspectives can help sustainability scientists to: (1) move beyond general discussions implying that values matter; (2) gain an awareness of the positionality of one's own values perspective when undertaking values related sustainability research; and (3) reflect on the operationalizations of values in different contexts.

Keywords Sustainability transformation · Transdisciplinarity · Value negotiation · Eliciting values · Value shift

Introduction

At its core, sustainability is a normative, value-based concept. It is increasingly recognised that science dealing with sustainability transformations has to engage with normative and values related issues (Seidl et al. 2013). However, values and their role are often discussed in elusive terms within sustainability research. Given the interdisciplinary nature of sustainability science, even when clear conceptualizations exist, these differ widely across fields of application. There is a diverse range of theoretical conceptualizations (for a comprehensive overview, see Rawluk et al. 2019) related to values: individual, shared, or social values; economic values; environmental and human values; held and assigned values; intrinsic, instrumental or relational values; and transcendental and contextual values (Dietz et al. 2005; Kenter et al. 2015; Tadaki et al. 2017). This diversity reflects not just different philosophical and scientific traditions, but also the multiple ways in which the notion of value shape and constrain our understanding of, and action, in the world. However, these diverse understandings of value seem to exist in relative isolation from each other. In contrast to the theoretical richness, there is less scientific discussion on how values should, or could, be operationalized in relation with

Handled by: Christopher M. Raymond, Swedish University of Agricultural Sciences, Sweden.

✉ Andra-Ioana Horcea-Milcu
milcu@leuphana.de

[1] Faculty of Sustainability, Leuphana University Lüneburg, Lüneburg, Germany

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transformation-oriented sustainability science. Partly, this lack of discussion may be because 'values' are a challenging research object, given their multifaceted nature and the difficulties in defining, eliciting, or measuring values in the context of transformational change.

How can the necessarily value-laden field of sustainability science navigate the diversity of perspectives to conceptualising and operationalizing values in relation with transformational change? Here, we suggest that a useful starting point is to consider the ways values are studied or operationalized in transformational sustainability science. To this end, we organise this paper around four perspectives of how and where values are engaged within transformation-oriented sustainability science, where by 'perspective', we mean a tradition of shared enquiry and practice. Each perspective is bounded by shared broad conceptualizations of, and research approaches to, values in relation with transformational change. In describing such perspectives, our intention is not to provide a definitive typology or framework for considering values in sustainability science. Rather, we wish to surface the multiple roles values are thought of as having, and to encourage a more systematic and explicit consideration of their interactions and importance in investigating and seeking transformational change towards sustainability.

As previously noted, a large number of different values typologies exist in the academic literature. Here, we focus on transcendental and contextual values, as they seem particularly apt in the context of how values are engaged within sustainability science. We acknowledge that this provides a particular lens through which to view the four values perspectives that we develop, but note that this is a necessary constraint of any discussion of values in sustainability science. Following Kenter et al. (2015), we differentiate between: (1) transcendental values—referred to by Brown (1984) as held, first-order preferences—that transcend specific situations and guide selection or evaluation of behaviour and events and (2) contextual values—ascribed, second-order preferences—that relate to the worth or importance of a particular object, choice, or state of the world. Unless mentioned otherwise, in this paper, we focus on transcendental values defined as "concepts […] that pertain to desirable end states or behaviours, transcend specific situations, guide selection, or evaluation of behaviour and events, and are ordered by relative importance" (Schwartz 1992:4; 2012), in agreement with the *Transcendental values* concept in the overview of value concepts provided by Rawluk et al. (2019).

Within the broad class of transcendental values, different typologies exist, each with different dimensions to discriminate between values. For example, in his seminal work, Schwartz (2012) distinguishes between ten motivational types of values recognised across cultures. Alternative typologies differentiate between values operating at various levels: from individual to collective (e.g., social and cultural values). This paper focuses on social values, rather than individual values, where social values refer to the outcome of social processes of deliberation about transcendental values (see also Kenter et al. 2015; Rawluk et al. 2019). We make this distinction between individual and social values, because the practice of sustainability and sustainability science are inherently social processes involving the negotiation of values among different stakeholders, shaped by institutional (including institutions of science) norms. We also make a distinction between social and cultural values; while both operate at supra-individual level, cultural values are less abstract than social values (Rawluk et al. 2019) and more dependent on the local context (Van Riper et al. 2019) rather than on the outcomes of deliberative social processes.

The four values perspectives in sustainability science we describe in more detail below are:

The surfacing implicit values perspective, which revolves around the often unexpressed and unacknowledged values that sustainability science embeds within transformational research. This perspective questions how such underpinning transcendental values shape and constrain insights and solution opportunity spaces in sustainability science. The negotiating values perspective relates to the plurality of transcendental and contextual social values that interact in transformational processes. This perspective asks questions related to whose values count, and how such values are accommodated in, and shape, the outcomes of participatory and group decision processes. The eliciting values perspective looks at the explicit articulation of transcendental values as revealed in contextual value judgments such as ascribing values to particular choices, objects, or actions related to specific sustainability challenges and potential changes in the state of the world. This perspective asks questions regarding which values are ascribed, and how these values are elicited to inform decision-making and management processes. The transforming through values perspective engages with questions related to values as intervention points for transformational changes towards sustainability, arguing that the latter require systemic shifts in deeply held values (Table 1, Fig. 1). For each of these perspectives, we focus on: (1) a general description of the perspective and the way in which values are engaged with; (2) the relevance of the perspective for sustainability science; (3) the identification and importance of under-considered aspects of the perspective; and (4) a practical suggestion for how each perspective could be considered in sustainability science. To illustrate the perspectives, especially point (4) above, we present examples based on a single research project called 'Leverage Points for Sustainability Transformation' (Abson et al. 2017). The project is a transdisciplinary endeavour aiming to explore system characteristics, where interventions can lead to transformational as opposed to incremental changes in the

Table 1 Summary of the four proposed values perspectives for sustainability transformation

	Main focus of operationalization	Main question (How?)	Context of operationalization (Where?)	Examples
Surfacing implicit values	Surfacing implicit values	How do underpinning values shape insights and solution opportunity spaces in sustainability science?	Research models and practices	Transdisciplinarity
Negotiating values	Navigating the plurality of values	Whose values count, and how do such values shape the outcomes of participatory processes?	Facilitating group decision-making and policy processes	Participatory processes involving multiple actors
Eliciting values	Eliciting values ascribed to particular objects or states of the world	Which values, and how values are elicited to inform decision-making processes?	Informing decision-making and management processes	Ascribing values processes (valuation exercises)
Transforming through values	Leveraging values for changing states of the world	How can values serve as intervention points for facilitating transformational changes?	Transformational processes	Systemic value shift

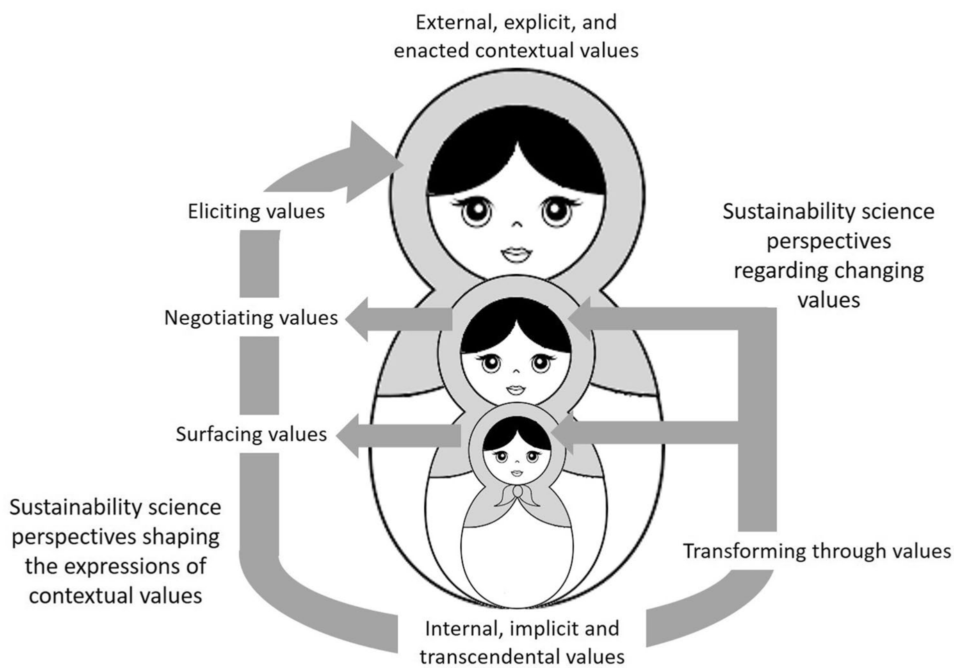

Fig. 1 Distilling the complexity of values concepts within transformational sustainability science in four perspectives. This visual analogy represents a heuristic that does not imply a linear progression or a hierarchy of elements of process. (Perspective 1) Surfacing implicit values: how values inform (scientific) understandings of how the world is. (Perspective 2) Negotiating values: whose values count in assessing states of the world. (Perspective 3) Eliciting values: how we elicit values ascribed to different states of the world. (Perspective 4) Transforming through values: using values as levers for changing states of the world. The four closely interrelated perspectives have different degrees of depth in undertaking value enquiries, or ultimately values related interventions, hence the rationale for using stacking elements for their visual representation

system as a whole. Two empirical examples are drawn from the iterative engagement and experiences of the approximately 25 interdisciplinary scientists working in the project (Tables 2, 3).

Perspective 1: Surfacing implicit values

The surfacing implicit values perspective is about the underpinning assumptions and norms shaping

Table 2 Example of engaging with Perspective 1 (Surfacing implicit values) within the Leverage Points project

The Leverage Points project has a formative accompanying research (FAR) work package, to study the experience of working together
The FAR work has sought to make implicit values visible to the team so that these are available for discussion. In sustainability, researchers may assume that their colleagues share the same underlying assumptions and norms. This can cause confusion when colleagues' research priorities or practices diverge from their own, or from stated project objectives.
To surface implicit values early on in the project, the FAR researcher did two things. First, she interviewed team members about the value of sustainability to them personally. She presented the team with headline results of these interviews so that all members were more aware of the range of implicit values, instead of blindly assuming homogeneity.
The interviews indicated:
(a) A range of personal priorities
E.g. *Sustainability is annoyingly central in my life; I can tie myself in knots worrying about it*
E.g. *Certain physical comforts are important to me and I won't give them up, even for reasons of sustainability*
(b) A range of assumptions about what it means to lead a sustainable life
E.g. *I no longer have a car, just a bicycle*
E.g. *For me, sustainability is less about riding a bicycle instead of a car. It's about being kind, having empathy, or taking responsibility for someone in trouble*
Second, the FAR researcher facilitated an exercise to make team members' epistemological assumptions and research practices more apparent to each other. During this exercise, the team explored assumptions about what would constitute success in the project. This generated 14 success criteria. Members of the team mapped the degree of convergence or divergence in their responses to these criteria, which included realising individual achievements and pursuing collective achievements. While unstated individual and collective ambitions could appear to be in conflict, surfacing their implicit underlying values makes it more possible to discuss different priorities and find overlapping values.

sustainability research. Sustainability is a normative concept with a vast array of overlapping and diverging understandings, theories, and narratives regarding its meaning (Schmieg et al. 2017). For example, the concept of sustainability appears to be more strongly derived from the Western culture rather than indigenous cultures (Van Kerkhoff and Lebel 2015; Sacks 2018). In turn, sustainability science is an unavoidably value-laden endeavour not only because of the mere notion it addresses, but also due to the values underpinning scientific understandings of the world and scientific institutions.

In addition to the way in which ontological assumptions about the nature of reality shape scientific enquiry (e.g., Blaikie 2008), scientists hold pre-analytic visions (Schumpeter 1954) that underpin and shape scientific models and research practices. Such pre-analytic visions are largely formed based on transcendental values, and relate to themes such as how we judge different states of the world, notions of progress and what we conceptualise as 'good'. For example, the notion of efficiency (defined as non-wastefulness) is a primary, normative measure by which resource allocation is judged. However, this value judgement underpinning economic thought potentially conflicts with the normative notion of ecological resilience premised on ideas of redundancy. The underlying transcendental values (for efficiency or resilience) fundamentally shape judgements about the sustainability of a particular system or even how such systems are defined and studied. Moreover, the inherently interdisciplinary sustainability science is embedded in an organisation of science shaped by ontological, epistemic and normative assumptions, as well as institutional and power structures (e.g., Fazey et al. 2018). Assumptions of scientific models are also institutionalised and reinforced via scientific traditions and disciplines (e.g., Raymond et al. 2010); thus, transcendental values create powerful, constraining, and rarely questioned narratives in the sciences.

Being aware of, and making transparent, the assumptions of the current epistemological and ontological models of the world may seem an ambitious task (Miller et al. 2014). However, ignoring them limits the opportunity space of sustainability science by reducing epistemological agility, or perpetuating false confounding or fragmented ontological meanings. Being more critical and reflective upon the process of theorising and conducting research requires that the transcendental values shaping the research processes and scientific institutions (such as the demand for 'global relevance' in research findings) are justified and made explicit (Jerneck et al. 2011; Spangenberg 2011). Studies that observe, or critically reflect on research practices are increasing (Wuelser and Pohl 2016). For example, making explicit the normative assumptions and goals associated with ecosystem services research has been suggested as a means of harnessing its transformational potential (Abson et al. 2014).

Ultimately, the challenge of sustainability science is to co-produce actionable knowledge for intervening on sustainability problems in a way that permits a plurality of values and perspectives to co-exist (Miller 2013). Therefore, especially within scientific research practices, surfacing and acknowledging the underpinning assumptions (or pre-analytic visions) of scientists are a vital first step. Transdisciplinary research practice characterised by actively involving actors outside academia provides a useful avenue for more explicit reflection on the constraining and enabling roles of underpinning transcendental values in sustainability science and transformational change (Popa et al. 2014). Starting with problem framing, and going through all the main phases of the conceptual model of a transdisciplinary process (Lang et al. 2012), sustainability scientists make choices. Compared to research traditions where the values and norms shaping research are not explicitly discussed, in the case of transdisciplinarity, an essential role is played by a continuous dialogue and exchange between people from both scientific and societal bodies of knowledge. Sustainability problems are identified and bounded in value-explicit ways, as is the co-production and application of co-created knowledge (Ruppert-Winkel et al. 2015). Transdisciplinary research, and to a lesser extent interdisciplinary research, uses methodologies for eliciting and integrating the knowledge, goals, values, and norms of research participants, and translating them in the research design (e.g., Lang et al. 2012). Hence, by surfacing the tacit knowledge and the assumptions of diverse scientific backgrounds, transdisciplinary approaches allow generated knowledge to reflect multiple value systems in an integrated manner (Tschakert et al. 2016).

Value-laden assumptions within sustainability science often become less transparent when moving from abstract discussions (e.g., "What are the underpinning normative assumptions in ecosystem service research?") to concrete sustainability research projects (e.g., "How do we assess ecosystem services in this context?") (Fig. 1). Here, we argue that exploring the values underpinning and shaping individual research questions or projects is potentially fruitful for ensuring pluralistic problem framing and solution spaces. Particularly, in the case of science dealing with managing change, it is essential that researchers are aware of their own set of values, and their intended and possible role(s) as researchers (Wittmayer and Schäpke 2014), while explicitly providing time and space for self-reflection (Raymond et al. 2010). Such reflection gives researchers an inner-oriented understanding of reality. This under-considered aspect of sustainability science chimes with recent developments pointing to the importance of subjectivity and personal dimensions—the deep inner side—of sustainability transformation (Page et al. 2016; Fazey et al. 2018; Parodi and Tamm 2018) and goes back to the personal and tacit dimensions of knowledge of Michael Polanyi (1958) (see also Perspective 4).

Questions such as: "What are the normative assumptions that I bring to the research that I am carrying out?" and "How does this influence my choices about methodological and conceptual approaches?" are often overlooked, but especially important in the case of inter- and transdisciplinary sustainability research, where the lack of transparency can hinder or even undermine its results. As a practical starting point for Perspective 1, researchers may refer to the different continua of ontological, epistemological, and philosophical perspectives provided by the literature, for example, from an objectivist to a subjectivist approach (e.g., Moon and Blackman 2014; Raymond et al. 2014). Rawluk et al. (2019) also present a framework for mapping value concepts across ontology and epistemology, as well as different levels of abstractness and context dependency. These proxies for normative and value positions matter because they influence how sustainability science is conducted (choice of method, analysis, interpretation, and application) and the legitimacy of its outcomes. Tackling the above under-represented aspects and mapping how scientists through their positionalities build meaning and understand the world adds the needed nuance and transparency to the field of sustainability science (Jerneck et al. 2011, see also Table 2 for how we applied Perspective 1 to an ongoing research project). Finally, giving explicit consideration to value judgements that underpin scientific endeavours supports moving away from decision-making based solely on supposedly objective scientific information.

Perspective 2: Negotiating values

While Perspective 1 is concerned with the implicit values that scientists bring to transformational research, Perspective 2 focuses on the plurality of values that actors bring to participatory and group decision-making processes. This perspective asks questions around whose values count, how they are included, and how they shape participatory processes in sustainability science. Participatory approaches that seek to include values held by different actors generally enhance a solution orientation and the feasibility of sustainability interventions (Wiek et al. 2014). Solution strategies for sustainability problems require values to be expressed and understood during decision-making. Accounting for values, managing conflicts, and reconciling plural values builds civic participation and social legitimacy for the proposed transformational processes. This must be done at various scales of participation and by trading-off participants' views in the light of power relations (Bennett et al. 2015; Van Kerkhoff and Lebel 2015). Much of the focus in sustainability science has been on ensuring that all relevant stakeholders are included in participatory processes, where they are able to express their values (e.g., Leventon et al. 2016; Newig and Fritsch 2009). However, there is less focus in Perspective 2 on how the values of multiple stakeholders are negotiated in created shared positions or policies regarding specific sustainability challenges or contexts. We illustrate this under-represented element of the negotiating values perspective via the conceptual framework of Institutional Analysis and Development, IAD (Ostrom 2011).

The IAD framework (Ostrom 2011) provides a useful heuristic for understanding how social values are negotiated in group decision-making processes. It mentions different structural variables of existing institutional arrangements that constrain and influence the outcomes of such decisions. This framework does not directly articulate the value systems of actors, but rather focuses on actors' influence on policy outcomes and how well these outcomes fit their interests. After defining a policy problem, the focus of the IAD analysis moves to behavioural aspects in the action arena, as influenced by the context (biophysical conditions, attributes of the community, and rules in use). The 'action' refers to those behaviours to which the acting individual or group attaches a subjective and instrumental meaning (Kiser and Ostrom 1982). As such, some of the operational concerns in this framework include the ways in which actors assign value to their resources, how their information, beliefs, and institutional constraints shape these valuations (see also Perspective 3), and which internal mechanisms they use to ultimately decide upon strategies (Ostrom and Cox 2010). The influence of contextual factors on the action situation could bring forward the idea of changing values deeply embedded in the socio-cultural context (Perspective 4).

Scholars use approaches such as the IAD to focus on negotiating values. This helps to identify the different normative rules and social values that determine change in decision-making strategies. However, the origin of the actors' individual values, which shape their original positions, is often ignored or under-considered. This is also evident in the fact that the discussion about conflicts across transcendental values is relatively neglected. More work is dedicated to reconciling contextual values tied to a specific sustainability challenge, action, or intervention (Kenter et al. 2016). With this caveat in mind, insights from social psychology theories of behaviour, e.g., Stern's (2000) value–belief–norm model, might be beneficial in developing tools for surfacing transcendental values in the incipient phases of participatory processes. This in turn might allow for a more open and transparent negotiation of the values and beliefs that shape collaboration, as well as for the development of shared goals in relation with transformational change.

Perspective 3: Eliciting values

Perspective 2 focuses on how transcendental values shape the outcomes of decision processes within opportunity spaces bounded by sustainability science and its underpinning assumptions (Perspective 1). In contrast, the eliciting values perspective engages with how contextual values can be elicited and aggregated to judge particular choices, objects, or actions related to specific sustainability challenges. This perspective asks questions about which ascribed values and associated valuation processes are used to inform decision-making and management processes: how we elicit social values related to potential changes in the state of the world, and how the types of elicited values and the methods for their assessment influence research outcomes and consequently decision-making processes. This perspective includes ethical discussions regarding the appropriateness of monetary and non-monetary valuations of changing states of the world (e.g., Gowdy 1997), along with more technical discussion regarding explicit valuation frameworks such as cost–benefit analysis (e.g., Wegner and Pascual 2011). While we use the example of value elicitation in relation with nature and biodiversity to illustrate this perspective, we argue that contextual values elicited in other fields, such as Likert scale style elicitations in environmental psychology and other social science disciplines, are similarly constraining.

Many disciplines devote immense effort to trying to categorise and assess the various values assigned to nature (Turner et al. 2003). However, most valuations of nature or landscapes fall into the realm of quantitative assessments, often with monetary assessments focusing on a subset of ascribed values that can easily be measured. Led in part by The Economics of Ecosystems and Biodiversity (TEEB 2010), quantification of environmental values or of benefits people derive from nature were encouraged to be compatible with other quantitative metrics used for decision-making, particularly economic ones (Gómez-Baggethun et al. 2010; Norgaard 2010). The basis for economic valuations is postulations within welfare economic theory, where it is believed that changes in human well-being can be measured in terms of utility expressed in exchange value. Consequently, whole socio-cultural contexts are reduced through quantitative assessments to monetary values, reinforcing the mainstreaming of economic rationales for valuation. For example, emotional attachment to nature or the whole spectrum of values assigned to (cultural) ecosystem services are not captured by many mainstream valuation processes, and are not translated in the values associated to potential changes in the state of the world (Milcu et al. 2013).

Using the restrictive language of economics to elicit contextual values related to changing states of the world can silence the voices of those expressing less anthropocentric values and preferences, such as ecosystem dependent communities, indigenous peoples or nature itself. Consequently, authors working in the field of ecosystem services have long argued that acknowledging and identifying the plurality of values that lie beyond monetary or even instrumental ones (e.g., Kumar and Kumar 2008; Pascual et al. 2017; Arias-Arévalo et al. 2018) is key to advancing towards sustainability transformation. While the hegemony of economics logic and its consequences in terms of contextual values and valuation methods of choice is recognised and criticised (e.g., Gómez-Baggethun et al. 2010; Abson and Termansen 2011), the deeply ingrained paradigm underpinning such valuation methods, that of control and subordination of nature is less talked about. Consequently, the majority of the available valuation methods elicit values from the perspective of the current, arguably unsustainable economic system, not from the perspective of a desired state of the economic system (Norgaard 2010). Hence, similar to Perspective 1, one under-represented, yet relevant, aspect of this perspective consists of the inherent political and normative assumptions of methods and methodologies used to investigate values, and the relationship between the evaluating agent, the evaluated object or state, and the method used for valuation. As a response, scholars who argue for their transparency also call for valuation methods that are co-created. These are expected to help surface pluralistic, enacted contextual social values tightly linked with historic developments, local landscapes and cultural environments through which such values arise (Gunton et al. 2017). Moreover, such integrative valuation approaches allowing the expression of value plurality are more congruent with the multiple meanings of human well-being, of a good quality of life, and with concerns for the well-being of other beings. The movement that is rising in response to this under-recognised aspect and that is demanding the acceptance of multiple worldviews and associated values of nature has consolidated around, for example, a number of international science–policy platforms such as IPBES (2015) in its notion of nature's benefits to people and related approaches (Christie et al. 2019b). Another recent milestone in the extension of rationales for attributing value to nature beyond intrinsic and instrumental values is the introduction of relational values derived from all-encompassing human–nature relationships (Pascual et al. 2017). However, these movements also encounter challenging value conflicts associated with the different ways of eliciting values. Hence, we recognise that no form of value elicitation (or integration) can be presented as a panacea; rather, we need complementary approaches. Synergistic benefits should emerge from their co-existence and plurality (see also Perspective 2).

Another under-considered aspect of Perspective 3 stems from making explicit the dichotomy between transcendental and contextual values (Kenter et al. 2015). There is less research on the elicitation of transcendental (or first-order/held) values (Brown 1984), and on how such values influence second-order preferences/contextual values (Abson and Termansen 2011). Underlying transcendental values held by individuals are more difficult to aggregate to provide social values, than are second-order ascribed values that flow from them (Brown 1984). However, changes to transcendental values hold the greatest transformational potential as strong motivational driver that can explain human behaviour (Abson et al. 2017, Perspective 4). We suggest that deliberative valuation methods, co-produced through more transdisciplinary approaches, are potential ways to capture a broader range of values of nature (Raymond et al. 2014). Such methods also provide a means of eliciting explicit contextual social values related to specific states of the world that can also actively incorporate the exploration of transcendental social values (see also Perspective 4).

Perspective 4: Transforming through values

The first three values perspectives are based on surfacing, navigating, and eliciting existing social values related to sustainability transformations with the premise that better understanding such values can help foster desired societal change. In contrast, the transforming through values perspective engages with questions around interventions for activating (Raymond and Raymond 2019), nurturing, or shifting transcendental values as a means of facilitating transformational societal changes. The rationale is that transcendental values underpin individual behaviours and, at a collective level, the societal paradigms from which institutions, rules, and norms emerge. As such, this perspective adopts a complex system approach, with individuals at the same time being shaped by the system they are part of, and having the agency to shift (together with others) the goals of that system (Hausknost et al. 2016; Sacks 2018).

This perspective takes an interventionist stance: it assumes a certain degree of control of humans over their context, maintaining that people are able to reflect on and break through the structures that constrain them, as well as to take collective action for changing those structures. This perspective links values to notions such as triple-loop learning, which argues that outcomes of decision-making may not only improve practices (single-loop), but also lead to changes in the assumptions and values driving those practices (double-loop), and ultimately in the norms and broader context shaping the latter (triple-loop) (Armitage et al. 2008). Social learning is a closely related concept, as it emphasises, in certain conceptualizations, a change in understanding that is situated at wider social units than the individual and which takes place as a result of social interactions (Reed et al. 2010). The claim is that by creating shared spaces for joint deliberation and reflection, it is possible to influence a critical mass of people towards making decisions that benefit society. Participation processes, thus, become more than opportunities for negotiating values within a determinate action situation (Ostrom 2011), but are instances of broader and iterative societal engagement that can lead to changes in biophysical conditions, the attributes of the communities and the rules in use, i.e., can alter the context sensu IAD (see also Perspective 2). Horcea-Milcu et al. (2017), for instance, illustrate how shared transcendental values co-evolve in slow processes over time, and how central such processes are for ensuring the resilience of a cultural landscape.

Adherents to the transforming through values perspective also highlight the dynamic nature of values, with some explicitly linking societal learning processes to changes at the individual level. Van Riper et al. (2019) present a multi-level model of value shift through social learning and emphasise how individual and cultural values inform each other. Which conceptualization of values is employed matters a great deal in upholding such claims, with contextual values being seen as more malleable than transcendental ones (Kenter et al. 2015). Transcendental values appear to be both relatively slow to change and relatively stable (Ives and Kendal 2014; Fischer et al. 2012) compared to attitudes (i.e., an expression of contextual values), so processes of participatory group learning might be more likely to only trigger shifts in contextual values. Some authors also talk about such processes in terms of "value activation", suggesting that different contexts may awaken or bring forward different values, which consequently play a role in filtering information and setting goals (Verplanken et al. 2009). However, there is some recent empirical evidence that deliberative processes can also lead to more fundamental changes of values, i.e., target transcendental values (e.g., Raymond and Kenter 2016), although it is unclear whether such changes are lasting or not. To the extent to which transcendental values are regarded as the underlying canvas of behaviours—e.g., according to theories such as the value–belief–norm model by Stern (2000) or the behaviours–attitudes–values cognitive hierarchy model adapted from Fulton et al. (1996)—individual value change has potential to function as an intervention point for sustainability transformations. For example, Christie et al. (2019a) mention the notion of "ecological conversion", as a personal change of transcendental values towards sustainability. An open question remains, though, about which values support sustainable outcomes, how those values (and not others) can be activated, and by whom (Miller et al. 2014)? A potential answer comes from positive psychology which strives to activate pre-existent but hitherto not enacted desirable values (Raymond and Raymond 2019).

Following from this, one important partly under-considered aspect of Perspective 4 is that, at least in democratic societies, a critical mass of individual value change must be achieved to lead to visible changes in societal outcomes. As such, discussions often bleed into those of paradigms and dominant worldviews. For instance, some scholars adhering to the transforming through values perspective challenge the global paradigm of economic growth (D'Alisa et al. 2014), by calling for more reflexivity on the values underpinning it and for re-evaluating the goals that the economic system should serve (see also Perspective 3). While it may be possible to shift one's values (via e.g., deliberative processes) and trigger new individual behaviours, by which mechanisms would such shifts amount to widespread paradigm change at the level of an entire society?

One answer would point again to the link between individual and cultural values (van Riper et al. 2019). However, a second under-considered aspect of Perspective 4 is the claim of some scholars that it is not possible to influence the direction of a culture by changing individuals' values one at a time. Manfredo et al. (2017a, p. 775) maintain that values are "deeply entangled in a web of material culture, collective behaviours, traditions, and social institutions", and they are shaped by the context. As such, lasting value change is very slow and it is a consequence of other changes in the environment, as it follows from new behaviours, rather than precedes them (also see Manfredo et al. 2017b). In criticising the pretention of deliberate change that Perspective 4 inherently invokes, these authors plead instead for a focus on attitude, norm, and behaviour change in specific contexts (Manfredo et al. 2017a). Theorists of transition experiments (van den Bosch and Rotmans 2008) and transition initiatives (Gorissen et al. 2018) provide some insights into how phenomena that start out in niches might scale up to the level of an entire society by giving special attention to reflective learning, interaction, and experimentation at the level of society (see also McAlpine et al. 2015). As a result of such experiments, finding out whether values or behaviours should change first may amount to the chicken-and-the-egg question. The important effect is a shift in the dominant paradigm, i.e., a transformation. Within this context, individual agency and empowerment appear to play an important role, and the values underpinning personal action are part of the story (Westley et al. 2017). Along these lines, O'Brien (2018) considers the personal sphere of transformation, while Kendal and Raymond (2019) mention the influence of socio-psychological processes on the pathway of individual change for values shift.

This leads to a third under-considered aspect of Perspective 4, which pertains to the notion of personal sustainability (Parodi and Tamm 2018), and the relationship with oneself (Sacks 2018). Especially outside Western culture, inner dimensions of sustainability are considered as shaping the outside world. The processes taking place at individual level fundamentally affect the system level and are hence relevant for identifying the causes of the global sustainability deficit, as well as potential solutions (Villido 2018). As such, ignorance of the inner sphere and personal disconnections count among key causes for unsustainability (Villido 2018). In contrast, self-awareness of the values populating individual inner spaces, such as truth and love (Parodi 2018) paves the way to personal transformation that can foster our global transformation (O'Brien 2018). This under-considered notion of personal sustainability also echoes insights from psychology that concepts of "self" play a central role in moderating the relationship between values and behaviours (Verplanken et al. 2009; Raymond and Raymond 2019).

Perspective 4 emphasises the role of individual value change in fostering societal transformations while also highlighting possible guiding mechanisms or approaches, such as empowerment and self-awareness for triggering it. Especially, in relation with Perspective 1, it opens sustainability science to enquiries into the role of scientists in fostering such changes, or in modelling specific values themselves. It also raises questions on whether shifting values requires our research to employ new methods of envisioning, of reflecting, and of engaging with others such as serious games. Table 3 exemplifies how we applied Perspective 4 within our ongoing 'Leverage Points' project.

Implications and future directions

Sustainability is a normative concept often suffering from the lack of agreement regarding what is worthwhile and meaningful. Values are generally narrowly considered inside each of the four perspectives, and even more rarely across them. Paradoxically, the ontological and epistemological richness surrounding values creates a complexity that is hard to navigate. Our four non-prescriptive perspectives help to distil and embrace this complexity. They offer guidance on where, and how to think about values when aiming for scientific activities contributing to transformational change. There are different situations in which one or more of the perspectives becomes helpful. Our paper sought to facilitate a sustainability research practice that changes between the different perspectives, depending on what is needed. The surfacing implicit values perspective draws attention to the normative choices hiding in scientific models, concepts and practices, and how they frame (in the broadest sense) the opportunity spaces for sustainability science. The negotiating values perspective focuses on unfolding the values of different actors involved in participatory settings, and how these shape the outcomes of decision processes within opportunity spaces delineated in Perspective 1. In contrast, the eliciting values perspective investigates attributing contextual and transcendental values in relation with specific changing states of the world, while the transforming through values perspective looks at the potential of individual value change or activation to function as intervention point for sustainability transformations. The four closely interrelated perspectives are not part of a linear progression, and do not imply a hierarchy of elements of process, yet have different degrees of depth in undertaking value enquiries or ultimately values related interventions (Fig. 1, Table 1). They range from internal reflection within science and society, and directions to reform sustainability science and practice (Perspective 1) to a more external (Perspective 3) and interventionist stance (Perspective 4). For example, social representation theory asserts that to foster a shared social ground and achieve further interactions, we need to understand the perspectives used by different individuals and communities (Perspective 2) prior to eliciting social values (Perspective 3). The perspectives also call for fundamental paradigm shifts either at the level of science (Perspective 1, 3) or at the level of society (Perspectives 2–4). Documenting how the perspectives shape, constrain and interact with each other, and proposing strategic ways to combine their different aspects according to the sustainability problem at hand, support mainstreaming value enquiries into transformational sustainability science.

We discuss key messages of the four perspectives in terms of their implications for (1) transformational scientific practice, (2) transformational research agendas, and (3) sustainability transformations in practice. Across the perspectives, transdisciplinarity, as one key sustainability research practice seems well suited to systematically incorporate

Table 3 Example of engaging with Perspective 4 (Transforming through values) within the Leverage Points project

Serious games are appealing in social processes for shaping decisions because they: (a) create immersive spaces to experiment with situations that are impossible in the real-world (e.g. switch of roles); (b) allow for testing novel solutions in a safe, risk-free space, where immediate feedback on consequences is provided; (c) dismantle real-life power relations and provide equal access to the game situation (Medema et al. 2016; Hummel et al. 2011; Katsaliaki and Mustafee 2012). As a consequence, they are thought of as tools for facilitating social learning, through processes of trust building, empathy exchange, and competence and skill development (Hummel et al. 2011).
In models of behaviour change used to understand the contribution of serious games to societal change, value change appears as one important mediating variable.
In our transdisciplinary work with farmers managing a pasture in a Saxon village in Transylvania, Romania, we used a serious game about contributing to a common good as a means to enhance collaboration. As reported in informal discussions with the participants, the process allowed for a levelling out of pre-existing roles and power dynamics, focusing the attention on the common interest in maintaining the resource. For the first time in several years, the neutral space provided by the game context enabled real-life "enemies" to meet and discuss joint strategies, changing their previously free-riding or conflictual behaviours, while at the same time building an understanding that they might actually share common interests.
As a one-time event, this may not equate with the deep transformational value change required for long-term collaboration, but game theoretic research on repetitive interactions (Axelrod and Hamilton 1981) opens a promising avenue for the hypothesis that serious games might have a role as transformational interventions in social–ecological systems.

transcendental values in transformation processes guided or informed by sustainability science. Transdisciplinarity is typically envisaged as a science–society collaboration that spans a broad range of disciplines and that involves the perspectives and interpretations of actors affected by the problem constellation under scrutiny (Lang et al. 2012; Popa et al. 2014). Nevertheless, consideration of values in transdisciplinary research theory and practice remains in its infancy. In addition, this research practice also faces other challenges, such as navigating the tension between allocating a lot of attention to the process at the expense of expediting outcomes, or balancing scientific rigor with societal relevance. However, it is precisely at these interfaces, where a space exists to bridge different actors' disparate, value-laden assumptions and transcendental values. In so doing, transdisciplinary approaches provide the possibility to make visible and ultimately co-generate more robust, legitimate, and transparent social values that act as a guide for sustainability transformations. Such approaches enable mutual learning between scientists rooted in different academic traditions and actors outside academia from different knowledge domains.

Similarly, when considering implications for transformational research agendas, the notion of holistic, integrative approaches for considering values in transformational change become key across all perspectives. Each perspective calls for holding space for more inclusive approaches for co-producing knowledge (Perspective 1), deliberative participatory practices (Perspective 2), value elicitation methods (Perspective 3), or a more holistic consideration of where to intervene in complex socio-ecological systems to effect transformational change (Perspective 4). This opening up of knowledge systems (Cornell et al. 2013) and widening of valuation methodologies (Arias-Arévalo et al. 2018) also aims to steer current transformational research beyond the dominant Western-style scientific-rational way of seeing the world to include currently under-considered aspects in the values perspectives, such as indigenous and local knowledge (Van Kerkhoff and Lebel 2015). More reflexive and co-created approaches of operationalizing values in relation with transformational change are better tailored for the heterogeneity and complexity of value understandings.

For future research agendas, value shifts are probably not the *holy grail* of transformational change, yet they have the potential to go beyond incremental change. Values are theoretically associated with deep leverage points (Abson et al. 2017; Fischer et al. 2012), where interventions can lead to fundamental system transformation, as opposed to interventions at shallow leverage points such as modifying parameters or altering feedback loops in resource use (Meadows 1999) (see also Fig. 1). Kendal and Raymond (2019) point towards ways in which this potential could be leveraged over time, such as shifts in transcendental values in response to societal development or economic circumstances. Moreover, social values emerging from sustainability science processes (Perspective 1), or actively changed via such processes (Perspective 4) may determine our ability to envision and design systems to fulfil our needs in a just and sustainable manner (Abson et al. 2017). Similarly, by explicitly considering how different transcendental and contextual values are navigated and expressed in social processes related to transformational change we open the prospect for transdisciplinary processes that better reflect what those societal needs are (rather than imposing understandings of those needs for specific traditions of science).

At the level of sustainability transformations in practice, the four perspectives invite reflexive introspection from sustainability scientists themselves (Perspective 1, Popa et al. 2014; Wittmayer and Schäpke 2014), and from actors in other societal domains (Perspective 4, Ives et al. 2018). Weaving self-reflection and self-awareness in everyday research practice might be a way forward for researchers' interactions among themselves, with young scholars or societal stakeholders (Lang et al. 2017). Our calls to enliven the inner dimensions of sustainability and transformation through reflexive practices and habits of mind set a clear agenda for scientists and policymakers to move beyond the discomfort created by such a deep and complex concept by embracing its complexity.

Praxis recommendations

To incorporate social values in transformational processes and critically deal with their plurality, we suggest that there is a need to actively reflect on one's own positionality in relation with the particular operationalization of values identified in the four values perspectives. This requires organising deliberative fora to surface how these different faces of social values shape sustainability science and transformational processes. When multiple actors are involved (in surfacing, negotiating or eliciting values), engaging a 'values broker' may help mediate between the expressed competing values to prevent conflict (see e.g., Ingold and Varone 2012) or shape consensus. Unpacking and negotiating conflicting values through deliberation are also likely to affect what transcendental values and preferences people express. This calls for a new negotiation and agreement on the terms of deliberation at the incipient phases of participatory and elicitation processes that facilitate and inform decision-making. Similarly, the impact of how values are ascribed and elicited for guiding policy formation and for being incorporated into policies needs to be assessed. It is increasingly apparent that the terms of deliberation or valuation do not necessarily need to lead to unanimous consensus, but rather plastic ways to deal with value conflicts while maintaining the naturally occurring plurality of expressed differences. Seeing that sustainability is considered a collective balancing act involving a continuous process of negotiation of social values and interests (Loorbach et al. 2011), the four perspectives presented here help articulate a collaborative approach to policy and practice that promotes mutual learning between practice and science.

Conclusion

By examining different ways to operationalize values in transformational sustainability science, this paper provides a foundation for advancing a value-based perspective in transformational research, from which to further develop sustainability theory and transformational practice. Explicit recognition of the four interconnected perspectives can help sustainability scientists to: (1) move beyond general discussions implying that values matter while being vague about how and where, (2) gain an awareness of the positionality of one's own values perspective when undertaking values related sustainability research, and (3) reflect on the operationalizations of values in different contexts such as those shaped by local perspectives. While it is important to recognise that our categorization of four values perspectives in relation with sustainability science and transformational change does not encompass the diversity of narratives around values and change in the literature, we believe that it can enable boundary work at the science–policy–society interface for sustainability transformation. There would be numerous rewards from bringing such a hidden topic to light.

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Overview of articles included in this cumulative Ph.D. thesis

(in accordance with the guideline for cumulative dissertations in Sustainability Science [January 2012], in the following termed “the guideline”)

Title of Ph.D. thesis: Biophysical human-nature connectedness: conceptualizing, measuring, and intervening for sustainability

Papers included:

[1] Christian Dorninger, David J Abson, Joern Fischer, Henrik von Wehrden (2017): Assessing sustainable biophysical human–nature connectedness at regional scales. *Environmental Research Letters* 12, 055001, https://doi.org/10.1088/1748-9326/aa68a5

[2] David J. Abson, Kathleen Klaniecki, Christian Dorninger, Henrik von Wehrden, Christopher D. Ives, Maraja Riechers (submitted): Human-nature connections: aligning biophysical and sociopsychological approaches for sustainability. [Submitted to: *People and Nature*]

[3] Christian Dorninger, Henrik von Wehrden, Fridolin Krausmann, Martin Bruckner, Kuishuang Feng, Klaus Hubacek, Karl-Heinz Erb, David J. Abson (submitted): The myth of decoupling? A global analysis of humanity’s biophysical connections to nature. [Submitted to: *Nature Sustainability*]

[4] Christian Dorninger, Alf Hornborg, David J. Abson, Henrik von Wehrden, Anke Schaffartzik, Stefan Giljum, John-Oliver Engler, Robert L. Feller, Klaus Hubacek, Hanspeter Wieland (submitted): Global patterns of ecologically unequal exchange: implications for sustainability in the 21st century. [Submitted to: *Proceedings of the National Academy of Sciences of the United States of America*]

[5] Christian Dorninger, David J. Abson, Cristina I. Apetrei, Pim Derwort, Christopher D. Ives, Kathleen Klaniecki, David P. M. Lam, Maria Langsenlehner, Maraja Riechers, Nathalie Spittler, Henrik von Wehrden (submitted): Leverage points for sustainability transformation: a review on interventions in food and energy systems. [Submitted to: *Ecological Economics*]

[6] Christopher D. Ives, David J. Abson, Henrik von Wehrden, Christian Dorninger, Kathleen Klaniecki, Joern Fischer (2018): Reconnecting with nature for sustainability. *Sustainability Science* 13:1389–1397, https://doi.org/10.1007/s11625-018-0542-9

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Authors' contributions to the articles and articles publication status (according to §16 of the guideline):

Article #	Short title	Specific contributions of all authors	Author status	Weighting factor	Publication status	Conference contributions
[1]	Assessing sustainable biophysical human–nature connectedness at regional scales	CD, DA, HvW: conception of research approach CD, DA, JF, HvW: wrote the paper	Co-author with predominant contribution	1.0	Published in: *Environmental Research Letters* (IF=6.192)	ESEE 2017, Resilience Conference 2017
[2]	Human-nature connections: aligning biophysical and sociopsychological approaches for sustainability	DA, KK, CD: conception of research approach DA, KK, CD, HvW, CI, MR: wrote the paper	Co-author with equal contribution	1.0	Submitted to: *People and Nature* (no IF yet)	Leverages Points Conference 2019†
[3]	The myth of decoupling? A global analysis of humanity's biophysical connections to nature	CD, HvW, DA: designed the study CD, HvW, FK, MB, KF, DA: analysis and interpretation of data CD, HvW, DA, FK, MB, KF, KH, KHE: wrote the paper	Co-author with predominant contribution	1.0	Submitted to: *Nature Sustainability* (no IF yet)	Leverages Points Conference 2019
[4]	Global patterns of ecologically unequal exchange: implications for sustainability in the 21st century	CD, AH, DA, HvW, HW: designed the research CD, RF, JOE, HW: carried out the computations CD, AH, DA, HvW, AS, SG, JOE, RF, KH, HW: wrote the paper	Co-author with predominant contribution	1.0	Submitted to: *PNAS* (IF=9.58)	ESEE 2017

[5]	Leverage points for sustainability transformation: a review on interventions in food and energy systems	CD, DA, HvW: designed the research CD, CA, PD, KK, DPML, ML, MR, NS: reviewed the papers CD, DA, HvW: did the analysis CD, DA, CA, PD, CI, KK, DPML, ML, MR, NS, HvW: wrote the paper	Co-author with predominant contribution	1.0	Submitted to: *Ecological Economics* (IF=3.895)	Leverages Points Conference 2019
[6]	Reconnecting with nature for sustainability	CI, DA, HvW, CD, KK, JF: developed the conceptual approach CI, DA, HvW, CD, KK, JF: wrote the paper	Co-author with important contribution	0.5	Published in: *Sustainability Science* (IF=3.855)	
[7]	Human–nature connection: a multidisciplinary review	CI, HvW: designed the study CI, MG, KK, CD, JL, SB, PA, BML: reviewed the papers CI, MG, JF, DA, KK, CD, JL, SB, PA, BML, CR, DK, HvW: wrote the paper	Co-author with small contribution	0	Published in: *Current Opinion in Environmental Sustainability* (IF=5.545)	Transformations Conference 2017†
[8]	Values in transformational sustainability science: four perspectives for change	AIHM, DA, DL: developed the conceptual approach AIHM, DA, CA, IAD, RF, MR, DPML, CD, DL: wrote the paper	Co-author with small contribution	0	Published in: *Sustainability Science* (IF=3.855)	
			Sum:	5.5		

Explanations

Specific contributions of all authors

CD = Christian Dorninger, HvW = Henrik von Wehrden, DA = David J. Abson, CI = Christopher D. Ives, MG = Matteo Guisti, KK = Kathleen Klaniecki, JL = Josefine Laudan, SB = Stephan Barthel, PA = Paivi Abernethy, BML = Berta Martin-Lopez, CR = Christopher Raymond, DK = Dave Kendal, AIHM = Andra-Ioana Horcea-Milcu, DL = David Lam, CA = Cristina Apetrei, IAD = Ioana Alexandra Duse, RF = Rebecca Freeth, MR = Maraja Riechers, DPML = David P. M. Lam, DL = Daniel Lang, ML = Maria Langsenlehner, NS = Nathalie Spittler, KF = Kuishuang Feng, KH = Klaus Hubacek, FK = Fridolin Krausmann, KHE = Karlheinz Erb, AS = Anke Schaffartzik, SG = Stefan Giljum, HW = Hanspeter Wieland, RF = Robert Feller, JOE = John-Oliver Engler, MB = Martin Bruckner, JF = Joern Fischer

Author status

according to §12b of the guideline:
Single author [Allein-Autorenschaft] = Own contribution amounts to 100%.
Co-author with predominant contribution [Überwiegender Anteil] = Own contribution is greater than the individual share of all other co-authors and is at least 35%.
Co-author with equal contribution [Gleicher Anteil] = (1) own contribution is as high as the share of other co-authors, (2) no other co-author has a contribution higher than the own contribution, and (3) the own contribution is at least 25%.
Co-author with important contribution [Wichtiger Anteil] = own contribution is at least 25%, but is insufficient to qualify as single authorship, predominant or equal contribution.
Co-author with small contribution [Geringer Anteil] = own contribution is less than 20%.

Weighting factor
according to §14 of the guideline:

Single author [Allein-Autorenschaft]	1.0
Co-author with predominant contribution [Überwiegender Anteil]	1.0
Co-author with equal contribution [Gleicher Anteil]	1.0
Co-author with important contribution [Wichtiger Anteil]	0.5
Co-author with small contribution [Geringer Anteil]	0

Publication status

IF = ISI Web of Science - Impact Factor 2018

Conference contributions (acronym, society, date, venue, website)

ESEE 2016, European Society for Ecological Economics, 18-23 June 2016, Budapest (Hungary), http://esee2017budapest.org/

Resilience Conference 2017, Stockholm Resilience Center, 20-23 August 2017, Stockholm (Sweden), http://resilience2017.org/

Leverages Points Conference 2019, Leverage Points Team, 6-8 February 2019, Lüneburg (Germany), http://leveragepoints2019.leuphana.de/

Transformations Conference 2017, Transformations Forum, 30 August – 1 September 2017, Dundee (Scotland), https://www.transformationsforum.net/transformationsconferences/2017

† Paper presented by co-author]

Declaration (according to §16 of the guideline)

I avouch that all information given in this appendix is true in each instance and overall.

Declaration

I hereby certify that the submitted dissertation entitled 'Biophysical human-nature connectedness: conceptualizing, measuring, and intervening for sustainability' has been written by me without using unauthorized aids. I did not use any aids and writings other than those indicated. All passages taken from other writings either verbatim or in substance have been marked by me accordingly.

I hereby confirm that in carrying out my dissertation project I have not employed the services of a professional broker of dissertation projects, nor will I do so in the future.

This dissertation, in its present or any other version, has not yet been submitted to any other university for review. I have not taken or registered to take another doctoral examination.

Wien, 06.10.2019

Christian Dorninger