Sustainability Science (2021) 16:727–747
https://doi.org/10.1007/s11625-020-00872-0

SPECIAL FEATURE: ORIGINAL ARTICLE

Leverage Points for Sustainability Transformations

Transformation for sustainability: a deep leverage points approach

Danielle Davelaar[1]

Received: 8 January 2020 / Accepted: 5 October 2020 / Published online: 19 January 2021

Abstract

Change and transformation of human systems are increasingly seen as the fundamental solution space for treating the root causes of unsustainability. What does transformation of human systems for sustainability exactly mean and entail, and how to effectively transform human systems? This paper addresses these essential questions in a holistic, systems thinking approach following and extending the leverage points tool for systemic change proposed by Meadows (*Thinking in Systems: a primer*. Chelsea Green Publishing, White River Junction, 2008). The paper focuses on the often unquestioned, largely unconscious, systemic realm of mental models and human intent. It targets Meadows' deepest leverage points of purpose and paradigm; beyond, it deals with worldview, core metaphor, and human thinking. The fundamental outcome of this conceptual study is that unsustainability roots in a cognitive illusion coupled to a lack of teleological thinking. Transformation needs us to see and reconceive the human–world bond through the systemic lens of dynamic inclusion, aliveness, purpose and value. Learning to think in terms of living systems, physical and mental, and substituting the iceberg metaphor-in-use in conventional systems thinking with a holistic metaphor of nested leverage points are the first transformation steps toward a new sustainability paradigm. Practical evidence and ecological content come from the transformative design discipline of biomimicry, which consciously turns to nature as the source of its conceptual system. The paper concludes that transformative practice for sustainability will gain momentum by braiding together systems thinking in practice and biomimicry thinking. In sum, this transdisciplinary approach opens up exciting research horizons in ontological, epistemological, methodological and teleological directions.

Keywords Biomimicry · Holistic systems thinking · Leverage points · Metaphor · Nested hierarchies · Sustainability paradigm

Introduction

"Give me a lever long enough and a place to stand and I will move the Earth" said the Greek physicist Archimedes (ca 285 BC–ca 212 BC), as he discovered the principle of the lever. Less than two and a half millennia later, *Homo sapiens* turn Archimedes' famous science fiction into reality. Human impact now equals geological forces in influencing the trajectory of the Earth system (Steffen et al. 2011). For some, the proclamation of the Anthropocene (Crutzen and Stoermer 2000) is the much needed paradigm shift in the human mindset to resituate humanity within the Earth system. For others, the very notion that humans have become the shapers of the Planet dangerously reinforces the fallacy of anthropocentrism and dominion (Kumar 2013). As we approach a planetary threshold (Steffen et al 2015a), those who subscribe to the anthropocentric narrative of separation (Henning 2016) face an evident dilemma: the irreversible collapse of the Biosphere versus the great decoupling. The latter refers to a future of planetary boundaries (Steffen et al. 2018). It is the illusory option of limiting, by governance, the playgrounds for *Homo sapiens* to evolve without rejecting our misleading, anthropocentric self view of planetary stewards, controllers and managers.

The systems archetype of the 'boiled frog' (Kim 1992) comes to mind. Either reality awakens us from the flaw in

Handled by Julia Leventon, Leuphana University, Faculty of Sustainability, Germany.

✉ Danielle Davelaar
danielledavelaar@t-online.de

[1] Water and Sustainability Professional, P.O. Box 100338, 67403 Neustadt-an-der-Weinstraße, Germany

the anthropocentric narrative and we jump out of the boiling water on time, or we pursue our lifestyles of doing things better and doing better things until the Earth system simply decouples us. But what opportunity will make humans react on time: a natural catastrophe, a pandemic? Is a virus, primary driver of human evolution by any means, likely to catalyze a shift in consciousness and turn the tide of history? Real change is as much about understanding what is and accepting the truth, as it is about creative aspiration and envisioning a different future (Senge 2004). If indeed we are to re-align with the Earth system we have, in the words of the cultural historian and profound thinker Thomas Berry (1914–2009) but one option: to re-invent the human, ourselves, one's self. The Great Work and Transition to an Ecozoic Era and Civilization (Berry 2000), the Great Turning (Macy and Brown 2014), the Rising Culture (Capra 1983) are all visions of a desirable future based on a cosmocentric narrative of re-union, wholeness, and interbeing (Wahl 2016) that understands transformation as a deep learning journey. For those taking up the challenge, the leverage key to transformation was gracefully crafted by Donella Meadows (2008). A bold start into the new, real world is already being pioneered by many change makers on the planet (Benyus 2002; Glasser 2019).

From this bird's eye view of the bifurcation between tragedy and transformation at which humanity stands I now zoom into what is, from my scientific perspective, the focal point for research and topic of this paper: the perception of transformation as solution space. The urgent need for radical, rapid change toward sustainability is widely agreed upon; however, what fundamental change entails and how this comes about is a topic of research and debate in the social sciences and beyond (Feola 2015). How to transform ourselves, our science, institutions and societies for a better future? What interventions are required? These are also the puzzling questions now driving a new line of transformational research for sustainability. Researchers at Leuphana University, Germany recently proposed a leverage points (Meadows 2008) perspective as a potentially powerful systems thinking approach to sustainability issues (Abson et al. 2017). These researchers aim at transformational, deep systemic interventions, arguing that the largely problem-focused orientation so far in sustainability science could only target relatively ineffective, shallow leverage points. At the same time, they recognize that acting on deep leverage points is difficult in practice, even if the benefits could be substantial (Fischer and Riechers 2019).

As an independent sustainability researcher and practitioner, I am foreign to the institutionalized research enterprise and its path dependencies. From this outsider's position, my appreciation is that the Leuphana researchers' transformational aims and approach (Abson et al. 2017; Fischer and Riechers 2019) might not be bold enough to attain the aspirational goal of transformation. Defining broad realms of deeper leverage on the levels of design and intent does not bring into sharp focus the most influential, deep leverage points: paradigm and beyond (Meadows 2008). Consequently, this approach will not hit, nor come to terms with the final (teleological) root cause (singular) of unsustainability. For the same reason, this line of research cannot as yet relate to the solution space of nature's time-proven designs for sustainability, nor attune to the transformative design practice of biomimicry and its powerful vision (Harman 2013; Baumeister et al. 2014). Perhaps most importantly, the insufficiency in approach also has a methodological dimension. By deliberately choosing for an epistemological position to system thinking, the transdisciplinary research agenda by Abson et al. (2017) fails to bridge the ontological versus epistemological divide, which duality is only transcended in taking a true holistic system thinking approach (Ison 2016). In other words, experimenting with the how to transform human systems of interest without fundamentally understanding what transformation is and entails, personally and collectively, can only lead halfway to successful theory informed practice for sustainability. The purpose of this paper is to tackle this blind spot in the very promising leverage points approach to and perspective on sustainability (Abson et al. 2017; Fischer and Riechers 2019).

Objective, approach, and outline

The goals of this study are: (i) to gain a deeper understanding of transformation for sustainability; (ii) to identify the root cause of unsustainability and to articulate its cure; (iii) to put Meadows' (2008) deep leverage points to the test as a dual, holistic instrument for analytical digging and systemic curing; (iv) to showcase biomimicry design and practice (Benyus 2002) as a substantial proof for the conceptual findings in this study. The overall objective is largely conceptual in nature; therefore, this paper essentially reports a thinking-and-reasoning process and its mental outcome. Reflecting on my personal experience in thinking, I follow the theory of Lackoff and Johnson (2003) that our conceptual system in terms of which we think, design and act, is fundamentally metaphorical in nature. Consequently, the conscious use of conceptual metaphors and models plays a prominent role in transmitting my ideas and reasoning. I reason back and forth between theory and observation using deduction and induction, thereby extending concepts and expanding conceptual models, and building a working hypothesis where needed. The disciplines touched upon are: sustainability science, philosophy of science, environmental philosophy, cultural philosophy, fundamentals of ecology and design for sustainability. Observations either source from, or are supported by literature. My systems thinking approach is holistic (Ison

2016): analytical and synthetic, systematic and systemic, ontological and epistemological; findings are transformational (understanding) and transformative (practicability and practice). Meadows' (2008) famous leverage points for intervention in systems underpin this conceptual study as a core metaphor, a model for gaining understanding and an instrument for causing transformation. The tool consists of a scale of entry points for systemic change ranging from shallow to deep leverage potential. Table 1 gives an overview of Meadows' list of the 12 intervention points. Most transformative results come from small, well-focused shifts in qualitative systems characteristics. The leverage points introduce a practical way of holistic thinking and intervening in systems from a perspective that pays attention to what is important, not just quantifiable (Meadows 2008; Fischer and Riechers 2019). The key concepts of paradigm, worldview and metaphor explored in this paper are used in the meaning of human, mental constructs and deep leverage points.

I understand this study as a case of solo transdisciplinarity. Solo because it is no team work but an individual thinking piece. By transdisciplinarity, I mean Ison's (2017) interpretation of the word: it is by virtue of my holistic, transcendent systems thinking approach serving the goal of transformation that I qualify my work as transdisciplinary. The structure of this paper follows its transdisciplinary nature and purpose. Occasionally it may transgress the rules of traditional, scientific writing. The line of argumentation toward my goals divides the remainder of the paper in 6 self-contained but interrelated sections, and a conclusion. The first section "What is transformation?" explores the notion of transformation on a systemic, conceptual level of understanding. Next section "Re-thinking the present (un) sustainability paradigm" moves forward on that level by successively inquiring the notions of paradigm and sustainability paradigm. Next section "An emerging worldview that fundamentally re-connects" digs even deeper, questioning the notions of worldview and core metaphor to get at the root cause of unsustainability. Next section "The conceptual root cause of unsustainability and its cure" then postulates the working hypothesis that a core metaphor is a highly effective, deep leverage point to cascade conceptual and consequently practical transformation. Building on this hypothesis, the section "Transforming the iceberg metaphor in nested leverage points" demonstrates that the leverage points successfully transform into a conceptual, systemic frame for sustainability thinking. The final section "Biomimicry: seeds of transformative practice for sustainability" offers evidence for my deep leverage points approach from biomimicry thinking and practice. The paper closes by briefly reflecting on the line of thought and its major outcomes.

When taken at heart within the sustainability discourse, Einstein's statement that "we cannot solve problems at the same level of thinking that we created them" urges researchers to elevate their thinking. I invite the reader to jump out of traditional mental models and to follow me in a challenging thought process of sharp analysis, critical reflection, creative

Table 1 Places to question and intervene in a system, listed as the 12 leverage points (LP) (after Meadows 2008). In increasing influential order, from shallow to deep, the LP boost analysis and understanding of a system; in reverse direction of use, from deep to shallow, they foster innovation and system transformation

Leverage point number and description			
▼ Deep LP for qualitative analysis and intervention (structure and function)			
LP 1	Transcending paradigms—(worldview, core metaphor, mode of thinking)[a]	LP 7	Reinforcing feedback loops—the strength of the gain of driving loops
LP 2	Paradigms—the mind-set out of which the system—its goals, structure, rules, delays, parameters—arises	LP 8	Balancing feedback loops—the strength of the feedbacks relative to the impacts they are trying to correct
LP 3	Goals—the purpose or function of the system	LP 9	Delays—the lengths of time relative to the rates of system changes
LP 4	Self-organization—the power to add, change, or evolve system structure	LP 10	Stock-and-flow structures—physical systems and their nodes of intersection
LP 5	Rules—incentives, punishments, constraints	LP 11	Buffers—the sizes of stabilizing stocks relative to their flows
LP 6	Information flows—the structure of who does and does not have access to information	LP 12	Numbers—constants and parameters such as subsidies, taxes, standards
		▲ Shallow LP for quantitative analysis and intervention (mechanistic aspects)	

[a]These leverage points beyond paradigm are proposed by the author in this paper

synthesis and pragmatic practicality. This paper looks at transformation for sustainability through a mind opening, horizon widening, holistic systems thinking lens.

What is transformation?

A systems thinker's approach

The key questions in this first section are: what is transformation? And, what is transformation for sustainability? Change and its manifestation are all around us; yet, the clue to systemic, radical change for a better future continues to elude us. According to Ferguson (1980), transformation is a dimension of change; other ways of change are: change by exception, incremental change, pendulum change. The term transformation has interestingly parallel meanings in all domains of knowledge (Ferguson 1980). It is indeed a common concept of physics, chemistry, mathematics, biology and evolution, of the social and behavioral sciences, and is reflected upon in the humanities. Feola (2015) provides a tentative systematic characterization of the concept, by mapping its plurality of meanings and diversity of uses in social research. My intention is to develop a more solid and fundamental, systemic understanding of the notion. Literally taken, transformation is the process of forming over; it is a fundamental property of systems and thus an important concept in systems thinking. Systems thinking in turn offers a rational framework, a language, a methodology, and tools (Bosch et al. 2007; Monat et al. 2015) to deal with systems complexity, behavior and change on a level that transcends the diversity of disciplinary approaches to and understandings of transformation.

For the purpose of clearly conceptualizing the notion of transformation from a systems thinking perspective, I am combining three different thinking tools: (i) the iceberg model (Kim 1999; Bosch et al. 2007), which is at the core of human systems thinking and is frequently used in practical applications fields of the social and behavioral sciences; (ii) Meadows' (2008) leverage points hierarchy (Table 1) and its interpretation by Abson et al (2017), a meaningful instrument for intervention in unsustainable, human systems and fostering change; and, (iii) the three orders of learning and change model developed by Bateson (1972), and adapted by Sterling (2010) in the context of education for sustainability. Figure 1 illustrates the three thinking tools placed side by side, how they connect and overlap.

Prior to applying a model to any system, it is necessary to define the kind of system under consideration. Clearly, sustainable development is about people or living systems, and not about objects or inert systems (Max-Neef 2010). Human sustainability issues always relate to humans and human-made systems embedded in, and in interaction with their direct and more remote surroundings: cultural and physical, living and non-living, human and non-human. I assume the global sustainability situation today to be the resultant of two opposite forces: the human Earth system and the non-human Earth systems. People, humans, all of us are the object of primary concern even if human concern in sustainability issues is very much diverted to the non-human world called Planet. In this study, I consider the systems of interest in need of transformation to be *human systems,* as much in socio-cultural as in individual and personal sense.

A heuristic model based on the iceberg metaphor and the leverage points

The iceberg model (Fig. 1) explains human systems through their behavior (Kim 1999). The popular tool shows, by analogy to the iceberg, how observable events on the surface and hazy patterns of behavior around the water line are manifestations of invisible, underlying systemic structures, goals, mental models and rusty mindsets. The iceberg per se mirrors any human system, person, or organization abstracted from their natural context. Figure 1 shows five layers in the iceberg (events, patterns, structures, purpose, mental models), which represent from a systems thinking perspective successive levels of understanding of and possible intervention in the system of concern. Figure 1 also shows that the level of systems thinking of an actor, insider or outsider to a system of concern, is crucial to both: the actor's interpretation of this system's behavior and the actor's following response through a typical mode of intervention. The iceberg model basically says that as systems understanding and awareness increase, so do the quality and impact of systemic interventions. Meadows' listed leverage points (Table 1) essentially articulate the same relationship between thinking and acting. It is my reason to superimpose this list onto the iceberg model as an elevator shaft with multiple entry points in Fig. 1. Each level of thinking in the iceberg analogy is now equipped with two or three successive leverage points, or entry points for intervention. Leverage point 3 (goal/purpose) has an exceptional position and meaning: it straddles two adjacent thinking levels as it bridges the divide between the physical and the mental parts of a human system. A regrouping of Meadows' 12 leverage points into four sets as proposed by Abson et al. (2017) defines successive levels of possible intervention, in increasingly influential order: materials and flows, feedbacks, structures, and intent. The so defined hierarchical levels of intervention match the thinking levels, or layers in the iceberg as suggested in Fig. 1 from the center to the left. Intervention aims at and it results in change; but, change does not equal change. Change itself must be understood in a hierarchical manner.

Drawing on Bateson's (1972) theory of learning, Sterling (2010) distinguishes three levels of change and learning:

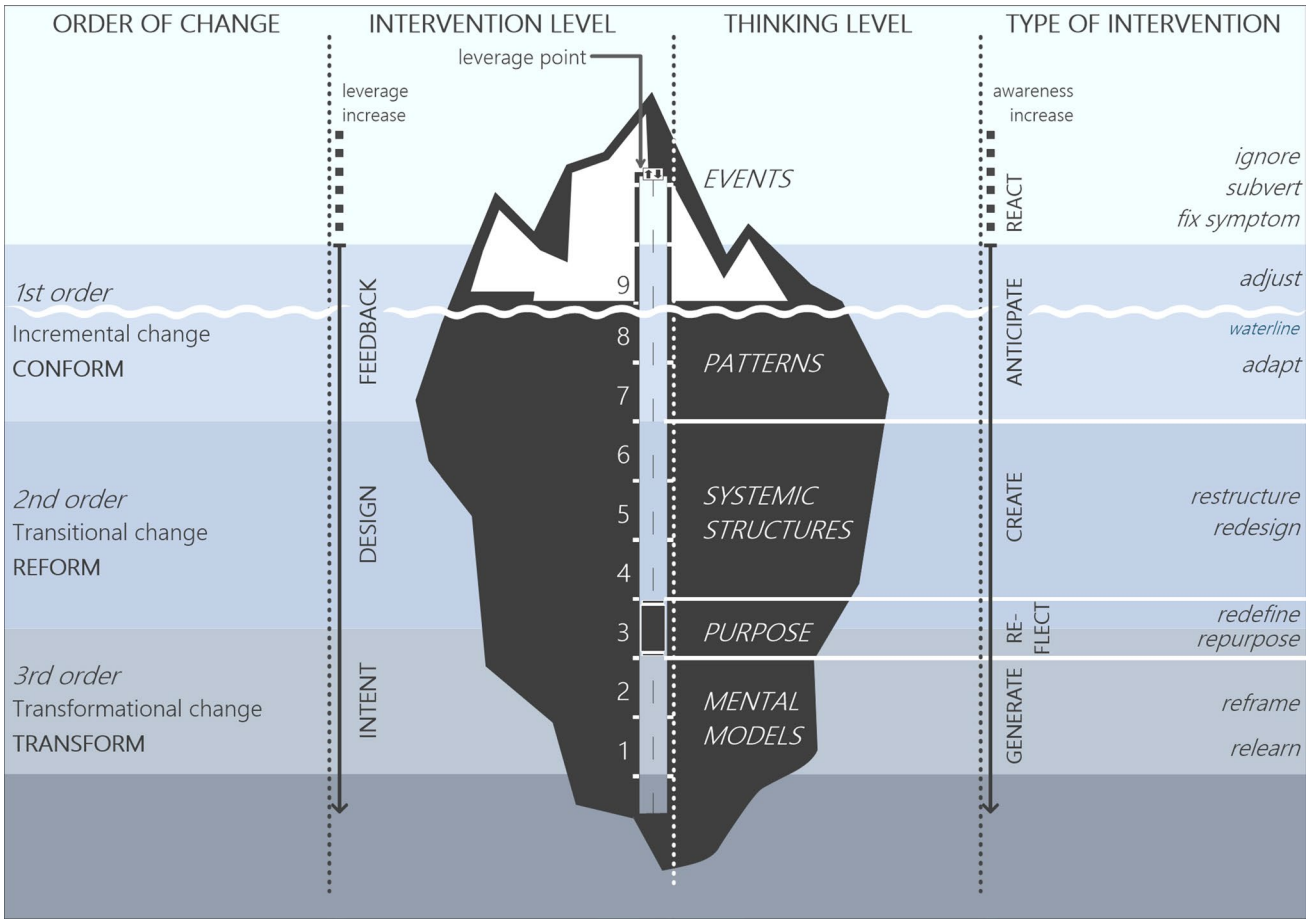

Fig. 1 A heuristic, composite model for understanding systemic behavior, intervention and change. From center to right: the iceberg model (Bosch el. 2007). From center to left: the leverage points 9–1 (Meadows 2008) and their clustering (Abson et al. 2017), and the orders of change (Sterling 2010)

first-, second-, and third-order change that can be labelled, respectively, as: doing things better; doing better things; and, seeing things differently. I have included the three orders of change in the far left part of Fig. 1. Feedbacks that influence behavior patterns cause incremental, first-order conformative change. Design modifies internal structures and organization, and consequently the behavior of a system: it results in transitional, second-order reformative change. Intent and basic mindset have the potential to change a system entirely: it is third-order change qualified as radical, transformational and transformative. The intensity of change thus increases with leverage, awareness and learning. The three juxtaposed models are in good mutual agreement. Together they serve the purpose of consolidating the concept of transformative change in a systems thinking perspective. However, the resulting, composite model as depicted in Fig. 1, which is based on the iceberg metaphor and ultimately on a physical principle, has limitations. In particular, it does inaptly model the leverage points as a systemic inclusion chain across the successive levels of thinking, intervention and change. Such a nested order has indeed been suggested by a number of authors (Meadows 2008; Sterling 2010; Abson et al. 2017; Fischer and Riechers 2019). This shortcoming is touched upon in a later section of the paper.

Cornerstone finding: the criterion for transformation

From Fig. 1 it appears that the realization of a particular order of systemic change is a function of the level of systems thinking in the approach to an issue of concern, and the choice of typical leverage points and influential actions on that level. Consequently, when transformation of human systems is the issue of concern as discussed above, third-order or radical change involving paradigm change is required. Radical, from the Latin *radix* meaning root, implies seeking for and treating the fundamental cause or origin of unsustainable human behavior patterns. This goal is not to be mistaken with the objective of a root causes (plural) analysis, which is a systems thinking tool in sustainability science

that targets the level of systemic structures and result at best in second-order change. The composite model in Fig. 1 suggests that a sufficient but necessary condition to achieve transformation for sustainability is to intervene at the root, on the deepest level of mental models where the final intent of a human system lays consolidated. It means learning to find the deepest leverage point and highest form of intervention possible in the ambiguous world of paradigms, mindsets and beyond (Table 1). A paradigm is a human mental construct. When the goal of transformation is sustainable practice, it is in the understanding of sustainability that a paradigmatic shift is required. Is there a role to play for sustainability science on this level of systems thinking and intervention? The answer is yes, as I will argue in the following sections.

Re-thinking the present (un)sustainability paradigm

This section explores the concept of transformation for sustainability on the paradigmatic level of understanding and influencing systems (Fig. 1). The concept is insufficiently grounded in systems thinking by merely defining it as contingent upon scientific paradigm change. The next immediate questions are: what is a scientific paradigm? What is paradigm change? What is a paradigm shift? And, how does this all apply to the issue of sustainability?

Paradigms as mental, living systems

In his 1962 influential work on the structure of scientific revolutions, the physicist and philosopher of science Thomas Kuhn (1922–1996) coined both terms: paradigm and paradigm shift. A paradigm is a frame of common thoughts, beliefs, values, theories, methodologies that guides the research enterprise of a scientific community in a period of normal science (Kuhn 1996). Against the prevailing opinion of his time, Kuhn argued that the history of science is best understood as exhibiting a pattern of stable periods, which he calls normal science, punctuated by periods of crisis, transition, and revolutionary change. A paradigm shift marks the event that a mature, disabled paradigm becomes replaced by a new, compatible one emerging from a plurality of pre-paradigmatic research activities. From a systems thinking perspective, Kuhn's theory of scientific revolutions is extremely interesting. It offers much evidence (like language use, pattern thinking, epistemic approach) supporting the idea that Kuhn pioneered a living systems thinking perspective on the development of science, whereby the overall goal of the scientific enterprise remained in dispute. Such an analysis of Kuhn's work is beyond the scope of this paper. Based on my interpretation of Kuhn's theory, and on the fact that paradigms emanate from the mental activity of living human systems I argue that paradigms must be considered as *living*, mental systems. A paradigm rises, grows, and falls in accordance with the general pattern of a life cycle in which a shift represents an abrupt, shocking event comparable to birth and death. In the course of a life cycle, incremental change characterizes periods of normal paradigmatic and scientific development. Transitional change is typical for the period of paradigmatic discontinuity and re-orientation between two successive paradigms. A paradigm shift occurs when a new paradigm takes over the lead from its predecessor; it generates transformative change until the new and uncommon become assimilated in the habitual, and a new life cycle begins. How does this insight apply to the global sustainability issue under consideration? Under what paradigmatic circumstances has the sustainability issue evolved over the past decades? What is the present situation? Are there any signs of a forthcoming shift?

Fall and rise pattern of our cultural and scientific paradigms

To better position the multifaceted sustainability crisis and its paradigmatic roots, I propose to adopt a broader view. In systems thinking, expanding horizons both in space and in time allows to take a more holistic approach to the issue of concern. Physicist Fritjof Capra makes this larger trend visible through his very comprehensive engagement with the cultural and scientific dynamics underlying our present time. Capra (1983) extends Kuhn's notion of paradigm from science to culture; time perspective is shifted from present times to a time span encompassing the lifetime of two succeeding cultural paradigms. A dynamic pattern of cultural behavior and change becomes visible in which crisis is but one aspect, and science but one driver. Crisis, chaotic order and complexity characterize the transition period between the conventional, mechanistic tide and an alternative holistic paradigm. Capra (1983, p 143) schematically depicts the ongoing process of change in society and in science as two intersecting sigmoid curves: a declining and a rising movement. The S-shaped sigmoid curve is a familiar pattern in systems thinking to represent the lifetime of a system. Structurally, it consists of a reinforcing loop, engine of growth and decay, coupled with a balancing loop or goal-seeking process (Kim 1992). From the background of cultural history and criticism Zweers (2000) views a self-imposed, cultural re-orientation necessary to neutralize modern expansionism in values and norms. In the ecological perspective, a shift from quantitative to qualitative growth as a strategy of survival is a development pattern omnipresent in natural ecosystems and human social structures (Odum and Barrett 2005), and presumably mental models alike.

Figure 2 is my heuristic adaptation of Capra's (1983 p 419) diagram; it zooms in the period of paradigmatic discontinuity through which society and science are travelling since the post-1950 Great Acceleration (Steffen et al. 2015b). Figure 2 allows for a retrospect, an assessment of the present and a careful forecast. The dynamics result from a simultaneous process of resistance, deconstruction and decline of the mechanistic paradigm and a lagging, but rising and increasingly influential holistic movement. The transition phase is driven by crisis, initially environmental, later culminating in the sustainability and climate change dilemmas. Society and science are contained in the tension field between two opposite perspectives on the human–environment relationship: anthropocentrism and ecocentrism. A new, ecological and holistic systems thinking way of viewing reality challenges the dominant mechanistic, reductionist thinking tradition and causes further polarity (Zweers 2000; Capra and Luisi 2014). The transition phase is neither smooth nor rapid; it is a time full of contrast, duality and paradoxes. However, as Fig. 2 suggests, by the end of the transition period, a convergent trend will become apparent. At the turning point where downward and upward movements meet, the rising paradigm enriched with a valuable heritage from the falling paradigm will take over the lead. The tension between confronting dualities will dissolve in commonly embraced dualism as polar opposites unite into harmonious complementarity (Capra 1983). In the following brief historical outline, I sketch how the sustainability discourse evolved in this tension field.

Sustainability under the declining, anthropocentric mainstream paradigm

Over the past decades, the issue of sustainability was dealt with under the umbrella of a global, socio-cultural paradigm that equated sustainable with economic development. The environmental and social dimensions of sustainable development remained largely subordinate to the imperative of economic growth (Göpel 2016; Purvis et al. 2019). The shared ideas, assumptions, and beliefs in the global community followed from a sustained, unchallenged adherence to: (1) the Brundtland report (WCED 1987) definition of sustainability and consequently the goals, and sub-goals of sustainable development; (2) the three pillars or bottom lines (TBL) model, alternatively depicted as a Venn diagram or in a nested configuration (Purvis et al. 2019); (3) the leading principal of economic growth at any price (Max-Neef 2010; Göpel 2016) and the power of technology (Arthur 2009); (4) the underlying resistant perception in the Western culture of an anthropocentric world order (Zweers 2000; Naudé 2018); and, (5) the predominant idea of humankind's moral mission of stewardship of the Earth for the well-being of future

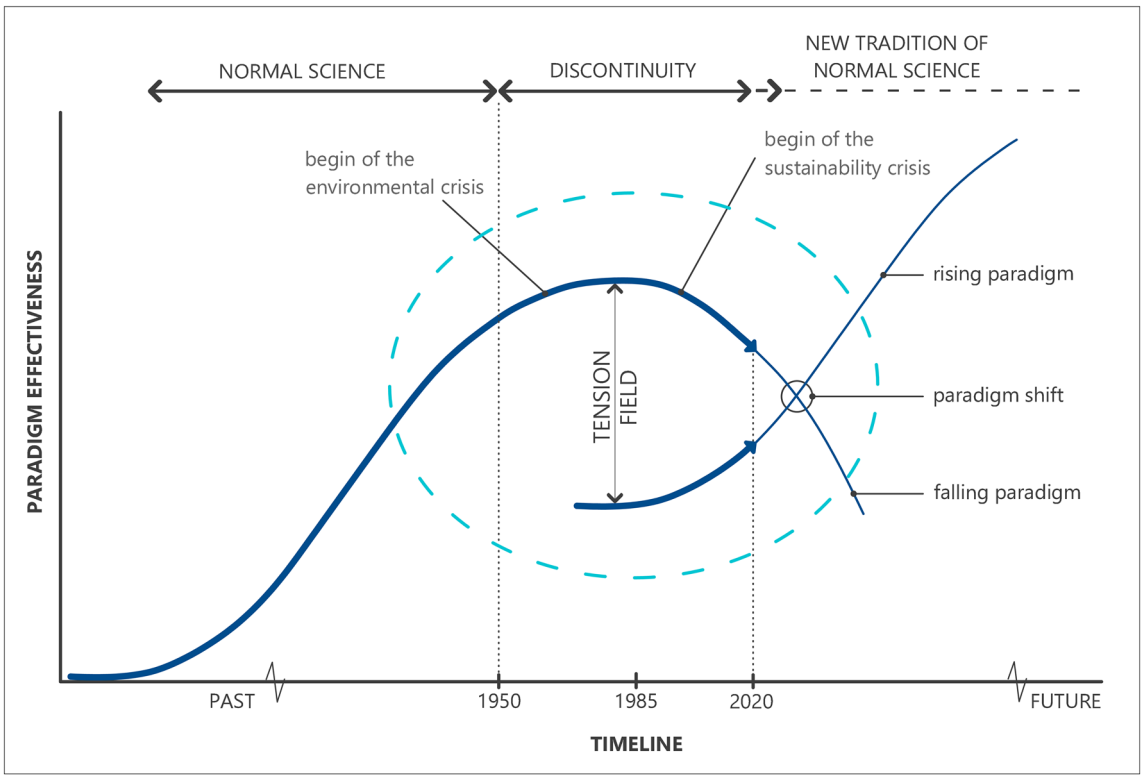

Fig. 2 A heuristic life cycle pattern model for understanding current, cultural and scientific paradigmatic dynamics, adapted from Capra (1983)

generations (Zweers 2000; Steffen et al. 2018). In the mainstream, sustainability and sustainable development were and remain political and normative ideas, a metric of the quality of human life rather than precise and scientific concepts. If today one trend is materializing from 30 years of TBL-based policy, science and technology it is not enduring progress, but a shared concern for accelerating unsustainability. The prevailing global paradigm of quantitative growth, even in a green or circular economy (Skene 2018) is running into a dead-end: it cannot resolve the sustainability crisis (Max-Neef 2010; Göpel 2016).

The sustainability crisis is challenging the scientific enterprise and methodology in a fashion that is being increasingly recognized as a scientific revolution (Kates 2011; Spangenberg 2011; Gonzáles-Márquez and Toledo 2020). Sustainability science emerged in the early 2000s under the common view of sustainable development as synonym to TBL, lacking any theoretical foundation (Purvis et al. 2019). From the outline above it now becomes clear that, so far, sustainability science has largely been operating under an anthropocentric, *non-scientific* sustainability paradigm. And precisely this anomaly, incoherence and paradox, I argue, turned out to be the grand challenge of the sustainability discipline. According to Kuhn (1996), there is no such thing as science in the absence of a scientific paradigm. Over the past 2 decades, the young discipline has indeed been fully absorbed in pre-paradigmatic activity: deconstructing and reconstructing frameworks, developing methodologies, and proposing transformational research agendas (Kajikawa 2008; Jerneck et al. 2011; Miller 2013; Miller et al. 2014; Wiek and Lang 2016; Abson et al. 2017). The field is vibrant and alive, critically reflecting on its own performance. In this respect, a recent call from perhaps the most transformative wing in sustainability science is a self-explanatory signal of decisive importance: *"Humanity sits at a crossroad between tragedy and transformation, with seemingly little idea of where we wish to go, or how we intend to get there"* (back cover Handbook LP2019 Conference). It is the urgent need for a reliable roadmap and a purposeful compass. By all means, it is the recognition of a missing scientific sustainability paradigm.

The social–cultural rising tide: ecocentric pre-paradigmatic dynamics

The notion of sustainability emerged 40 years ago from the awareness of a global environmental crisis already challenging the prevailing social–cultural order (Ferguson 1980; Capra and Luisi 2014). The idea of a harmonious partnership between economy and ecology was inappropriate to that time. Due to the coalescent social–environmental movement of the 1970s the term ecology, previously understood as a respectful branch of the biological sciences, gradually lost its prominence to become a controversial, popular term (Seidler and Bawa 2016). Neither politically nor scientifically could ecological thinking establish a breakthrough. A nested view of ecology as the sustainability bottom line supplanting the human, social and economic dimensions was premature. It could not develop into a sustainability framework generally adhered to. Much more, the ecological perspective tended to polarize the discourse instead of complementing the anthropocentric view and bringing both together in more holistic harmony.

Since the new millennium individual and community engagement, and later social networks and their impact have become the most promising developments for change. In accelerated fashion, grassroots movements and self-organizing, reformative enterprises for sustainability are proliferating in all sectors of activity (Glasser 2019). Adverse to symptom fixing and adaptive measures, they increasingly question underlying systemic structures and undertake to redesign systems based on new ways of thinking and doing. All root in slightly modified perspectives on the human–environment relationship. These grassroots movements diverge from first-order mainstream adaptive pathways in that they are perceived as essentially reformative (second-order change), although not radically new (Fig. 1). Daily life experience of and experiments with change prepares the individual, and the collectivity for the profound transformation ahead. In this pre-paradigmatic, non-academic, vibrant field of inspiration and innovation design for sustainability has started booming (Ceschin and Gaziulusoy 2016), in particular eco-design (Capra and Luisi 2014; Wahl 2016). Emergent in the early 2000s, the eco-design discipline of biomimicry is seen by some as the candidate for a new design paradigm (Fiorention and Montana-Hoyos 2014). Biomimicry is grounded in a novel epistemology of learning from nature (Benyus 2002), and develops a sustainability framework that uses standards from the scientific discipline of ecology (Baumeister et al. 2014). In a later section of this paper I argue that biomimicry is well placed to help unleash a scientific, sustainability revolution.

Milestone finding: evidence for the rise of a new paradigm

Drawing from Kuhn (1996) and Capra (1983), I argue that paradigms typically develop according to natural life cycles: they are to be considered living mental systems. On a global scale, society and science transit since approx. the 1950s through a phase of paradigmatic discontinuity characterized by the tension field between two major, cultural paradigmatic movements (Fig. 2). Coming of age is the dominant, mechanistic and anthropocentric, scientific paradigm which is subject to a goal-seeking, balancing loop. This goal, I argue, is the search for an effective sustainability roadmap and compass. The rising social–cultural tide, ecological and

holistic by nature, is still evolving in a pre-paradigmatic lag phase. It is subject to a reinforcing, growth loop and in need of more scientific recognition and impulse. Both opposite but complementary movements, traditional and alternative, contribute equally in the process of re-orientation towards a new paradigm. A convergent trend is emergent. Sustainability science, firmly rooted in the anthropocentric tide, is re-orienting research with a strong focus on systems thinking and transformation. Biomimicry, the most transformative exponent of the rising eco-tide, changes design practice from a fundamental ecological perspective on sustainability. The current paradigmatic circumstances prepare for radical change. Effective transformation will start only once the anticipated, cultural and scientific paradigm shifts take place. In preparation for this event, it is opportune to research what exactly, deeply hidden in the mental world of individuals, causes a paradigm to shift radically. This question is explored in the following section.

An emerging worldview that fundamentally re-connects

In this section, I propose to deepen the concept of transformation for sustainability beyond the leverage level of paradigm. I ask: what would it take for a new sustainability paradigm, cultural and scientific, to breakthrough? From where might it spring? What causes the shift? And, what is it at the core of a paradigm shift that could transform a global, unsustainable situation into a sustainable one?

Worldview: a leverage point beyond paradigm

Meadows (2008) says that paradigms are the sources of systems. What then could be the source of a paradigm? Kuhn (1996) understands scientific revolutions as changes of worldview, brought about in individual researchers by flashes of intuition. The environmental philosopher Zweers (2000) addresses the notions of paradigm, basic attitude and worldview and how they are related. Like Capra (1983), the philosopher Zweers (2000) extends Kuhn's paradigm notion from scientific to cultural. In Zweers' conceptualization of a nascent ecological worldview humankind no longer sees itself as steward of the Earth; henceforth, it learns to become partner and participant in a wider cosmic reality (Zweers 2000). Steward, partner and participant pertain to Zweers' typology of the human–nature relationship. Zweers distinguishes six archetypes or basic attitudes to nature, ranging from deep anthropocentric to deep ecocentric. These six basic attitudes are human perspectives on reality that precede action, both the disposal to act and its realization. According to Zweers (2000), a basic attitude or perspective is a posture, a disposition out of which typical paradigmatic behavior and practice develop. Paradigm thus arises from basic perspective and patterns itself upon it. However, the very fact of a grounded attitude to reality suggests an underlying, primary perception or awareness of the basic structure of reality. Perception then is the intuitive lens one sees the world through; it is one's first grasp and comprehension of a given situation, person, or object. Perception, I content, precedes basic attitude and paradigm in leverage order on Meadows' scale (Table 1). Individuals experiencing a major shift of perception hit an inner leverage point that totally transforms their basic attitude, and consequently the family of paradigms that guide all aspects of their thinking and doing. Referring to Fig. 1, it would appear that the level of mental models is in itself systemically structured, which does not come as a surprise when we consider mental models as living systems. There is an ascending hierarchy with increasing leverage potential from paradigm to perspective and perception. Transitional paradigm change arises from minor change in archetypical position like e.g. variations in interpretation of the steward archetype. In its most radical manifestation, paradigm shift follows a dramatic shift of perception that involves a fundamentally new way of seeing and thinking, of relating to the world and to ourselves. It is a change of worldview in the sense of Kuhn (1996), Zweers (2000) and Capra (Capra and Luisi 2014). According to Sterling (2003 with further references), it is an emergent phenomenon to which an increasing number of authors are pointing.

Construing worldview shifts as deep structural shifts in thinking

Zweers goes further in explaining that "our view of nature and our view of humankind constitute, as it were, each other's complement, or one could say mirror image… My view of nature and my view of humankind are brought together in my relation to nature" (Zweers 2000, p 15). Here I extend Zweers' human–nature relationship to the human–world bond; and, it is this dual perception of humankind and the world that I call worldview. A worldview then is a particular level of awareness of reality generating a corresponding, archetypical way of thinking or core metaphor, e.g. the mechanistic worldview and its clockwork metaphor (Capra and Luisi 2014). Lakoff and Johnson (2003) explain the fundamental role of metaphors in thought and language, in shaping our understanding and interacting with the world. The cultural philosopher van Peursen (1920–1996) has typified the changes taking place in human ways of thinking and living in a practical developmental model. Based on critical thinking, reflection, and evaluation of his contemporary world the philosopher observed that a particular worldview ingrains into the fabric of the mind a particular mode of thinking, and consequently acting. Van Peursen

(1974) distinguished three broad phases in the development of human thinking: mythical, ontological, and functional/relational. Van Peursen's simple diagrams of the human–world bond in each of the three thinking phases are depicted in Fig. 3a. The explicit question in each stage reflects the particular angle of vision and thus the standpoint of the human subject, corresponding to Zweers' notion of basic attitude. The pointing to "that" of mythical thinking implies a non-self-contained subject without identity. The "what" of ontological thinking indicates liberation to the position of observer; now, subject and object exclude one another. The "how" of relational thinking builds an interconnected relationship between the human subject and the outer world. The three stages still co-exist today; also, we find these stages back in our personal development. The thinking stages are not sharply delimitated; rather, they form a continuum. I compare them to the development stages of a butterfly (Fig. 3a). Van Peursen aimed at outlining a broad, in my view holistic perspective on the strategy of culture that eventually is the ecological strategy to survive and thrive; cultural parallels to ecosystem development are also suggested by Zweers (2000) and Odum and Barrett (2005). For a more comprehensive look into the strategy of culture model I refer to van Peursen's book (van Peursen 1974).

The relational diagrams in Fig. 3a are meaningful entry points in systems thinking: they define in a particular mode of thinking, how the boundary between subject and object in the human–world relationship is being conceived. Furthermore, the concept of a core metaphor (Lackoff and Johnson 2003; Capra and Luisi 2014), which translates the experience of a particular worldview into a corresponding way of thinking and doing, is instrumental for a systems thinking

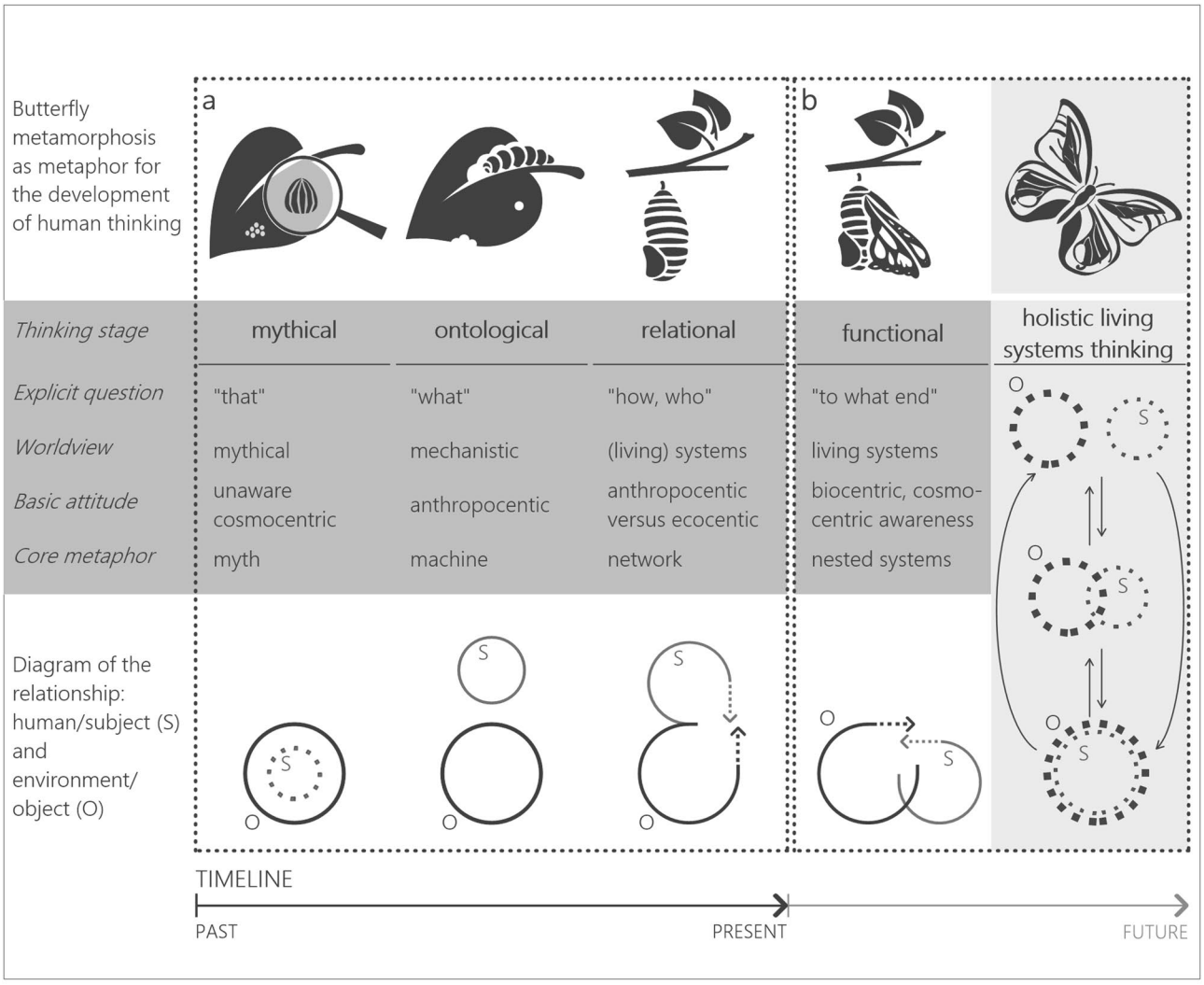

Fig. 3 A model of the development of human thinking. The stages are freely interpreted after van Peursen (1974), Zweers (2000), and Capra and Luisi (2014): **a** hindsight; **b** foresight

approach to van Peursen's model. In descending order of leverage, an inner, perceptual worldview shift provokes a more conceptual and transmittable shift in core metaphor that affects the human way of thinking, which in turn causes entire paradigms to shift and transformation cascades to follow.

The emergence of a new dimension of thinking: teleology

How could today's still predominant separation thinking and mechanistic paradigms transform into an ecological worldview and holistic thinking as envisioned by Zweers (2000) and Capra and Luisi (2014)? Van Peursen's (1974) model (Fig. 3a) suggests a life cycle pattern in the development of human thinking and awareness. It is the equivalent on the worldview level of what Capra's model (Fig. 2) conveys on the level of paradigm. But, van Peursen's work dates from 50 years ago; since then much has changed in our way of thinking and doing. Therefore, I propose to tentatively extend the model with a next, fourth stage that I see emerging (Fig. 3b). From a point of view of systems thinking, the simple model in Fig. 3 is essential in forecasting a forthcoming worldview shift and a new mode of thinking. Learning to understand and value living systems through their overall function and purpose would logically complete a development cycle of human thinking. The explicit questions "what for; to what end" mirror today's increasing quest for meaning, purpose, function and value. The complete unfolding of functional, living systems thinking during the transition from stage 3 of relational complexity to stage 4 of holistic simplicity is a process as complex as the transformation of a pupa in a butterfly. Figure 3b depicts the four important changes which need to take place. First, the gradual transition from mechanistic to relational thinking, which phenomenon started with van Peursen's (1974) observations of stage 3 and is well described in the works of Bateson (1972) and Capra (Capra 1983; Capra and Luisi 2014), now culminates in function (teleological) thinking. Second, the build-up to stage 4 witnesses a radical shift in perception of the human–world bond, marked by a fundamental change in attitude from steward of the Planet to partner of and participant in a wider cosmic reality (Zweers 2000). Humanity no longer stands above nature but is on a par with it, thereby drastically shifting its system of values. In the butterfly metaphor, the pupa hangs upside down whereas the butterfly will emerge head upwards. Likewise the planetary steward will need to accomplish a mindset revolution to understand the meaning of surviving and thriving in successful partnership with the Planet. Third, the fundamental tension between the anthropocentric and ecocentric perspectives dissolves into a powerful, harmonic complementation of opposite views: a new life-centered, bio-geocentric worldview results. It is no return to mythical thinking but a cosmocentric attitude on a higher level of awareness. Seeing oneself embedded in, equivalent and complementary to the outside world generates a worldview of participation, connection, nested co-evolution and meaning. Transformation then results from a perceptual, moral and cognitive shift to a basic attitude that re-affirms human's identification with life and desire to act accordingly. Finally, the thinking skills and knowledge acquired in previous stages are not lost. To the contrary, each new stage of thinking simply is more encompassing and liberating; the constraints of former thinking melt away thereby helping our awareness of reality to increase.

Milestone finding: the deepest leverage point to address is the core metaphor

The philosophical approaches to human thinking and acting developed by van Peursen (1974), Zweers (2000) and Capra and Luisi (2014) deal with deep leverage points beyond the level of paradigm (Table1). It appears that a worldview and its core metaphor generate the conceptual system that brings about a basic mode of systems thinking which then structures reality in paradigms. Holistic living systems thinking based on an ecological worldview is expected to tackle the root cause of unsustainability. Holistic thinking essentially includes all three ways of thinking in one: ontological, relational, and teleological (Fig. 3). It requires an all-round fluency and the mental agility to aptly switch between core metaphors and ways of thinking, each of which has its merit and limitation. The machine metaphor is at the root of our material expansionism, but it overlooks the living systems view of life and its inherent interconnectedness. While resolving this shortcoming, the network metaphor generates confusing and complicated complexity thinking. Here I posit that the metaphor of nested order will transform complexity in holistic simplicity by focusing on the one functional relationship that defines a system in terms of its meta-system(s). Below I will argue that functional, living systems thinking is abstracted systems ecology, itself founded on the concept of nested hierarchies ubiquitous in nature (Odum and Barrett 2005; Meadows 2008). The machine metaphor in our conceptual system must make place for a metaphor of living nested order, I claim, to provoke transformation that is compatible with an ecological worldview, its holistic way of thinking and scientific sustainability paradigm. Paradigms will shift as a result of a significant shift in our human conceptual system: the core metaphor is the transformation point.

The conceptual root cause of unsustainability and its cure

What does a change in core metaphor exactly entail? How does a change in metaphor relate to a shift in perception? How does all this relate to the sustainability issue, the need for transformation and the emergence of a new scientific paradigm? This short section introduces a turning point in my line of argumentation from divergent to convergent, from gaining conceptual understanding of transformation to designing a conceptual strategy for transformative practice in the context of sustainability.

Unsustainability roots in a cognitive illusion

Bateson's notion of epistemological error implies the necessity of paradigm shift and new epistemic learning (Sterling 2010). With his famous quote: "the major problems in the world are the result of the difference between how nature works and the way people think" Bateson points out that reductionist separation thinking is not compatible with the holistic, ecological way in which the world functions. The difference that makes a difference is also present in Einstein's popular quote saying that "no problem can be solved from the same level of thinking that created it". Our human thinking is causing all the trouble. We are trained to think in ways we hardly notice; our thinking patterns are so ingrained that we fail to distinguish between an image of reality mirrored by our thinking, and reality itself. In the tradition of the mechanistic worldview, we do unconsciously mistake a human-made world, which we call culture, for the real world. This mistake leads us to understand and act on the natural world, and likewise to consider culture through the lens of human design, e.g. as if the world were a machine. But as Bateson says, the organic world does not function in a mechanistic way. It is our metaphorical conceptual system that forms the core of the matter. By means of a metaphor, an experiential or familiar concept is projected onto an abstract concept, which then serves to shape the world of human needs and intent (Lakoff and Johnson 2003; Ruse 2002). Where culture supplants nature as source domain of experience, alienation from nature is the result (van Peursen 1974). An insufficient, incongruent clockwork conception of the world is at the root of the sustainability issue we face today. Unsustainability rests on a cognitive illusion that needs transformation. Like the figure-ground distinction in an optical illusion (Kuhn 1996), e.g. the Rubin vase/face, reversing our perception of background and foreground might very well work as a silver bullet. The frame of reference must flip from human to nature so that the natural, organic world becomes source of understanding and model for human design and culture. In the final section of this paper I point out that the originality and potential of the biomimicry approach to sustainability arise from precisely this inversion in the metaphorical domain of reference (DeLuca 2016). It transmits biology into design.

Unsustainability overlooks function

The cardinal point I make with my extension of van Peursen's model (Fig. 3) is that we need to learn to expand our thinking skills to teleological and ecological thinking to complete the transition from a mechanistic to a holistic worldview. Referring to Bateson (1972), not only is the mechanistic worldview founded on an epistemological error, it is the same perception of and belief in separateness that in addition leads us to make a teleological and axiological error, an error of valuing function and purpose. This next difference that makes a difference logically follows from flipping the source domain of our metaphors from physics to biology and nature. The notion of function, absent in physics is indeed essential in nature. In biology function and design, form and structure, are inseparable (Buller 2002). The physical sciences by contrast miss the point of function (Ruse 2002). Capra's (1983) view, reinforced in Capra and Luisi (2014, p 15) is that "the paradigm shift in science at its deepest level, involves a perceptual shift from physics to the life sciences". For Zweers (2000, p 346) "it seems more probable that a kind of system theory synthesis" between physics and biology will develop. Systems ecology that incorporates the fundamental laws of thermodynamics indeed brings the functional aspects of living systems to the forefront. Function in ecology and function in design thinking are strong reconnecting concepts to counter the separation and alienation caused by mechanistic thinking. Odum and Barrett (2005) envision ecology as a bridge between the natural and the social sciences. Referring to sustainability science, they even suggest that "the continued development of ecology will likely evolve into that much needed integrative, transdisciplinary science of the future" (Odum and Barrett 2005, p 16). Sustainability science so far rooting in a non-scientific paradigm could not recognize the fundamentals of ecology as the basic science of sustainability. The discipline certainly draws on systems thinking but fails to leverage its powerful, and re-connecting teleological dimension. Function, or purpose, is indeed a system's characteristic often forgotten or taken for granted under the mainstream paradigm. From a leverage points perspective, by failing to consider whole-system goal, function and purpose one is often missing the most crucial opportunity to understand and influence systems (Meadows 2008).

Keystone finding: a working hypothesis on core metaphor and leverage points

If I am right in suggesting: (1) that our core metaphor-in-use is the deepest and most effective leverage point to address in the context of transformation for sustainability; (2) that a holistic concept of nestedness is to be considered the core metaphor in holistic systems thinking; and, (3) that a deliberate, radical change in core metaphor from machine to nested systems is the turning point at which the final cause of unsustainability transforms into the key for its solution, then transformation and innovation for sustainability start from this point onward. The change in metaphor will precipitate a transformation chain from deep to shallow leverage levels, from new ecological worldview and metaphor to a compatible paradigm of sustainability and sustainable systems. The leverage points tool itself changes purpose: from onion peeling instrument it becomes a *paradigm*—in its literal, etymological meaning—for systemic transformation and innovation. From a device for ontological analysis it transforms through teleological re-orientation into a device for epistemological change. A paradigm translates and transmits the parental, core metaphor to lower systemic levels in terms of a fundamental overall goal and a structure to follow. In the remainder of this paper I seek evidence from systems thinking, systems ecology and biomimicry practice for my argument that a new sustainability paradigm sources in Meadows' leverage points.

Transforming the iceberg metaphor in nested leverage points

This section deals with the metaphorical modification necessary to disclose the systemic structure and overall function of a new sustainability paradigm springing from the leverage points. For this purpose, I take an almost mathematical approach to the notions of worldview, core metaphor and paradigm, previously understood as mental models/systems. A worldview establishes a functional relation, e.g. between humans and the world. A core metaphor is an application from source domain to target domain that transmits the functional aspect between both domains as defined in the parental worldview. A paradigm translates the information transmitted by the metaphor into a template for overall systemic structure and function. In holistic systems thinking for sustainability, the core metaphor should define a functional application from nature or biology, as experiential or cognitive source domain, to systems thinking as abstract domain. The function is: to re-connect, ultimately humans with the world.

Holistic systems thinking is abstracted systems ecology

Departure point for my reasoning is our conventional systems thinking (Table 2, central column). Because of its

Table 2 From conventional systems thinking to holistic living systems thinking: transformation of the iceberg metaphor reveals structure and overall goal of a new, systemic sustainability paradigm springing from the leverage points

	SYSTEM KNOWING		SYSTEMS THINKING		
	experiential source domain		*abstract target domain*		
Source of knowing and mode of thinking	Experience of nature	Systems ecology Biology	Conventional systems thinking	Holistic systems thinking	Holistic living systems thinking
Conceptual level	natural system original model	1st order abstraction biological model	heuristic model	2nd order abstraction systemic model	application
Conventional systems thinking	iceberg		iceberg metaphor		
Holistic living systems thinking (structure)		nested hierarchies link structure and function	iceberg model and leverage points	nested leverage points: core metaphor	meta-paradigm: nested structure
Conventional systems thinking	onion bulb scales		onion bulb metaphor		
Holistic living systems thinking (function)	*Allium cepa* plant	onion plant life cycle: function is to sustain life	onion bulb	growth & decay coupled to goal-seeking feedback loops	paradigm life cycle overall goal: to sustain life

popularity, I assume the iceberg metaphor to represent the core metaphor of conventional systems thinking. The leverage points are considered in close relationship with the iceberg model and metaphor (Fig. 1). As argued in the previous section of this paper, there are three essential requirements to a new core metaphor: (1) the introduction of functional thinking; (2) the organic or biological nature of the experiential source domain; and (3) thinking in living systems. The systemic metaphor out of which a scientific, sustainability paradigm should arise needs to connect the domain of ecological knowing to the domain of systems thinking (Table 2). The latter is an abstraction, or image, of the former which serves as original, or source model. Systems ecology is the model, thinking in systems its abstracted image. Systems thinking indeed is highly based on ecosystems thinking. Ludwig von Bertalanffy (1901–1972), the creator of General Systems Theory (GST) was as much a biologist as he was a systems thinker. GST clearly has its roots in the author's biological work (Ramage and Shipp 2020).

If holistic systems thinking is abstracted systems ecology could then nested hierarchies, a concept at the core of ecology, after abstraction into a systemic concept of nestedness likewise be at the core of holistic systems thinking? Von Bertalanffy's (1968 p 27) claim that hierarchic order is fundamental in GST supports the assumption. Meadows (2008) says that hierarchy is one of the reasons why systems work so well. The concept of nested hierarchies that links structure to function is so fundamental to ecology (Odum and Barrett 2005) that I consider its abstraction into a nested order metaphor for use in holistic systems thinking to be a valid translation (Table 2). Such a metaphor would by virtue of the leverage points hierarchy be precursory to a new paradigm of nestedness, itself applicable in living systems thinking. Bringing in my working hypothesis on transformation of the leverage points into a paradigm as formulated in the previous section, now leads me to suggest that the very leverage points frame is the systemic core metaphor of holistic systems thinking. This presumption, however, requires revisiting Meadows' (2008) description of the leverage points to gain evidence for their nestedness.

From iceberg to nested leverage points: the systemic structure for a new paradigm

Meadows offered her 1999 list of 12 leverage points with much humility and wanting to leave room for its evolution. By presenting a simple list but clearly describing it as a hierarchical inclusion chain, Meadows might well intentionally have avoided any tempting but biasing visualization of the concept forasmuch her view was that any model "falls short of representing the real world fully" (Meadows 2008). Nevertheless Meadows' summing up of the 12 places to intervene in a system is more than a set of separate, mutually disconnected leverage points. A set is defined as the sum of its parts; by contrast a system is more than the sum of its parts. Is then a nested hierarchy a valid, systemic model for the leverage points frame? Are leverage points a systemic tool? Are leverage points a holistic, systemic tool?

The cornerstone for my systems thinking approach to transformation was established in Fig. 1. I superimposed the leverage points on the iceberg model thereby assuming successive groups of leverage points to be homological to successive levels of systemic understanding. The metaphor of the iceberg, by virtue of its shallow–deep, visible–invisible, physical–mental dualism was suited to my initial ontological position in systems thinking. The limitation of my approach, and of all those who successfully use the iceberg model to explain and influence human behavior, was that my inquiry in human systems ultimately built upon a physical metaphor. By contrast, Meadows (2008) largely focusses on human systems as she develops her thinking in systems. A few, crucial phrases taken from Meadows' book "Thinking in Systems—A Primer" (2008) highlight the shortcoming of the iceberg model, and help converting it into an organismic model more congruent with reality. I cite:

> "System behavior reveals itself as a series of events over time."
> "System structure is the source of system behavior."
> "The least obvious part of the system, its function or purpose, is often the most crucial determinant of the system's behavior."
> "Paradigms are the sources of systems." – End of citations.

The kind of order that Meadows suggests is a nested one, implying as she clearly describes that behavior *follows* structure *follows* goal or purpose *follows* paradigm *follows* what is beyond, namely *worldview/core metaphor* as I proposed in the previous section. Basically the iceberg model for understanding human systems is conform with Meadows' thinking in systems, except for the crucial property of nestedness. Systemic characteristics ranging from quantitative parameters to feedbacks, design and intent follow a nested order as Meadows (2008) clearly points out in her description of systems and leverage points. Now it seems justified to transform the heuristic iceberg-and-leverage-points model in Fig. 1 into a single, nested model of leverage points emphasizing their structural and functional interdependency (Fig. 4, left part). Nestedness is a quality measure for structure and function (Buller 2002). I contend that the so-obtained nested leverage points meet my above established criterion for a core metaphor in holistic systems thinking (Table 2). The metaphor is holistic indeed. It bridges all possible dualistic thinking: structure and function; causality and finality; shallow and deep; physical and mental; quantitative and qualitative; inner and outer; ontological and epistemological.

The model works in two directions: travelling through the nested chain of leverage points from shallow to deep deepens analysis and understanding; and back, from deep to shallow it empowers transformation and innovation (Table 1). By applying the nested leverage points in living systems thinking they become the nested archetype, or meta-paradigm for understanding and acting upon living systems, and thus the precursor of a holistic living systems sustainability paradigm (Table 2). This nested order reveals structure, but not yet the overall systemic goal connecting and aligning the successive levels in the nested hierarchy. Next, I propose to leverage the property of nestedness to uncover the overall goal of sustainability in a tangible, living systems thinking experiment.

From iceberg to onion bulb: structure reveals function

The iceberg is a concept taken from the physical, natural world. The comparison, on which the tip of the iceberg metaphor rests, stems from its physical property of density whereby 90% of the iceberg's volume remains invisible under the water line. As argued earlier, models and metaphors based on physical principles loose efficacy as the mode of thinking shifts to teleological and living systems thinking. Now organic models become increasingly informative. A tangible example illustrates this idea: imagine the iceberg changing into an *onion bulb* (Table 2, central column). Regarding the density aspect, iceberg and onion compare well. Onion peeling is a figure of speech meaning going to the root of an issue; the analogy with delving into the iceberg, layer by layer to find the source of a problem is striking. Indeed both, the onion and the iceberg metaphors-in-use to interprete culture, in fact explain systems; interestingly, the first stems from an organic and the latter from a physical source of perception. While the mainstream use of the onion metaphor is limited to peeling back its layers, this organic metaphor is substantially more informative. An onion bulb not only is a living system with a typically nested structure, it is above all the manifestation of a functional phase in the life cycle of the onion plant *Allium cepa*. When moving from conventional to functional biological thinking, some salient details that are not contained in the iceberg model become apparent. The fleshy scales of the bulb protect and nurture deep inside an apical bud that will sprout, and emerge to the surface once conditions are conducive to *sustain* a new life cycle of the plant. The onion bulb analogy suggests the presence of an embryotic solution sprouting from the core of a problem: sustainability as solution to the root cause of unsustainability. It echoes Kuhn's (1996 p 86) observation that: "often a new paradigm emerges, at least in embryo, before a crisis has developed far or been explicitly recognized". An aging paradigm then could be thought of as the breeding ground for a new paradigm. Effectively, the many literature resources used in this paper that date back to the last century are surprisingly well in touch with present paradigmatic reality and meeting current needs.

A short digression to botany learns that the onion plant has two reproductive systems: a sexual one based on seed formation, and an asexual or vegetative one based on the sprouting of onion bulbs which produce clones, genetically identical to the parent plant. I observe that the life cycle pattern of two successive paradigms as depicted in Fig. 2 is remarkably similar to the twofold, life cycle pattern of the onion plant. In this analogy the aging mainstream paradigm compares to the vegetative life cycle of the onion bulb. The seed production, dispersion and germination stages of the onion plant's sexual reproductive cycle are a model for the phase of pre-paradigmatic emergence, pioneering activity and competition preceding a breakthrough. The onion bulb metaphor (Table 2) not only is a perfect analogy for conceiving living paradigms and paradigm life cycles, it also informs living systems thinking on the overall function of a living system. The reproductive pattern in the biological model, in all its diversity, is directed at a single overarching goal: namely to sustain life. Likewise should the purpose of a new sustainability paradigm be understood. This view suggests that sustainability simply means to *sustain Life*.

Touchstone finding: nested leverage points as standard for a living systems paradigm

In this section, I have consolidated Meadows' leverage points frame as a nested, systemic structure. I have reasoned the core metaphor of holistic systems thinking to be the nested leverage points concept. Applied in living systems thinking the nested leverage points transform into the systemic, nested blueprint for a new sustainability paradigm. The overall goal implicit in a sustainability paradigm is to sustain life. The metaphorical strategy used in this section has a lot in common with the discovery and creation phases of the biomimicry design method (Baumeister et al. 2014). The procedure starts with a natural model or systems ecological concept, abstracts it in systems thinking and applies the result to living systems (Table 2). This strategy of transmitting biology into living systems thinking could prove to be the panacea that Fischer and Riechers (2019) exclude from the equation. The rational in this section, based on convergent thinking, may or not convince. Ultimately, it is the practicality of a nested order concept that will establish the significance of Meadows' leverage points as a transformation tool, and systemic standard for a living systems paradigm. In the last section of this paper I, therefore, address practice.

Biomimicry: seeds of transformative practice for sustainability

This section is the tangible counterpart of the previous, highly abstract, systems thinking approach to a new paradigm. As observed earlier in this paper, the field of design for sustainability has exploded over the last 2 decades (Wahl 2016; Ceschin and Gaziulusoy 2016). As a serious and robust approach foreign to the mainstream academic tradition, design is co-evolving on a vital complementary trajectory towards the emergence a new paradigm (Fig. 2). By highlighting the field of design as a relevant instance of transformative practice in the context of sustainability, my methodological intent is to consciously and purposely braid systems thinking and design practice.

Why practice?

Transformation is a process of change not only in connection with conceptual and theoretical systems. Individually, collectively, even as a global society people increasingly engage in practical actions for sustainability. The practice of change for sustainability, which essentially is a process of learning, unlearning and relearning, is in no way exclusive for scientists. It even has a longer tradition in non-strictly scientific, more practice-oriented fields like design, business management, education, and even daily life. The urgency but also the freedom to break with paradigmatic limitation and a worldview tradition considered outdated explain the leading role of practice. There is indeed a reciprocal link between worldview and practice outcome as Ison (2018) mentions in the context of systems thinking in practice (STiP), as Wahl (2016) observes in regenerative design, Senge et al. (2004) in organizational learning, Laininen (2019) in education. Kuhn (1996) points out that the inspiration source for a replacement paradigm often is rooted in the practice of extraordinary (post-normal) science itself. And, more generally it is known that *"…efficient practice precedes the theory of it"* (Gilbert Ryle, The Concept of Mind, 1949). If indeed an upcoming worldview and the contours of its scientific sustainability paradigm are already surfacing, then it is certainly opportune to closely study the diverse, existing fields of sustainability practice for more clues.

Why design practice for sustainability?

Design practice is a particularly relevant field for consideration as it offers significant examples of co-evolution towards sustainability over the last two decades: it is a solution-oriented and user-centered practice involving stakeholder participation and co-creation (Sanders and Stappers 2008). Moreover, as Wahl (2016) observes: "design is at the nexus of theory and practice". Using a design lens to address any issue is an epistemological approach. Design practice for sustainability is human-centered as it serves human needs, the reasons why it is so well placed to make a difference. Design provides the vision and the solution pathway, design occupies a dialectical space between the world that is and the world that could be, it bridges present and future reality. Transition design (Irwin 2018) for sustainability brings together an evolving body of practices relevant to design for systemic change. Interestingly, its well-developed methods and articulated approach have a lot in common with transformational sustainability science and STiP (Ison 2018). They include: present situation analysis, future vision framing, backcasting from a desirable future, designing a multiple step transition pathway, identifying promising intervention points, and a waiting-and-observing feedback phase. Collective future visioning often is a rich and co-creative stakeholder learning process; conversely, participating worldviews and values typically narrow down to a common denominator during the phase of vision building, levelling the vision outcome and its impact. By contrast, nature inspired design and eco-design (Capra and Luisi 2014; Wahl 2016) are stronger in coming up with new sustainability frameworks and solution spaces. The natural step, cradle to cradle, circular economy, industrial ecology, green architecture and ecocities, biomimicry to name but a few, all incorporate basic principles of ecology and are informed by systemic thinking. For radical change two things are important: a vision and the practical pathway to achieve it. Biomimicry offers both: it is at once pragmatic and culturally transformative (Benyus 2014).

Why biomimicry design practice?

As defined by biologist Janine Benyus (2002), who introduced the term and concept, biomimicry is the conscious emulation of life's genius. Biomimicry is a practice that learns from the strategies found in nature, and echoes these time-tested ideas to solve human design challenges sustainably. Along the way innovation inspired by nature changes our lens on the world. A comprehensive overview of the field of biomimicry is beyond the scope of this paper. Here I refer exclusively to the way biomimicry is understood and practiced at The Biomimicry Institute and the Biomimicry 3.8 Consultancy (Baumeister et al. 2014). Biomimicry centers on seeking nature's advice as a guiding framework for a cultural shift toward sustainable living. This particular school of nature inspired design offers a powerful sustainability scheme and meme—a meme is a unit of cultural transmission, an appealing transformation narrative, a working method designed to integrate biomimicry thinking into any design process, and a hands-on toolkit. In my opinion, biomimicry proposes today's best articulated, pragmatic

framework for re-aligning human design with nature and ecological thinking (Benyus 2002; Harman 2013; DeLuca 2016). The three foundational dimensions of biomimicry, *ethos, re-connect and emulate*, position its practice at the intersection of the three domains of knowledge: philosophy, spirituality, and science. They inherently relate worldview and design and confer to biomimicry its fundamentally transformative propensity: the leverage power to bridge inner and outer worlds. It is by encouraging a new form of global, conscious stewardship over our personal lives versus stewardship over nature and the planet that biomimicry envisions deep change. Not only are biomimicry thinking and design based on the panacea of holistic and living systems thinking; by practicing biomimicry authentically, individual practitioners within the field live the change. Those who subscribe to this new life-centered paradigm, combine personal with collective transformation and create a movement for true sustainability.

The biomimicry sustainability framework

The early biomimicry developers were indeed inspired by Meadows' work (Baumeister et al. 2014); to what extent exactly remains unknown. In what follows I draw on the Biomimicry Resource Handbook (Baumeister et al. 2014) for arguing that the biomimicry sustainability framework, established over the last 2 decades, matches amazingly well Meadows' qualitative leverage points LP 1 to LP 6 (Table 1). Both relate to another as hardware and software. The nested leverage points tool covering the qualitative levels of intent and design provides the paradigmatic structure (Fig. 4, left part). Its biomimicry counterpart supplies the ecological content. In the following paragraph I outline this content part (Fig. 4, right part).

Benyus (2002) fundamentally rejects all separation thinking between the human species and the rest of life on Earth. Her simple, affirmative phrase: "*the truth is that we are*

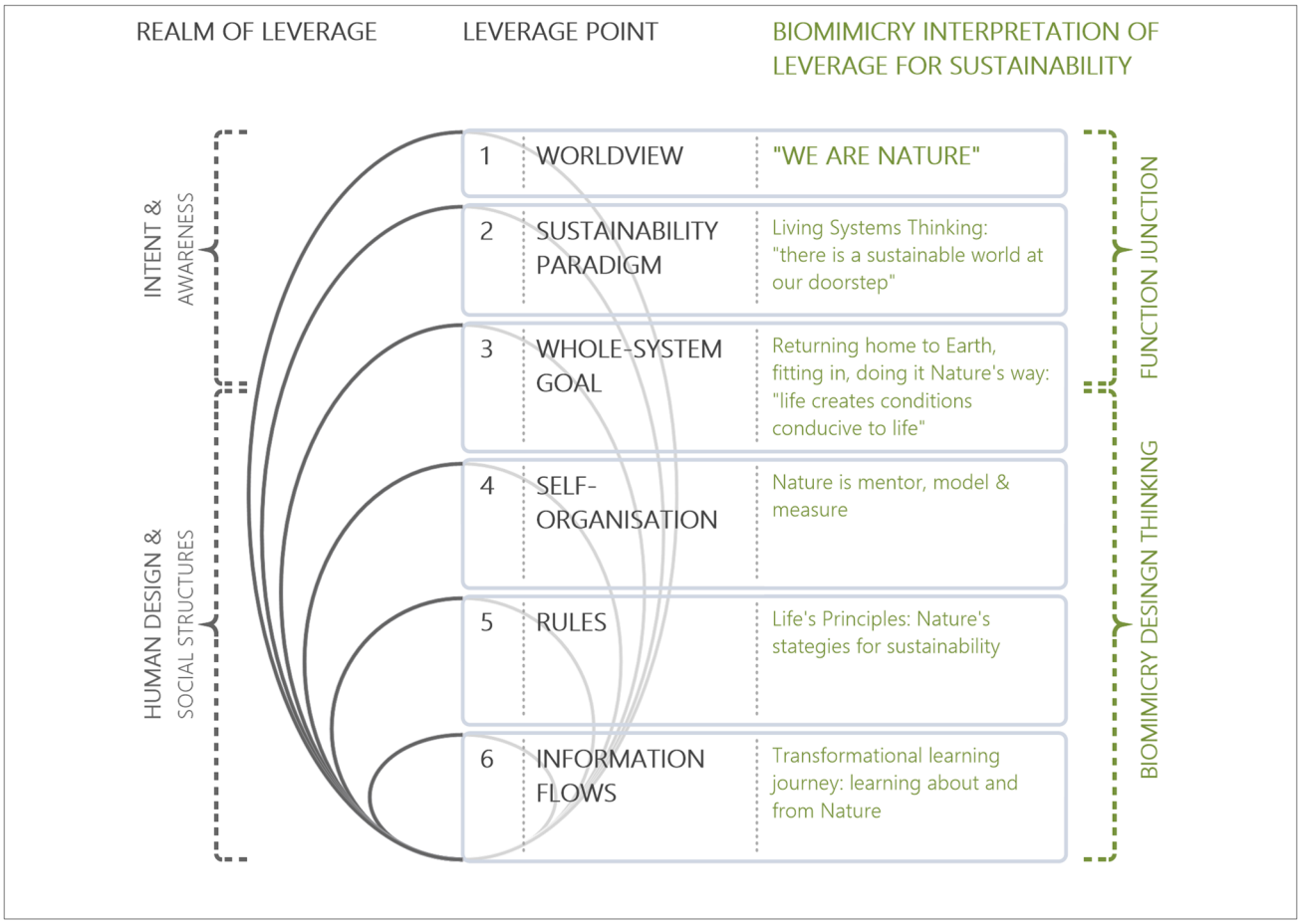

Fig. 4 Systemic structure and ecological content of an emerging, nature inspired sustainability paradigm. Left, the leverage points 1–6 in nested order (Meadows 2008). Right, the biomimicry sustainability framework (Baumeister et al. 2014)

Nature" ushers in a new, biocentric stance toward nature and the world (Benyus 2014). Seven words define a new worldview (LP 1). Humans are embedded in, and take part in the web of life like any other species. Hence all life and life supporting systems have in common: intrinsic value, the imperative to survive, the necessity of being sustained, and well-being needs. This new way of viewing and valuing life and all its diversity, including human life, acknowledges that *"the answers to how to live sustainably on our planet are all around us"*. The gist of biomimicry is to simply reverse conventional thinking (LP 2). Nature defines sustainability; humans can learn from nature's solutions and strategies for sustainability to transform a nature dominated, man-made unsustainable world. It is a re-orientation by paradigm change described in Kuhn (1996, p 85) as "picking up the other end of the stick". By proclaiming sustainability, the solution out of the crisis, there is at least a clear idea of what sustainability entails. A sustainability ethos marked by the desire to play by the rules and fit in on this planet is the new overall goal (LP 3) carefully phrased by Benyus (2014) as: "*life creates conditions conducive to life"*. In nature, systems self-organize in the direction of a purposeful function in the web of life (LP 4). To intervene in, regenerate, or create living human systems biomimicry thinking relies on the intellectual resources nature offers as much as it challenges our human, natural skills as practitioner, designer, system thinker. On the functional level of design *nature is mentor*, meaning that nature can guide us in understanding and defining purposeful function. On the level of systemic structures and processes, *nature is model* and informs human design. On the level of behavior, *nature is a measure* of quality, a benchmark for sustainable design. The imperative to navigate within non-negotiable operating conditions on Earth learned living organisms, in the course of evolution, to tap the power of limits and create extremely effective means to survive and thrive. A set of overarching patterns and rules (LP 5) found uniformly across almost all organisms, the *Biomimicry Life's Principles*, have been carefully studied, compiled and distilled from the scientific literature (Baumeister et al. 2014). The life's principles are intended to represent nature's strategies for sustainability. This important, practical tool is a central part of the biomimicry living systems paradigm; it is embedded into the many aspects of implementing and naturalizing biomimicry in our human culture (Baumeister et al. 2014). On the level of personal transformation, biomimicry practice in one's individual daily life is a challenging and rewarding experience in *learning from nature* (LP 6).

Merits and limitations of biomimicry practice

Biomimicry unfolds a radically new epistemology that rectifies the fundamental epistemic error and suppresses the deficiency in teleology, pointed out earlier in this paper to be at the root of unsustainability. The issue of cognitive illusion is indeed solved as biomimicry design is typically anchored in living systems thinking and uses the strategy of abstracting either natural, or biological models to create human design (Table 2). The biomimicry framework (Fig. 4) that informs thinking, design and action for sustainability can rightly be called a candidate paradigm. An important criterion of biomimicry design is the concept of function junction (Baumeister et al. 2014). It means that natural model and human design product should perform comparable functions in corresponding, ecological context, like e.g. designing a city or a factory as a forest. Modelling a function in nature for an implicit human goal that is not the explicit natural goal is no biomimicry for sustainability. Such a lack of strict correspondence is however typical for current mainstream *shallow* biomimicry. Due to the major constraint of path-dependency, a substantial biomimicry breakthrough still fails in most practical application fields. Although biomimicry subscribes to an emergent paradigm, in the practical reality of today's world the discipline necessarily operates under the still prevailing, dominant worldview and paradigms. I call the difference between its potential and current effectiveness, the biomimicry paradox.

Biomimicry is known to have two faces: a shallow, pragmatic and reformative one versus a deep transformative one. *Deep* biomimicry practice builds on advanced ecological and systems literacy, and on the competence of reflexivity. Deep biomimicry transforms in both directions, outside-in and inside-out, in a dual and interactive process of change. In design, the concept of human centeredness is confusing. Does it point to the anthropocentric, humans-first mindset, or counterintuitively to the deep leverage point for personal transformation when perspective shifts to inner worlds, values and spirituality (Russell 2002; Ives et al. 2020)? The practice of shallow biomimicry is a clear indication for rudimentarily developed literacy in systems ecology and very basic skills in systems thinking, characteristic for the transition phase from a mechanistic to a holistic worldview (Fig. 3). How could, at this stage, the sustainability practitioner have accommodated to the powerful concept of nested order and learned to leverage it? Although biomimicry capture one's imagination because of its promise, the innovation goals pursued are often not well in line with nature's overall goal of sustainability with all its consequences. The position of the biomimicry founders in this issue clearly is to encourage learning by doing. The more biomimicry is being practiced, the better practitioners will learn to master the art. Biomimicry presents itself as a practice and a guild, not as a scientific discipline. Interestingly the philosophical underpinning of the biomimicry phenomenon increasingly captures the mind of philosophers (Mathews 2011; Dicks 2016). As a tool to guide transformation, biomimicry's conceptual framework (Fig. 4) is much more powerful, I argue, than

current superficial, bio-inspired case studies. True biomimicry remains a perspective, a vision and for some a dream.

Keystone finding: the coalescence of STiP and biomimicry design thinking

Consistent holistic systems thinking and deep biomimicry practice for sustainability go hand in hand. They are the theoretical and practical sides of a transdisciplinary approach to the sustainability issue. The teleological position bridges the ontological and epistemological positions to systems thinking. Teleology is deeply rooted in the core metaphor of nested hierarchies and in biomimicry thinking and design. The biomimicry practitioner and the research practitioner complement another. There is a whole field of design thinking for sustainability at the researcher's doorstep. What can it teach? There is a whole field of reflexive STiP at the designer's doorstep. What can it teach? Moreover, both sustainability practitioners face the same challenge: their disciplines are emergent. STiP is as much a rudimentarily developed field (Ison 2018) as mainstream biomimicry practice is shallow. I expect the conscious braiding of STiP and biomimicry's nature inspired design thinking to become the holy grail (Fischer and Riechers 2019) of a transdisciplinary sustainability science that aims at guiding society on more sustainable trajectories.

Conclusion

With tragedy increasingly threatening *Homo sapiens,* the target in transdisciplinary sustainability science has become radical change. This paper shows that the way forward calls for a systemic understanding of transformation, for an equal development of the ontological and epistemological positions to systems thinking for sustainability, and for leveraging the fundamentally re-connecting teleological position. The deep leverage points approach (Table 1) in combination with holistic systems thinking used in this paper proves to be the powerful research strategy needed for now. The leverage-points-for-digging tool strikes at the root of the ontological issue of transformation for sustainability, while the leverage-points-for-cure frame effectively relates to the epistemological dimension of transformation and the practical solution space.

From a fundamental and ontological point of view, transformation for sustainability was found to be the cascading process of systemic change triggered by a paradigm shift in its most radical form (Fig. 1), itself sourcing in a worldview shift and entailing a new way of perceiving, thinking and acting (Fig. 3). This type of radical change was found necessary to treat the root cause of unsustainability. Unsustainability was recognized to rest on a cognitive illusion, a teleological deficiency and a lack of thinking in terms of living systems. The deepest target point to hit, beyond paradigm in Meadows' list of leverage points, was hypothesized to be our very conceptual system, metaphorical in nature, out of which we think, design and act. Changing core metaphors and ways of systems thinking from conventional to holistic is the turning point, at which the leverage points transform into a metaphor of nested order and the tool becomes the systemic standard for a new sustainability paradigm (Table 2 and Fig. 4).

The practical, epistemological position to systems thinking was not fully developed in this paper. The findings, however, reflect the status quo in transformative practice for sustainability from a broad, holistic perspective. Thinking in living systems and conceiving paradigms as living, mental systems that display the typical pattern of a life cycle is an effective approach. The paradigmatic dynamics that underpin the global sustainability issue are forecasting the likely emergence of a new, cultural and scientific paradigm (Fig. 2). Leading-edge, transformative exponents of the anthropocentric, academic mainstream and a non-academic eco-design tide contribute to the breakthrough of a new paradigm, equally but so far independently. A crucial, future role for transdisciplinary sustainability science will be in developing and imparting holistic, and living systems thinking. The promising field of biomimicry already re-introduces nature and biology in human thinking and design. Biomimicry teaches that sustainability no longer is the persistent problem: to create conditions conducive to life becomes the emergent solution and overall quest. Biomimicry provides ecological content for a living systems sustainability paradigm and the learning-from-nature epistemology for deep transformative practice (Fig. 4).

Human thought processes and mental models, I conclude, are at the root of the sustainability issue. The co-evolving practice for sustainability, in science and in nature inspired design, brought to light by this study is a factor of tremendous hope and importance on an emergent, transdisciplinary trajectory toward sustainability. It will help develop and disseminate living systems thinking in academia and in society. This co-evolution is very likely to culminate in a true symbiosis of know-what (science) and know-how (design) to transform human systems sustainably.

Acknowledgements I thank Julia Leventon and David Abson for supporting me as editors of the Special Issue on Leverage Points for Sustainability Transformations as well as two anonymous reviewers for their critical and constructive comments which helped substantially improve the manuscript. Many thanks to Frederiek van Lienen for discussing and commenting on the article, to Luisa Burgers for carefully reading the manuscript, and to Paula Davelaar Burgers for her helpful suggestions and professional assistance in drawing the figures which are an essential part of the article. This work was not funded.

References

Abson DJ, Fischer J, Leventon J et al (2017) Leverage points for sustainability transformation. Ambio 46:30–39. https://doi.org/10.1007/s13280-016-0800-y

Arthur WB (2009) The nature of technology. Free Press, New York

Bateson G (1972) Steps to an ecology of mind. The University of Chicago Press, Chicago

Baumeister D, Tocke R, Dwyer J, Ritter S, Benyus JM (2014) Biomimicry resource handbook: a seedbank of best practices. CreateSpace Ind Pub Platform, United States

Benyus JM (2002) Biomimicry: innovation inspired by nature. HarperCollins, New York

Benyus JM (2014) A biomimicry primer. In: Baumeister D (ed) Biomimicry resource handbook: a seedbank of best practices. CreateSpace Ind Pub Platform, United States

Berry T (2000) The great work: our way into the future. Broadway Books, New York

Bosch O, Maani K, Smith C (2007) Systems thinking—language of complexity for scientists and managers. In: Harrison S, Bosch A, Herbohn J (eds) Improving the triple bottom line returns from small-scale forestry. The University of Queensland, Gatton, pp 57–66

Buller DJ (2002) Function and design revisited. In: Ariew A, Cummins R, Perlman M (eds) Functions—new essays in the philosophy of psychology and biology. Oxford University Press, New York, pp 222–243

Capra F (1983) The turning point—science, society, and the rising culture. Bantam Books, New York

Capra F, Luisi PL (2014) The systems view of life—a unifying vision. Cambridge University Press, New York

Ceschin F, Gaziulusoy I (2016) Evolution of design for sustainability: from product design to design for system innovations and transition. Des Stud 47:118–163. https://doi.org/10.1016/j.destud.2016.09.002

Crutzen P, Stoermer E (2000) The Anthropocene. IGBP Glob Change Newslett 41:17–18

DeLuca D (2016) Re-aligning with nature—ecological thinking for radical transformation. White Cloud Press, Ashland Oregon

Dicks H (2016) The philosophy of biomimicry. Philos Technol 29:223–243. https://doi.org/10.1007/s13347-015-0210-2

Feola G (2015) Societal transformation in response to global environmental change: a review of emerging concepts. Ambio 44:376–390. https://doi.org/10.1007/s13280-014-0582-z

Ferguson M (1980) The aquarian conspiracy—personal and social transformation in the 1980s. Tarcher Inc., Los Angeles

Fiorentino C, MontanaHoyos C (2014) The emerging discipline of biomimicry as a paradigm shift towards design for resilience. Int J Design Objects 8:1–15

Fischer J, Riechers M (2019) A leverage points perspective on sustainability. People Nat 00:1–6. https://doi.org/10.1002/pan3.13

Glasser H (2019) Toward robust foundations for sustainable well-being societies: learning to change by changing how we learn. In: Cook JW (ed) Sustainability, human well-being, and the future of education. Springer Nature Switzerland, Cham, pp 31–89

González-Márquez I, Toledo VM (2020) Sustainability science: a paradigm in crisis? Sustainability 12:2802. https://doi.org/10.3390/su12072802

Göpel M (2016) The great mindshift—How a new economic paradigm and sustainability transformations go hand in hand. Springer Nature Switzerland, Cham

Harman J (2013) The Shark's paintbrush. Nicholas Brealey Publishing, Boston

Henning BG (2016) From the anthropocene to the ecozoic. Philos Glob Clim Change. https://doi.org/10.1111/misp.12061

Irwin T (2018) The emerging transition design approach. DMA. https://doi.org/10.21606/dma.2017.210

Ison RL (2016) Transforming nature-society relations through innovations in research praxis: a coevolutionary systems approach. In: Hubert B, Mathieu N (eds) Interdisciplinarités entre nature et Sociétés: colloque de cerisy. Peter Lang, Bern, pp 47–70

Ison RL (2017) Transdisciplinarity as transformation—a systems thinking in practice perspective. In: Fam D, Palmer J, Mitchell C, Riedy C (eds) Transdisciplinary research and practice for sustainable outcomes. Routledge, London, pp 55–73

Ison R (2018) Governing the human-environment relationship: systemic practice. Curr Opin Environ Sustain 33:114–123. https://doi.org/10.1016/j.cosust.2018.05.009

Ives CD, Freeth R, Fischer J (2020) Inside-out sustainability: the neglect of inner worlds. Ambio 49:208–217. https://doi.org/10.1007/s13280-019-01187-w

Jerneck A, Olsson L, Ness B et al (2011) Structuring sustainability science. Sustain Sci 6:1–14. https://doi.org/10.1007/s11625-010-0117-x

Kajikawa Y (2008) Research core and framework of sustainability science. Sustain Sci 3:215–239. https://doi.org/10.1007/s11625-008-0053-1

Kates RW (2011) What kind of a science is sustainability science? PNAS 108(49):19449–19450. https://doi.org/10.1073/pnas.1116097108

Kim DH (1992) Systems archetypes I: diagnozing systemic issues and designing high-leverage interventions. Pegasus Communications Inc., Waltham

Kim DH (1999) Introduction to Systems Thinking. Pegasus Communications, Waltham MA

Kuhn TS (1996) The structure of scientific revolutions. The University of Chicago Press, Chicago

Kumar S (2013) The ecozoic era—we are not in the anthropocene epoch, but entering into the ecozoic era. Resurgence 279:1

Laininen E (2019) Transforming our worldview towards a sustainable future. In: Cook JW (ed) Sustainability, human well-being, and the future of education. Springer Nature Switzerland, Cham, pp 31–89

Lakoff G, Johnson M (2003) Metaphors we live by. The University of Chicago Press, Chicago

Macy J, Brown MY (2014) Coming back to Life. New Society Publishers, Gabriola Island

Mathews F (2011) Towards a deeper philosophy of biomimicry. Organ Environ 24:364–387. https://doi.org/10.1177/1086026611425689

Max-Neef M (2010) The world on a collision course and the need for a new economy. Ambio 39:200–210. https://doi.org/10.1007/s13280-010-0028-1

Meadows DH (2008) Thinking in systems: a primer. Chelsea Green Publishing, White River Junction

Miller TR (2013) Constructing sustainability science: emerging perspectives and research trajectories. Sustain Sci 8:279–293. https://doi.org/10.1007/s11625-012-0180-6

Miller TR, Wiek A, Sarewitz D et al (2014) The future of sustainability science: a solutions-oriented research agenda. Sustain Sci 9:239–246. https://doi.org/10.1007/s11625-013-0224-6

Monat JP, Gannon TF (2015) What is systems thinking? A review of selected literature plus recommendations. Am J Syst Sci 4:11–26. https://doi.org/10.5923/j.ajss.20150401.02

Naudé P (2018) Can we overcome the anthropocentricism bias in sustainability discourse? Afr J Bus Ethics 11:56–67. https://doi.org/10.15249/11-2-189

Odum EP, Barrett GW (2005) Fundamentals of ecology, 5th edn. Thomson Brooks/Cole, Belmont

Purvis B, Mao Y, Robinson D (2019) Three pillars of sustainability: in search of conceptual origins. Sustain Sci 14:681–695. https://doi.org/10.1007/s11625-018-0627-5

Ramage M, Shipp K (2020) Systems thinkers, 2nd edn. The Open University, Milton Keynes

Ruse M (2002) Evolutionary biology and teleological thinking. In: Ariew A, Cummins R, Perlman M (eds) Functions—new essays in the philosophy of psychology and biology. Oxford University Press, New York, pp 33–59

Russell P (2002) From science to god. New World Library, Novato

Sanders EBN, Stappers PJ (2008) Co-creation and the new landscapes of design. Co-Design 4:5–18. https://doi.org/10.1080/15710880701875068

Seidler R, Bawa KS (2016) Ecology. In: Adamson J, Gleason WA, Pellow DN (eds) Keywords for environmental studies. New York University Press, New York, pp 71–75

Senge P, Scharmer CO, Jaworski J, Flowers BS (2004) Presence—human purpose and the field of the future. Crown Business, New York

Skene KR (2018) Circles, spirals, pyramids and cubes: why the circular economy cannot work. Sustain Sci 13:479–492. https://doi.org/10.1007/s11625-017-0443-3

Spangenberg JH (2011) Sustainability science: a review, an analysis an some empirical lessons. Environ Conserv 38:275–287. https://doi.org/10.1017/S0376892911000270

Steffen W, Grinevald J, Crutzen P, McNeill J (2011) Review—the anthropocene: conceptual and historical perspectives. Phil Trans R Soc A 369:842–867. https://doi.org/10.1098/rsta.2010.0327

Steffen W, Richardson K, Rockström J et al (2015) Planetary boundaries: guiding human development on a changing planet. Science 347:736. https://doi.org/10.1126/science.1259855

Steffen W, Broadgate W, Deutsch L et al (2015) The trajectory of the anthropocene: the great acceleration. Anthrop Rev 2:81–98. https://doi.org/10.1177/2053019614564785

Steffen W, Rockström J, Richardson K et al (2018) Trajectories of the earth system in the anthropocene. PNAS 115:8252–8259. https://doi.org/10.1073/pnas.1810141115

Sterling S (2003) Whole systems thinking as a basis for paradigm change in education: explorations in the context of sustainability. PhD Thesis, Centre for Research in Education and the Environment, University of Bath

Sterling S (2010) Transformative learning and sustainability: sketching the conceptual ground. Learn Teach Higher Educ 5:17–33

van Peursen CA (1974) The strategy of culture—a view of the changes taking place in our ways of thinking and living today. North-Holland Pub Company, Amsterdam

von Bertalanffy L (1968) General systems theory—foundations, development applications. George Braziller, New York

Wahl DC (2016) Designing regenerative cultures. Triarchy Press, Axminster

WCED (1987) Our common future. Oxford University Press, Oxford

Wiek A, Lang DJ (2016) Transformational sustainability research methodology. In: Heinrichs H, Martens P, Michelsen G, Wiek A (eds) Sustainability science. Springer, Berlin, pp 31–41. https://doi.org/10.1007/978-94-017-7242-6_3

Zweers W (2000) Participating with nature—outline for an ecologization of our worldview. Int Books, Utrecht