Master's thesis

Sustainable Business and Innovation

# Are new green ideas getting harder to find?

## The burden of knowledge in sustainability science

14 July 2021

Max Callies

Utrecht University (UU)
Centre for Science and Technology Studies (CWTS)

Student number: 5518601
Supervisor UU: Gaston Heimeriks
Supervisor CWTS: Thomas Franssen

# Abstract

**Introduction** Research in sustainability science contributes to the transition towards a sustainable society. Alarmed by recent evidence of declining research productivity, this study asks whether new ideas in sustainability science are getting harder to find due to a burden of knowledge. The burden of knowledge hypothesis states that innovation requires increasing input, as more preceding knowledge needs to be processed and remaining problems are increasingly complex. **Theory** First, the nature of sustainability science is assessed in terms of growth, interdisciplinarity and cumulativeness of knowledge. These indicators yield insights into the maturity, relative autonomy and strength of the paradigm of sustainability science. Second, it is hypothesized that the burden of knowledge causes increasing trends in collaboration, the complexity of new knowledge, the threshold to produce a new piece of knowledge and the threshold for researchers to publish their first article. The burden of knowledge effect is expected to be stronger after establishment of a strong research paradigm. **Methods** Sustainability science is operationalized as the Web of Science category *Green and Sustainable Science and Technology* (GSST). Twelve indicators are measured using a set of 117.808 records of articles published in GSST retrieved from the Web of Science. Publicly available data is used for author disambiguation and to compute the age at entry. **Results** Sustainability science is a rapidly growing field, that is integrating knowledge from an increasing area of scientific landscape. Cumulativeness of knowledge increased at a high rate until 2010 and less steeply thereafter. A linear increase in team size indicates increased collaboration. Longer titles and abstracts together with an increasing number of keywords and pages indicate increasing complexity of new knowledge. The threshold for production of a new piece of knowledge increases, as indicated by the number of references. The threshold for researchers to publish their first article decreases. **Discussion** The findings suggest that sustainability science should be regarded as an umbrella term and does not seem to develop into an autonomous discipline. Furthermore, it is confirmed that the strength of a knowledge burden relates to cumulativeness of knowledge, adding to the literature on knowledge production. **Conclusion** Patterns related to a burden of knowledge can be detected in sustainability science, although the effect on individual researchers and quantitative output is limited. Further maturation of the field and refinement of the paradigm is expected to lead to decreasing research productivity on the long term.

# Table of contents

**1. Introduction** .......... **6**

**2. Theory** .......... **9**

*2.1 What kind of science is sustainability science?* .......... *9*
  2.1.1 Growth .......... 10
  2.1.2 Interdisciplinarity .......... 12
  2.1.3 Cumulativeness of knowledge .......... 16

*2.2 The burden of knowledge* .......... *18*
  2.2.1 Collaboration in the production of knowledge .......... 20
  2.2.2 Complexity of the produced knowledge .......... 21
  2.2.3 Reaching the threshold of knowledge production .......... 21

**3. Methods** .......... **23**

*3.1 Research Design* .......... *23*
  3.1.1 Interdisciplinarity .......... 23
  3.1.2 Cumulativeness of knowledge .......... 25
  3.1.3 Collaboration in knowledge production .......... 26
  3.1.4 Complexity of newly produced knowledge .......... 26
  3.1.5 Threshold of knowledge production .......... 27

*3.2 Delineating sustainability science* .......... *29*

*3.3 Data collection* .......... *32*

*3.4 Data analysis* .......... *34*

*3.5 Validity and reliability* .......... *35*

**4. Results** .......... **38**

*4.1 Growth* .......... *38*

*4.1 Interdisciplinarity* .......... *39*
  4.1.1 Diversity of WCs in global GSST .......... 39
  4.1.2 Diversity of WCs in *Dutch author set* .......... 41
  4.1.3 Diversity in cited references .......... 42

*4.2 Cumulativeness of knowledge* .......... *43*
  4.2.1 Median age of references .......... 43
  4.2.2 Price-Index .......... 44

*4.3 Collaboration in knowledge production* .......... *45*
  4.3.1 Team size .......... 45

*4.4 Complexity of the produced knowledge* .......... *46*
  4.4.1 Number of words in title and abstract .......... 46
  4.4.2 Number of keywords and pages per article .......... 47

*4.5 Reaching the threshold of knowledge production* .......... *48*
  4.5.1 Number of references .......... 48
  4.5.2 Age at and number of publications before entry .......... 49

**5. Discussion** .......... **52**

*5.1 Growth, interdisciplinarity and cumulativeness* .......... *52*

*5.2 Patterns of a knowledge burden* .......... *54*

*5.3 Limitations* .......... *55*

*5.4 Implications for policy and society* .......... *57*

**6. Conclusion** .......... **58**

**7. Acknowledgements** .......... **59**

**8. References** .......... **60**

# List of tables and figures

## Tables

Overview of the research design ........ 28
Overview of operationalizations of sustainability science used in previous studies ........ 31

## Figures

Growth of sustainability science according to three distinct methods of operationalization ........ 11
Growth of publications on environmental, social and economic sustainability. ........ 12
Growth in the number of authors in and unification of sustainability science ........ 14
The number of WCs and interdisciplinarity in sustainability science ........ 15
Cluster analysis showing the changing landscape of sustainability science ........ 14
Schematic representation of the attributes of diversity ........ 23
Schematic overview of the sets of bibliographic records retrieved from the Web of Science. ........ 32
Schematic overview of data collection for the age at entry and number of publications before entry ........ 33
New publications in the WC Green & Sustainable Science & Technology ........ 38
Diversity in the distribution of WCs in the base set ........ 39
Diversity in the distribution of WCs in the Dutch author set. ........ 41
Average diversity of WCs in the cited references of articles in the Dutch set. ........ 42
Average relative age of references in the base set. ........ 43
Average Price Index per year in the base set. ........ 44
Average team size per year in the base set and proportions and occurrences of team sizes one to five. ........ 45
Average number of words in titles and abstracts per year in the base set. ........ 46
Average number keywords and pages per year in the base set. ........ 47
Average number of references per year in the base set ........ 48
Average age at entry of sustainability scientists per year ........ 49
Average number of publications before entry of sustainability scientists per year. ........ 49

# 1. Introduction

In the second half of the previous century, it slowly dawned on humanity that the economic system that had brought unprecedented prosperity was also the source of new environmental and social problems. In response to challenges such as climate change, biodiversity decline and global inequality, the concept of 'sustainable development' emerged (Fang et al., 2018; González-Márquez & Toledo, 2020; Kajikawa et al., 2014; Kates, 2011; Spangenberg, 2011). The Brundtland Commission famously defined it in 1987 as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). The concept served as a spot on the horizon in the search for solutions to the issues. Scientists from various disciplines embarked on such a search, often challenged by the real-world problems to cooperate across the disciplinary boundaries they were used to (Bettencourt & Kaur, 2011). At the turn of the millennium, Kates et al. (2001) observe that from these interdisciplinary efforts a new research field had emerged: sustainability science.

Sustainability science is expected to deliver solutions to some of the most pressing issues humanity is facing. In that regard, it is promising that the field is creating new knowledge at a rapid pace. Between 2006 and 2016, the number of new publications grew exponentially (Bautista Puig et al., 2020; Fang et al., 2018; Pandiella-Dominique et al., 2018). However, recent insights from economic science suggest that despite the growth in output, there may be reasons for concern. Bloom et al. (2020) make an important observation concerning Moore's law, which states that the number of transistors on a computer chip doubles every two years thanks to technological innovation. They find that the number of researchers necessary to double chip capacity is now 18 times larger than in the 1970s, revealing that research productivity is in fact declining sharply at a rate of 7% per year. Similar findings of declining research productivity in agriculture, medicine and the aggregate U.S. economy lead them to the troubling conclusion that new ideas are getting harder to find (Bloom et al., 2020).

A possible explanation for the decline in research productivity is provided by Jones (2009) in the oft-cited paper "The Burden of Knowledge and the 'Death' of the Renaissance Man': Is Innovation Getting Harder?". According to Jones (2009), if knowledge accumulates within a certain domain, successive generations of knowledge producers in that domain face an increasing educational burden. Knowledge is cumulative if new knowledge components are built on top of older ones, therefore requiring the older components to be processed first. Isaac Newton was already aware of the cumulativeness of scientific knowledge in 1676, when he wrote: “If I have seen further it is by standing on ye shoulders of giants.” Jones (2009) further poses that knowledge producers can cope with the ‘burden of knowledge’ by narrowing their expertise, spending more time in education and cooperating with others. However, since the capacity of humans to absorb knowledge is ultimately limited, he expects the knowledge burden mechanism to have negative implications for growth on the long term (Jones, 2009).

While economists are concerned that declining research productivity may lead to the end of economic growth (Bloom et al., 2020; Gordon, 2016), the potential implications for our ability to accomplish sustainable development are – at least – equally alarming. If the burden of knowledge causes the stream of new ideas from sustainability science to dry up, achieving a smooth transition towards a sustainable society would become extremely difficult. The early identification of patterns associated with a burden of knowledge can be helpful in designing a successful organization of knowledge production in sustainability science, e.g. policies that facilitate and cooperation of increasingly large teams or redesign educational programs. Therefore, the research question of this study is highly relevant from a societal and policy-maker perspective: are new ideas getting harder to find in sustainability science because of a burden of knowledge?

To answer this question, the characteristics of knowledge production in sustainability science need to be known. Therefore, the aim of this research is twofold. First, to establish the context of a potential burden of knowledge. To this end, the following question is answered: what kind of science is sustainability science in terms of growth, interdisciplinarity and cumulativeness of knowledge? The second aim is to detect patterns indicating the existence of a burden of knowledge, should it exist, and thereby answer the research question.

Jones (2009) finds empirical evidence for the existence of a burden of knowledge in patent data, i.a. an increasing team size and an increasing number of references – indicating the amount of knowledge required to process before the technology could be invented. Schweitzer and Brendel (2020) use Jones’ (2009) conceptual model and data from bibliographic records to show empirically that new ideas are also getting harder to find in the long-established scientific disciplines of economics and mathematics. Their conclusions are not generalizable for the entire scientific realm, since fields can be characterized by very different dynamics of knowledge production. For example, natural sciences have stronger research paradigms – in which knowledge is more cumulative – than social sciences or the humanities (Franssen & Wouters, 2019; Price, 1970). Furthermore, the maturity of a field and its phase in Kuhn’s cycle of science is relevant to the dynamics of knowledge production (González-Márquez & Toledo, 2020; Kuhn, 1970). Thus, by studying the burden of knowledge mechanism in a field that emerged relatively recently and is regarded as a “different kind of science” (Kates, 2011), this thesis adds a new perspective to the literature on scientific knowledge production and research productivity in general.

Sustainability science is considered to be a ‘post-normal’ or ‘mode 2’ research field (González-Márquez & Toledo, 2020; Spangenberg, 2011). These are mission-oriented and highly interdisciplinary fields, in which scholars and practitioners collaborate to combine fundamental and applied knowledge components to address societal problems (Bautista Puig et al., 2020; Kates, 2011). Studying the burden of knowledge in sustainability science requires an understanding of those particular dynamics of knowledge production. This research contributes to the literature on the nature and development of sustainability science by measuring three characteristics that are relevant in terms of knowledge production.

First, the growth of new publications reflects the quantitative knowledge output of the field. Second, interdisciplinarity, i.e. the extent to which the field integrates knowledge from other disciplines, indicates whether the field is mature and produces knowledge autonomously. Besides, interdisciplinary cooperation can be regarded as a strategy to overcome the burden of knowledge. Third, the cumulativeness of knowledge in sustainability science, i.e. the strength of its paradigm, is measured. This relates to the burden of knowledge, since its weight depends on the extent to which old knowledge components are required to build new ones.

The model that was developed by Jones (2009) and extended by Brendel (2018) is used to derive three hypotheses related to the existence of a knowledge burden. Cooperation among authors is expected to increase, as it is a strategy to deal with the burden of knowledge. Furthermore, new knowledge is expected to be increasingly complex, since more and more knowledge components are built on top of each other. Lastly, the threshold of knowledge production for researchers is expected to increase, since more knowledge needs to be processed before new knowledge can be produced.

The remainder of this paper is structured as follows. In the next section, relevant literature on the nature and development of sustainability science is presented. Furthermore, the burden of knowledge and its related concepts are discussed, from which the hypotheses are formulated. In the methods section, the operationalizations of the concepts to be measured are explained, along with the methods of data collection and analysis. Next, the results of the analyses are presented and subsequently discussed in relation to the theory. The discussion moreover provides the limitations of this study and suggestions for future research. In the last section, conclusions are drawn and the research question is answered.

# 2. Theory

This research draws on and contributes to three bodies of literature, which are discussed in this section. First, studies on the nature and development of sustainability science are used to paint an initial picture of the field. Particular attention is directed towards growth, interdisciplinarity and cumulativeness of knowledge, since these attributes provide relevant context when studying the burden of knowledge. Contrary to growth and interdisciplinarity, cumulativeness of knowledge has not yet been studied in sustainability science. Therefore, literature related to this concept in science in general is discussed. Third, literature on research productivity is used to derive three conceptual hypotheses related to the existence of a knowledge burden.

## 2.1 What kind of science is sustainability science?

Sustainability science can be defined as “an emerging field of problem-oriented research that analyzes the interactions between natural and social systems to contribute to a sustainable society” (Kates, 2011, p. 19449). The field has its origins in the concept of sustainable development, which was defined by the Brundtland Commission in 1987 as development that does not compromise the ability of future generations to meet their needs (World Commission on Environment and Development, 1987). The scientific efforts in various disciplines to contribute to such sustainable development evolved into a new discipline in the last two decades of the previous century. From 2000 onwards the field gained momentum and after 2006 the number of articles published in the field grew exponentially (Fang et al., 2018; Olawumi & Chan, 2018). Moreover, research institutes, academic associations, schools, programs and journals were launched or created, focusing solely on sustainability science (Fang et al., 2018).

Scholars agree that sustainability science is a new and different kind of science. Kates (2011) states that it is “primarily use-inspired, as are agricultural and health sciences, with significant fundamental and applied knowledge components, and commitment to moving such knowledge into societal action” (p. 19450). Others also highlight interdisciplinarity, transdisciplinarity and the mission-oriented nature of sustainability science as its defining features (Irwin et al., 2018). These features are regarded as the features of ‘mode 2’ or ‘post-normal’ science, as opposed to ‘mode 1’ and ‘normal’ science (González-Márquez & Toledo, 2020). ‘Normal’ science is science through which a research paradigm is extended and refined without questioning its fundamental claims (Kuhn, 1970). ‘Mode 1’ science is oriented at solving theoretical puzzles within the boundaries of a discipline. Traditional disciplines such as mathematics are considered to be ‘normal’ and ‘mode 1’ sciences. ‘Mode 2’ knowledge production in ‘post-normal’ fields, on the contrary, is application-oriented, context-driven and transcends disciplinary boundaries (Spangenberg, 2011).

With respect to the burden of knowledge, three attributes of sustainability science are considered to be relevant. The first is growth, i.e. the number of new publications per year, which reflects the quantitative output of the field. A potential burden of knowledge would ultimately lead to a stagnation in that output. Therefore, it is relevant to see if such a stagnation is occurring.

### 2.1.1 Growth

Previous studies conclude that sustainability science emerged around the year 2000 and started growing exponentially in 2006 (Fang et al., 2018; Fernandes & Philippi, 2017; Kajikawa et al., 2014; Olawumi & Chan, 2018; Pandiella-Dominique et al., 2018; Rosulnik, 2012).

shows the growth graph of three of the most recent studies on the development of the field, using three distinct methods of operationalization (see Methods). Fang et al. (2018) find that the growth in the number of articles published on sustainability science follows the shape of an S-curve in the period 1994-2017 (see

). They suggest that after a period of exponential growth between 2006 and 2013, the growth rate starts to decline and the field enters a stage of asymptotic growth. Note, however, that Fang et al. (2018) identify articles *on* sustainability science, not *in* sustainability science (see Methods). Hence, the suggested growth trajectory does not necessarily hold for the entire field. The other growth trajectories in
, which are the result of operationalizations that identified articles *in* sustainability science, do not suggest a stagnation.

Pandiella-Dominique et al. (2018), who operationalize sustainability science as the Web of Science category (WC) *Green & Sustainable Science & Technology* (GSST), find a compound average growth rate (CAGR) of 19,28% for the period 1996-2016. One recent study assesses the growth in science on environmental, social and economic sustainability separately (Bautista Puig et al., 2020). It finds that the environmental branch has grown faster between 1997 and 2017, with a CAGR of 21,15% compared to 20,01% and 19.57% in the social and economic branches respectively (see Figure 2). For comparison, average growth rates of science overall are estimated at four to five percent (Bornmann & Mutz, 2015; Price, 1963).

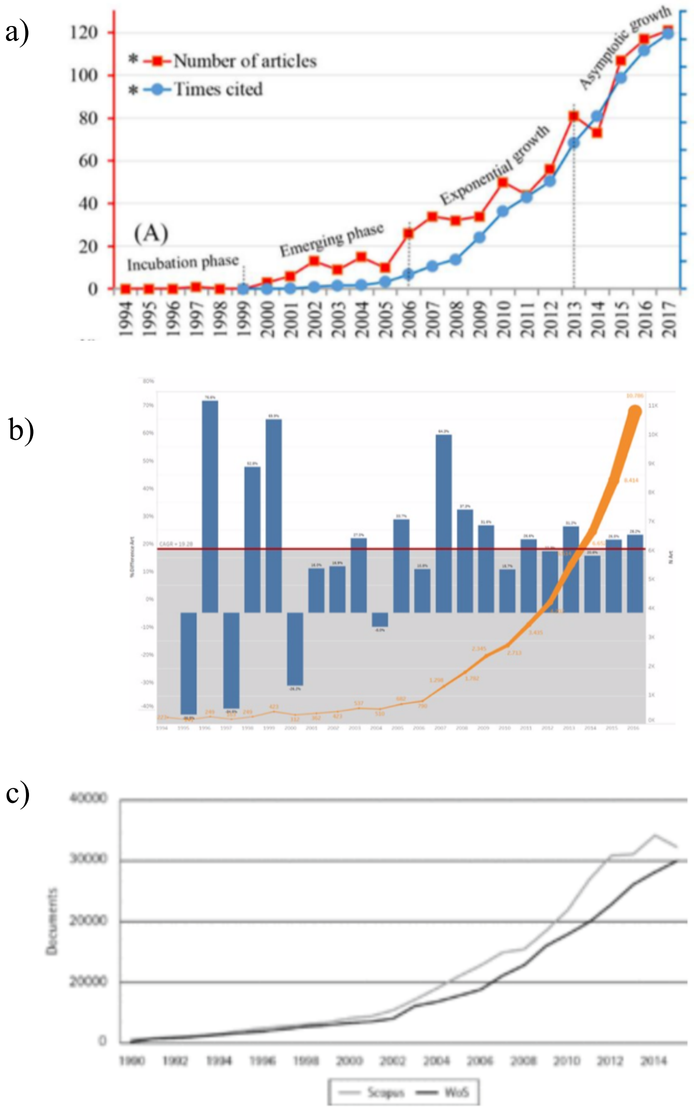

**Figure 1** Growth of sustainability science according to three distinct methods of operationalization:

a) the number of articles *on* sustainability science and their citations per year as found by Fang et al. (2018).

b) The number of articles per year (orange line), year-on-year growth (bars) and the compound annual growth rate (CAGR) of the WoS category GSST, as found by Pandiella-Dominique et al. (2018).

c) The number of articles per year as found by Fernandes & Philippi (2017) searching for "sustainab*" in abstract, title and keywords, both in Scopus (grey line) and WoS (black line).

Since the most recent previous studies on the development and growth of sustainability science collect articles up to 2017 (Bautista Puig et al., 2020; Fang et al., 2018) or 2016 (Fernandes & Philippi, 2017; Olawumi & Chan, 2018; Pandiella-Dominique et al., 2018), it is not known how the field has developed in recent years. If the field is stagnating, as suggested by Fang et al. (2018), this may be related to an increasing burden of knowledge. Note, however, that growth of the number of publications does not equal the growth of knowledge. Researchers are incentivized to publish as much as possible, sometimes leading to publications that do not actually contribute new knowledge (Brendel, 2018). Therefore, measuring the growth of publications in sustainability science can only provide context for the study of a potential burden of knowledge.

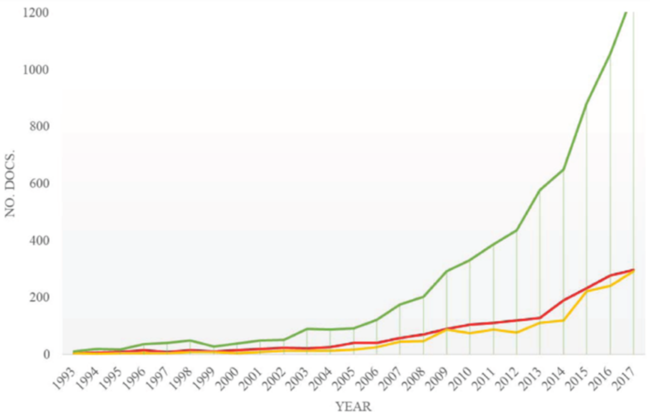

**Figure 2** Growth of publications *on* environmental, social and economic sustainability, as found by Bautista-Puig et al. (2020).

### 2.1.2 Interdisciplinarity

The second attribute of knowledge production in sustainability science that is relevant to this study is interdisciplinarity. Interdisciplinarity is defined as the integration of different bodies of knowledge (Rosulnik, 2012). Sustainability science is found to be more interdisciplinary than other fields, which is not surprising considering the interdisciplinary nature of real-world social and environmental problems. Interdisciplinarity provides relevant context for this research, since it is related to the maturity and autonomy of a discipline. Maturing fields are considered to be increasingly self-sustaining and thus: decreasingly interdisciplinary. Some scholars expect this pattern to occur in sustainability science. However, since sustainability science is considered to be a ‘mode 2’ science, constantly high or even increasing levels of interdisciplinarity are also a possibility. Hence, interdisciplinarity can contribute to revealing what kind of science it is.

Interdisciplinarity and transdisciplinarity can be regarded as stages in the development of a scientific field (Buter & Van Raan, 2013). The development starts with isolated contributions from multiple disciplines on a single topic, such as sustainability. Next, the efforts from these disciplines start to overlap in an interdisciplinary approach, which establishes shared methods and concepts. Finally, transdisciplinarity is the stage in which the approach is integrated on a level that research in the field is self-sustaining and based on the newly developed methods and concepts. In this stage, the field becomes less dependent on knowledge from other fields, leading to an increasingly lower diversity value (Buter & Van Raan, 2013). Note that this definition of transdisciplinarity is different from another frequently used definition, that describes a process of collaboration between scholars and non-scholars on a specific real-world problem (Haider et al., 2018). The former definition, however, is more relevant to this study.

Pacheco et al. (2017) describe a similar general process of development of scientific fields. They interlink the concepts of interdisciplinarity and innovation and observe that historically they occur almost simultaneously. They pose that the concepts should be regarded in the perspective of a larger cycle of crisis, creative destruction and stability, reminding of Kuhn's (1970) model of scientific revolutions. In Pacheco et al.'s (2017) view, the environmental crisis has triggered a concerted effort by scientists from various disciplines to find innovative solutions. They call this a process of creative destruction in which sustainability-related interdisciplinary research and innovation go hand in hand. This process will lead to a new equilibrium, which can be compared to Buter and van Raan's (2013) transdisciplinarity, in which there will be less interdisciplinarity and less innovation (Pacheco et al., 2017).

The extent to which sustainability science is an integrated, mature and autonomous discipline – i.e. in which stage of processes described above it finds itself – is debated. Some scholars observe a consolidation of the field and expect it to develop into a separate discipline (Bettencourt & Kaur, 2011; Buter & Van Raan, 2013; Fang et al., 2018 and Kajikawa et al., 2014), while others regard it as a research field subject to several disciplines (Fernandes & Philippi, 2017; Klein, 2020).

Bettencourt & Kaur (2011) study the development of sustainability science and find evidence that it has created a new community of practice and synthesis in terms of concepts and methods. They collect data on the number of authors and their collaborations in the field. Figure 3a shows the growth of the number of authors and key events in the development of the field. Around the year 2000, they show, isolated collaboration networks in sustainability science merged into one giant collaboration cluster, indicating the unification of the field. Figure 3b shows this: the relative size of the largest cluster in the collaboration network increases steeply, while the relative size of isolated clusters declines to almost zero (Bettencourt & Kaur, 2011).

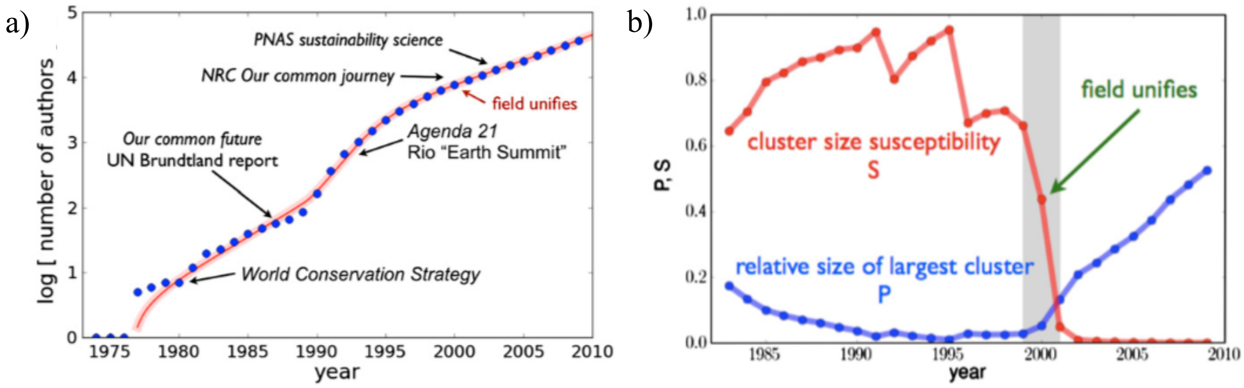

**Figure 3** a) The growth in number of authors in sustainability science and key events in its development. b) Fraction of authors in the largest collaboration cluster (blue line) and cluster size susceptibility (red line) of sustainability science. Cluster size susceptibility is large when there are independent collaboration groups and declines if authors become connected (Bettencourt & Kaur, 2011).

Kajikawa et al. (2007) and Kajikawa et al. (2014) study the academic landscape of sustainability science through citation networks. Whereas Bettencourt & Kaur (2011) find that the authors in the field became more connected, Kajikawa et al. (2014) conclude that the content of the academic landscape became more interconnected as well. Fewer and larger research clusters dominate the landscape relative to their earlier research (see Figure 4), indicating that sustainability scientists are creating common concepts and subfields.

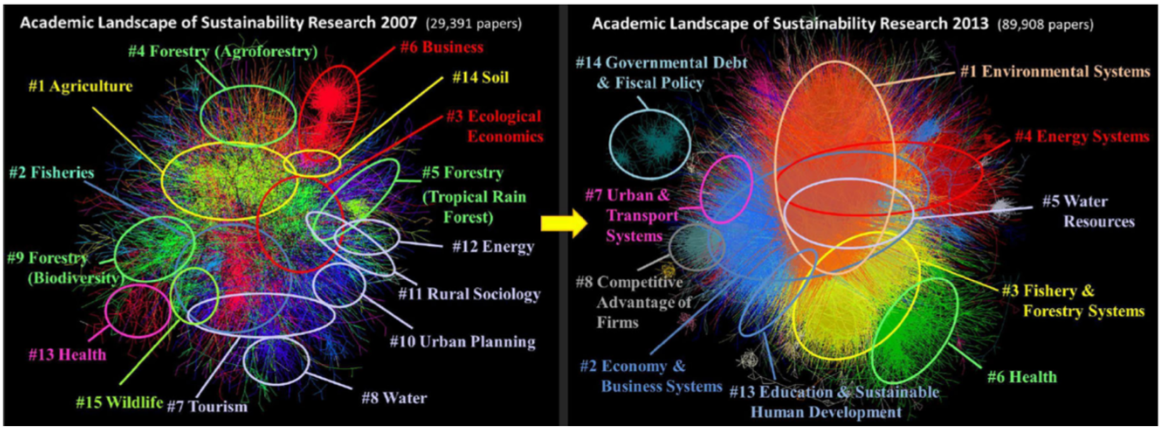

**Figure 4** Cluster analysis showing the changing landscape of sustainability science (Kajikawa et al., 2014).

Schoolman et al. (2012) and Rosulnik (2012) find that sustainability science is more interdisciplinary than other fields. A general trend of increasing interdisciplinarity has been identified in several disciplines (Cummings & Kiesler, 2014; Haeussler & Sauermann, 2020; Porter & Rafols, 2009). Rosulnik (2012) finds that the interdisciplinarity of sustainability science has increased in small steps between 1991 and 2011 (see Figure 5). Buter & Van Raan (2013) conclude that sustainability science is not yet developing towards transdisciplinarity, but expect this to start once the field is more established. The upward trend in diversity until 2011 found by Rosulnik (2012) supports this conclusion.

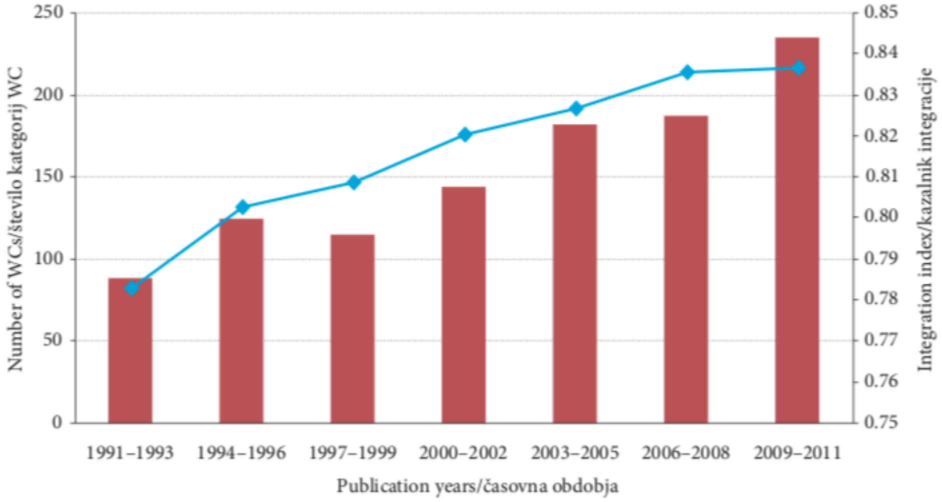

**Figure 5** The number of WCs (blue line) and the integration index, which measures diversity, of articles in sustainability science (Rosulnik, 2012).

Fang et al. (2018, p. 12) conclude that the field is in a “transition from a quantitative proliferation of publications to a qualitative consolidation and coalescence of ideas”, indicating that the field “is maturing.” Gonzalez-Marquez and Toledo (2020) state that the observed consolidation can be viewed as sustainability science turning into ‘normal science’. While some scholars agree with this view that sustainability science is evolving into an integrated and separate discipline (Bettencourt & Kaur, 2011; Buter & Van Raan, 2013; Kajikawa et al., 2014), Klein (2020) and Fernandes & Philippi (2017) argue that sustainability science should not be regarded as such. Interdisciplinarity, in Klein’s view, does not create “a new unified whole” and a successful field does not become “just another discipline” (Klein, 2020, p. 4). Rather, “it is more logical to think of sustainability as a research field (sustainability sciences) subject to several sciences than a single scientific discipline” (Fernandes & Philippi, 2017, p. 8).

Schoolman et al. (2012) find that while sustainability science is more interdisciplinary than other scientific fields, the level of integration between the environmental, social and economic pillars (i.e. sciences) falls short of their expectation. In particular, sustainability research in the environmental sciences integrates knowledge from the other two pillars significantly less than research in the social and economic sciences. These findings support the hypothesis that sustainability science is not developing into a unified and relatively autonomous discipline. Furthermore, it shows that the levels of interdisciplinarity can differ significantly *within* sustainability science, at least between its three main 'branches'.

The theories and scholarly debates discussed in this section underline the relevance of understanding and measuring the interdisciplinarity of sustainability science. Interdisciplinarity is linked to the maturity and autonomy of the field. Therefore, measuring the interdisciplinarity of the field is crucial to understand its development and establish the context in which a potential burden of knowledge is at play. Moreover, interdisciplinarity itself can be regarded as a strategy to deal with a burden of knowledge. If the unsolved puzzles within a discipline require too much time to process preceding knowledge, researchers may try to combine their expertise with knowledge from other disciplines to solve interdisciplinary puzzles. This interpretation is substantiated by Fontana et al., (2020), who view interdisciplinarity as the recombination of existing (disciplinary) knowledge components and argue that it overlaps with the Schumpeterian definition of novelty. Moreover, they find that indicators of interdisciplinarity and novelty "essentially capture the same property of a paper" (Fontana et al., 2020, p. 1). Taking this perspective and assuming the existence of a burden of knowledge, one would expect interdisciplinarity to increase. If a large amount of knowledge is already available, new ideas are getting harder to find because they need to be *increasingly new*.

### 2.1.3 Cumulativeness of knowledge

The third concept that is required to understand the knowledge dynamics in sustainability science is cumulativeness of knowledge, which means that new knowledge components are built upon older ones. Cumulativeness is a prerequisite for the existence of a burden of knowledge, because it requires the processing of older knowledge before new knowledge can be produced. Within the boundaries of a research paradigm, knowledge is considered to be cumulative (Stacey, 2021). If a revolutionary idea, e.g. Galileo Galilei's heliocentric model, causes a shift in paradigm, knowledge in the old paradigm – the geocentric model – becomes obsolescent (Jones, 2009; Kuhn, 1970). Not all scientific knowledge is equally cumulative. Philosophical ideas, for example, are less cumulative than mathematical theorems. A philosophical problem can be analyzed from a nearly infinite number of perspectives, while a mathematical problem can only be solved once, after which the solution can be used as a building block for the next theory.

The extent to which knowledge is cumulative is related to what one might call the ‘strength’ of a research paradigm. Price (1965) developed an index of the cumulativeness of knowledge in a field and shows that there is a difference between what he calls ‘hard’ and ‘soft’ sciences. The Price Index uses the ages of cited references in a field, i.e. the difference between the year of publication of the reference and the citing publication, and is the proportion of references that are not older than five years (Price, 1965). The Index reflects the “immediacy” of the new knowledge, i.e. the extent to which it is built on relatively recent pieces of older knowledge. Fields with a high immediacy have so-called research fronts, which are clusters of highly interrelated and cumulative publications (Franssen & Wouters, 2019). A research front can be understood as the direction in which knowledge production in a field is ‘accelerating’. Price (1970) finds that highly cumulative or ‘hard’ fields, such as physics and biochemistry, have a Price Index of 60 to 70% and therefore a clear and distinguishable research front. Sociology, which is a less cumulative or ‘softer’ science, has a Price Index of 46% and other social sciences around 42%. The cumulativeness of knowledge in sustainability science has not yet been studied. Since research in sustainability science to a large extent resides in the realm of the natural sciences, social sciences or a combination of these two, it is expected that the Price Index of the field is at least 42%.

In theory, cumulativeness of knowledge can have two consequences in terms of knowledge production. On the one hand, a strong paradigm or research front makes knowledge production easier, because there is no need to develop new concepts and frameworks (Cole et al., 1978; Franssen & Wouters, 2019). On the other hand, cumulativeness implies that preceding knowledge needs to be known, thus creating a burden of knowledge that eventually slows down knowledge production (Jones, 2009). This study argues that the effect of cumulativeness depends on the maturity of the research paradigm. In the earliest stage of development, papers draw on a relatively old body of knowledge and cumulativeness is low. Once research on the topic picks up momentum and shared methods and concepts are agreed upon, cumulativeness will increase (González-Alcaide et al., 2016). Initially, this causes a further acceleration of knowledge production. At a certain point, however, the low-hanging fruit has been picked and this effect decreases. In the meantime, the burden of knowledge has increased, because an increasing number of ideas has already been found within the paradigm. Once the accelerating effect of cumulativeness fades away, the burden of knowledge leads to a decline in research productivity and ultimately a slowdown of knowledge production.

Measurement of cumulativeness in sustainability science is essential to understanding patterns related to a burden of knowledge. Since the definition of sustainable development can be regarded as the birth of a new paradigm (Perez, 2015), sustainability science provides the opportunity to study cumulativeness and the burden of knowledge in the context of an emerging paradigm. Therefore, this research  adds valuable insights to the literature related to those concepts.

## 2.2 The burden of knowledge

The burden of knowledge can be defined as the educational burden that individuals need to bear in order to be able to contribute to the existing knowledge base (Jones, 2009). Existence of the burden of knowledge would mean that new ideas are getting harder to find, because more input is needed to generate them. Patterns indicating the existence of a burden of knowledge have been detected in specific fields such as medicine and agriculture, in the development of specific technologies such as microchips and in the economy as a whole (Bloom et al., 2020). Furthermore, a decline in research productivity of individual scientists has been found in the social sciences, biology and economics (Brendel, 2018). Some scholars draw the conclusion that the end of economic growth, which is fueled by innovation, is near (Gordon, 2016). The potential consequences for the transition towards a sustainable society, however, are equally alarming.

Several strategies and variables have been used by scholars in earlier studies to detect patterns indicating a burden of knowledge. Jones (2009) developed a formal model of the burden of knowledge mechanism and tests it on patent data. He poses that individuals can absorb knowledge only at a limited rate, which has two consequences. Firstly, it takes more time to process the increasing amount of available knowledge that is necessary to produce new knowledge. Secondly, the problems that remain unsolved are increasingly difficult, since rationally behaving researchers would choose to pick the low-hanging fruit first (Jones, 2009; Schweitzer & Brendel, 2020). The model predicts that over time the age of inventors at their first invention, the size of the teams, the degree of specialization and the number of references in inventors' first patents increase. All predictions are confirmed by the empirical data, indicating the existence of a burden of knowledge in technological knowledge production (Jones, 2009).

Jung & Ejermo (2014), who conducted a demographic analysis of Swedish inventors, find that the age at first invention is declining. One of their explanations is that emerging technological fields could provide opportunities of invention 'relatively free from the pile of knowledge', which younger inventors are better suited to make use of. This explanation implies that knowledge in a new field is not cumulative with regard to older fields. Jung and Ejermo (2014) note that this explanation may be particularly likely in the case of transformational technologies. Since sustainability science arguably is a transformational field, it is necessary to consider the possibility of transformational knowledge being created ‘free from the pile of knowledge’ when interpreting the results of the present study.

While Jones (2009) finds the burden of knowledge mechanism in patent data, Astebro et al. (2020) links it to an observed decline in high-tech start-up formation by PhDs in the United States. He finds that although an increasing burden of knowledge means an increasing workload for high-tech start-up founders, long-term earnings for founders of start-ups do not increase. Moreover, the complexity of the work that is done in research and development has increased because of the burden of knowledge. He concludes that established firms are better suited to cope with the burden of knowledge than high-tech startups founded by PhDs, explaining the observed decline in the formation of such start-ups and indicating the existence of a burden of knowledge mechanism in this area (Astebro et al., 2020).

Both Jones (2009) and Astebro et al. (2020) detect the burden of knowledge mechanism in the technological realm of knowledge production. Other scholars study mechanisms of knowledge production in the scientific realm, as this study will do too. Arbesman (2011) quantifies the ease of scientific discovery, by looking at the discovery of things that are easily quantifiable: mammals, minor planets and chemical elements. He concludes that the ease of scientific discovery is declining exponentially, but does not link this result directly to the burden of knowledge (Arbesman, 2011). The implication of his conclusion, however, is similar to the burden of knowledge hypothesis: the more we know (or discover), the harder it gets to access new knowledge (or discover new things).

In contrast, Schweitzer and Brendel (2020) explicitly investigate the burden of knowledge mechanism in scientific knowledge production. They apply Jones’ (2009) model to the fields of economics and mathematics and use analogous variables to those that Jones (2009) tests in patent data, namely: the age of authors at the time of their first publication, the size of the teams of authors working together on a publication, the number of references in authors’ first publications and the degree of specialization. All four variables show a significant increase over time, indicating the existence of a burden of knowledge in economics and mathematics (Schweitzer & Brendel, 2020). Moreover, Brendel (2018) also finds that the length of titles and abstracts in economics and mathematics increase, indicating increasing complexity of newly produced knowledge.

As Schweitzer and Brendel (2020) write, it would be worthwhile to test the burden of knowledge hypothesis in other scientific fields as well, since the results are not generalizable *per se*. Sustainability science is expected to be especially insightful, since it is not a traditional scientific field such as economics or mathematics, but an emerging field, that is characterized as a different kind of science. Therefore, this research contributes to the existing burden of knowledge literature. To this end, three conceptual hypothesis are formulated, which relate to the existence of a burden of knowledge.

### 2.2.1 Collaboration in the production of knowledge

Collaboration can be regarded as a proxy for the existence of a knowledge burden (Jones, 2009). According Schweitzer and Brendel (2020), collaboration is a strategy to deal with an increasing burden of knowledge, because multiple specialized authors can cover a breadth of knowledge that cannot be covered by a single author. Studies have found that specialization of individual authors and division of labor between them increases with team size, supporting this assumption (Haeussler & Sauermann, 2020; Walsh & Lee, 2015). Therefore, a burden of knowledge in sustainability science is expected to cause an increasing degree of collaboration.

*Hypothesis 1:* collaboration in knowledge production in sustainability science increases because of the burden of knowledge.

A trend towards more collaboration has been found almost everywhere in the scientific realm since the 1950's (Cummings & Kiesler, 2014; Haeussler & Sauermann, 2020; Schweitzer & Brendel, 2020). Rosulnik (2012) finds that, between 1991 and 2011, the team size of sustainability-related articles increased. Naturally, other factors than a knowledge burden could be drivers of these trends as well. Schweitzer and Brendel (2020) mention generational preferences and incentives for cooperation. Haeussler and Sauermann (2020) note that extra team members may not always be included in the pursuit of knowledge production, but also for educational purposes.

Increasing interdisciplinarity could also drive more collaboration (Wuchty et al., 2007). Since sustainability science is characterized by a relatively high and increasing level of interdisciplinarity (Rosulnik, 2012; Schoolman et al., 2012), this is a factor to consider when interpreting a development in collaboration. Increasing interdisciplinarity itself can also be regarded as a strategy to deal with a burden of knowledge. If possible new combinations of existing knowledge components *within* a discipline are getting harder to find, researchers may be inclined to look for easier combinations *across* disciplinary boundaries.

### 2.2.2 Complexity of the produced knowledge

According to Jones' (2009) model, a burden of knowledge causes unsolved problems to be increasingly difficult. Furthermore, if new knowledge is built from recombining an increasing number of older knowledge components, the description of that new knowledge can be expected to be increasingly complex (Brendel, 2018). Therefore, a burden of knowledge in sustainability science would cause newly produced knowledge to be increasingly complex. White and Hernandez (1991) find increasing complexity in psychology and sociology by measuring the length of titles and abstracts. Diodato (1982) finds an increase in the length of publication titles as an indicator of complexity in chemistry, economics and mathematics, while history and philosophy show no such trend. This may be related to the differences in 'hardness' and accumulativeness of knowledge in those fields.

*Hypothesis 2:* the complexity of new knowledge in sustainability science increases because of the burden of knowledge.

### 2.2.3 Reaching the threshold of knowledge production

A burden of knowledge can be regarded as an increasing threshold of knowledge production. Before a new piece of knowledge, e.g. a journal article, can be produced, a certain amount of preceding knowledge needs to be known. Schweitzer and Brendel (2020) use the number of references per publication to indicate this threshold and find that it is gaining height in economics and mathematics. Moreover, in the academic life cycle of the individual researcher, the threshold indicates the amount of knowledge the researcher needs to process before he or she can start to contribute to the knowledge base themselves. Schweitzer and Brendel (2020) find this threshold to increase over time in economics and mathematics as well.

*Hypothesis 3a:* the threshold to produce a new piece of knowledge (i.e. a publication) in sustainability science increases.

*Hypothesis 3b:* the threshold for individual researchers to start contributing to the knowledge base of sustainability science increases.

In the case of sustainability science, another factor may influence the height of the threshold. An increasing number of interdisciplinary educational programs aimed specifically at sustainability could help researchers reach the threshold more quickly by selecting the necessary knowledge components and transferring them more efficiently.

# 3. Methods

This study uses a bibliometric approach to assess the development of sustainability science and a potential burden of knowledge in that field. By conducting a descriptive study of three attributes of the field to provide context for the testing of three burden of knowledge hypothesis, an innovative approach is taken in researching scientific knowledge production. First, the growth, interdisciplinarity and cumulativeness of knowledge in sustainability science are measured to establish an understanding of the nature and development of the field. Second, eight indicators of a knowledge burden are measured to test the hypotheses formulated in the previous section. This section explains the research design and the methods of data collection and analysis. Furthermore, the validity and reliability of the methods is discussed.

## 3.1 Research Design

Table 1 provides an overview of the research design. First, the nature of sustainability science is assessed by looking at the three attributes discussed in the previous section. The *Growth* of the field is measured through the number of new publications per year and the compound average growth rate (CAGR).

### 3.1.1 Interdisciplinarity

Researchers operationalize interdisciplinarity through the concept of diversity (Buter & Van Raan, 2013; Leydesdorff et al., 2019b; Porter & Rafols, 2009; Rosulnik, 2012). Diversity consists of three factors: the number of distinctive categories (variety), the evenness of their distribution (balance) and the degree to which these categories are different or similar

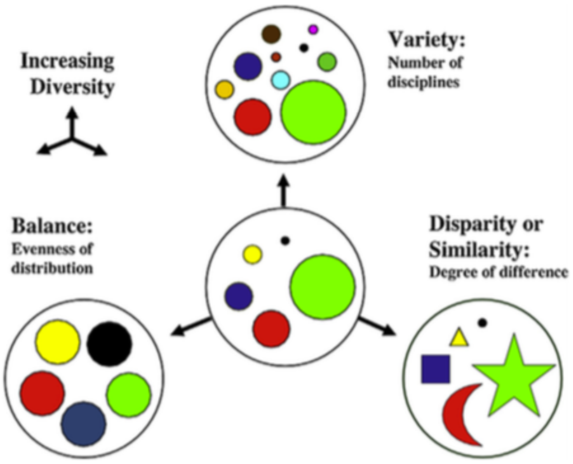

**Figure 6** Schematic representation of the attributes of diversity (Rafols & Meyer, 2010).

(disparity) (Porter & Rafols, 2009) (see Figure 6). While scholars agree that these three factors constitute diversity, their operationalization is debated (Leydesdorff et al., 2019b).

Most recently, Leydesdorff et al. (2019b) argue that earlier operationalizations of diversity are flawed, because variety and balance are combined *ex ante* into a dual-concept indicator (Rao, 1982; Stirling, 2007; Zhang et al., 2016). This led to counter-intuitive and puzzling results when applying the indicators in empirical analysis (Leydesdorff et al., 2019b). They propose *DIV** as a new indicator of diversity, in which variety, balance and disparity are operationalized independently and then combined *ex post*. While they acknowledge that one cannot expect an indicator of interdisciplinarity to meet all theoretical requirements, they find that *DIV** has significant advantages compared to others (Leydesdorff et al., 2019b).

The indicator is defined as:

$$DIV^{*} \; = \; n_c * (1 - \mathrm{Gini}_c) * \sum\nolimits_{i=1,j=1,i\neq j}^{i=n_c,j=n_c} \left(d_{ij}\right)$$

$n_c$ represents the number of distinctive categories, i.e. the variety. The Gini-coefficient is a measure of evenness in a distribution, i.e. the balance (Leydesdorff et al., 2019b). *DIV** should increase if either the variety, balance or disparity increases. The Gini-coefficient is maximally diverse for Gini = 0 and completely homogeneous for Gini = 1. Therefore, (1 – Gini) is used. $d_{ij}$ denotes a measure of the distance between two categories. The summation of all distances constitutes the disparity of the categories occurring in the unit of analysis (e.g. the cited references of a publication).

*DIV** is used in this research to compute the diversity on two levels of aggregation: 1) the diversity of disciplinary categories in the cited references of a set of publications and 2) the diversity of disciplinary categories assigned to the publications themselves. Diversity in cited references can be regarded as proof of interdisciplinary knowledge integration on a more specific level than diversity in categories assigned to a set of publications (Leydesdorff & Rafols, 2011). A set of articles published by Dutch sustainability scientists is used to measure this, because a global set would exceed the technical limits of the software that is used.

Diversity of categories occurring in a set of publications is indicative of interdisciplinarity on a higher level. This is assessed for two sets: 1) a set of articles in global sustainability science and 2) a set of articles published by sustainability *scientists* (thus, not necessarily in sustainability *science*). Measuring diversity in the latter is indicative of whether sustainability scientists are increasingly publishing in the same discipline and therefore yields insights into the maturity and relative autonomy of the field.

Disciplinary categories are operationalized through Web of Science categories (WCs) (Leydesdorff et al., 2019a; Porter & Rafols, 2009; Rosulnik, 2012). WCs are assigned to journals based on citation patterns and editorial judgment by ISI (Thomson Reuters). The accuracy of the classification is controversial, since it does not account for disciplinary discrepancies between individual articles in a journal (Milojević, 2020; Rosulnik, 2012).

### 3.1.2 Cumulativeness of knowledge

Cumulativeness of knowledge is measured using the age of the references cited in a set of publications. The age of references is the difference between years of publication of the citing and cited piece of knowledge, e.g. a journal article. Two indicators of cumulativeness are calculated using the ages of references: the median age of references and the Price-Index.

Studies show that research fronts have a relatively lower median age of references (Egghe, 2010; Franssen & Wouters, 2019; Jarić et al., 2014). A research front can be understood as a body of literature attempting “to grow from the skin, rather than from the body” (Price, 1970, p. 15). If new knowledge is built upon relatively younger old knowledge, that means that those recent pieces of knowledge are highly related and thus indicates cumulativeness. Similarly, the Price Index, i.e. the proportion of references that is not older than five years, is an indicator of cumulativeness. Moreover, the Price Index can be used to compare sustainability science to other fields and thus contribute to painting a picture of the field.

Note that, when looking at all scientific fields together, the average age of references is an increasing function of time, while the Price Index is a decreasing function of time (Egghe, 2010). This trend does not have a direct informetric explanation, but is a mathematical consequence of the exponential growth of science. If the number of available references grows exponentially, and references are distributed equally, the average age of references ‘automatically’ increases and the Price Index decreases over time (Egghe, 2010). Hence, the general expectation is that a field experiencing exponential growth over a long period of time shows an increasing average age of references and decreasing Price Index. This needs to be taken into account when interpreting the results of these indicators.

### 3.1.3 Collaboration in knowledge production

*Hypothesis 1* is tested by measuring team size, i.e. the number of authors per paper., which is an indicator of collaboration (Schweitzer & Brendel, 2020).

### 3.1.4 Complexity of newly produced knowledge

Even though new terminology may be able to capture more complexity in less words, one can safely assume that increasingly complex pieces of new codified knowledge can only be described adequately by an increasing number of words. Therefore, the number of words used in certain elements of journal articles are seen as indicators of complexity of the produced knowledge and thus used to test *Hypothesis 2*.

*The number of words in title and abstract*

The title and abstract of a journal article are important elements of a journal article. The title needs to draw attention and is the first representation of the content of the article a potential reader sees. White and Hernandez (1991) argue that the number of keywords in the title of an article correlates with the complexity of its content. Title length has been found to correlate with team size in various disciplines (Brendel, 2018; Rath & Wohlrabe, 2016).

An abstract is the most concise representation of the content of an article (Diener, 1984). An abstract ought to have as few words as possible, which is why it can be especially insightful regarding the knowledge content and complexity of an article. In principle, words are only added to an abstract if they are absolutely necessary to describe the content. The length of an abstract is strongly related to the length of the title (Diodato, 1982), but can yield deeper insights, since a title has other functions than summarizing the content, such as attracting attention.

*Number of keywords and pages per article*

Keywords are chosen by the author(s) and 'tag' the (sub)-topics of an article. Assuming that articles that combine an increasing number of knowledge components can be linked to an increasing number of topics, a burden of knowledge would cause an increase in the number of keywords chosen by authors.

Similar to the reasoning for title and abstracts, the number of pages per article is assumed to be a proxy for the complexity of the knowledge presented in an article. Scientific articles are expected to answer a research question in a parsimonious fashion. Hence, the length of an article is a proxy for the knowledge content and complexity of an article.

### 3.1.5 Threshold of knowledge production

The threshold of knowledge production exists on two levels. On the level of a publication, it reflects the amount of preceding knowledge that needs to be processed before the new piece of knowledge can be produced. The number of cited references is a proxy for the height of this threshold. In the life cycle of an academic researcher, the threshold reflects the amount of knowledge that needs to be absorbed before they can start to contribute to the knowledge base of a certain field themselves. The time spent in education is a proxy the height of this threshold. Besides, in case a researcher enters a field at a later stage in their career, the number of publications in other fields is a proxy for the threshold to enter the new field. Therefore, *Hypotheses 3a* and *3b* are tested by measuring the number of references, age at entry and number of publications before entry in sustainability science.

*Number of references*

References are used to show the origins of knowledge that was used to create new knowledge. The number of references, therefore, is a proxy for the amount of preceding knowledge necessary to create new knowledge (Jones, 2009; Schweitzer & Brendel, 2020).

*Age at entry*

The age at first publication is a proxy for the amount of education needed or knowledge absorbed for an author to start contributing to the knowledge base (Schweitzer & Brendel, 2020). If this amount increases over time, i.e. if there is a burden of knowledge, new authors will need more time to gather the necessary knowledge and thus, they will be older at the moment they start to produce new knowledge.

*Number of publications before entry*

Since many authors publishing in sustainability science for the first time have published in their original discipline before, it is also worthwhile to assess the size of their knowledge base at the time of their first publication in sustainability science. As an indicator for this, the number of previous publications of such authors will be measured over time. It is expected that the amount of knowledge necessary to ‘enter’ sustainability science from another discipline is increasing. The logic behind this hypothesis is that recombination of disciplinary knowledge into new sustainability knowledge is expected to be relatively easy in the emerging phase, but becomes more difficult once the low-hanging fruit has been picked and the field matures.

**Table 1** Overview of the research design

| **Variable** | **Operationalization** | **Data source(s) (see Data collection)** | **Method of analysis (see Data analysis)** |
|---|---|---|---|
| What kind of science is sustainability science? | | | |
| Growth | Number of new publications | WoS (base set) | Using function *biblioAnalysis* of *Bibliometrix* package in *R*Studio |
| | Cumulative Average Growth Rate (CAGR) | WoS (base set and number of publications in GSST until 2000) | Calculating the CAGR |
| Interdisciplinarity | Diversity of WCs in base set | WoS (proportion of WCs per year in base set)<br>Global map of science (Leydesdorff et al., 2013) | Using routine *wc19.exe* (Leydesdorff et al., 2019a) to compute DIV*, variety, balance (1 - Gini-coefficient) and disparity per year |
| | Diversity of WCs in Dutch author set | WoS (proportion of WCs per year in Dutch author set)<br>Global map of science (Leydesdorff et al., 2013) | Using routine *wc19.exe* (Leydesdorff et al., 2019a) to compute DIV*, variety, balance (1 - Gini-coefficient) and disparity per year |
| | Diversity of WCs in cited references of Dutch set | WoS (Dutch set)<br>Global map of science (Leydesdorff et al., 2013) | Using routines *jcitnetw.exe* and *mode2div.exe* (Leydesdorff et al., 2019a) and *Pajek* to compute DIV*, variety, balance (1 - Gini-coefficient) and disparity per article |
| Cumulativeness of knowledge | Median age of references | WoS (CR field in base set) | Computing median age of references in *R* |
| | Price Index | WoS (CR field in base set) | Computing proportion of references younger than 6 years in *R* |
| Is there a burden of knowledge in sustainability science? | | | |
| Collaboration in the production of knowledge | Number of authors per publication (team size) | WoS (base set) | Using function *biblioAnalysis* of *Bibliometrix* package in *R* |

| | | | |
|---|---|---|---|
| Complexity of the produced knowledge | Number of words in title per publication | WoS (TI field in base set) | Counting number of words in the TI field in *R* |
| | Number of words in abstract per publication | WoS (AB field in base set) | Counting number of words in the AB field in *R* |
| | Number of pages per publication | WoS (PG field in base set) | Directly available from PG field in WoS data |
| | Number of keywords per publication | WoS (DE field in base set) | Counting number of separators (“;”) in the DE field (and adding 1) in *R* |
| Threshold of knowledge production | Number of references per publication | WoS (CR field in base set) | Counting number of separators (“;”) in the CR field (and adding 1) in *R* |
| | Age of author in year of first publication in GSST (Age at entry) | WoS (Dutch set)<br>LinkedIn, university websites | Computing the ages at entry per author by subtracting their birthyears from their years of entry *R* |
| | Number of publications of Dutch authors in other WCs before first publication in GSST (Number of publications before entry) | WoS (Dutch author set) | Counting the number of publications per author before their year of entry in Dutch author set in *R* |

## 3.2 Delineating sustainability science

Conducting bibliometric research on sustainability science involves choosing a certain operationalization of the field, which influences the results of the research. There is no consensus among scholars regarding the delineation of sustainability science (Bautista-Puig et al., 2021). Table 2 provides an overview of the ways scholars have operationalized the field. The most common approach is to identify articles containing “sustainable” or “sustainability” in their title, abstract or keywords. Two of the most recent studies, Fang et al. (2018) and Fernandes & Philippi (2017) use the search term “sustainability science” to explicitly identify research related to the development of sustainability as a scientific field. This approach identifies a fraction of the number of articles found when using the more general approach (700 to 800 compared to 50.000 to 300.000). Olawumi & Chan (2018) use the search term "sustainability* AND sustainable development" and exclude articles in research areas not related to the built environment, limiting the number of identified articles to 2094.

Two recent papers use the Web of Science category "Green & Sustainable Science & Technology" (GSST) to operationalize sustainability science and identified 50.000 to 60.000 articles (Bautista-Puig et al., 2021; Pandiella-Dominique et al., 2018). According to the Web of Science, GSST "covers resources that focus on basic and applied research on green and sustainable science and technology, including green chemistry; green nanotechnology; green building; renewable and green materials; sustainable processing and engineering; sustainable policy, management and development; environmental and agricultural sustainability; renewable and sustainable energy; and innovative technologies that reduce or eliminate damage to health and the environment"[1].

GSST was assigned to 36 journals related to sustainability when Pandiella-Dominique et al. (2018) collected their data. Currently, 71 journals fall under this category. The largest contributing journals are *Sustainability, Journal of Cleaner Production* and *Renewable Energy*. While GSST is clearly related to sustainability science, the category has some biases towards the environmental pillar of sustainability (Bautista-Puig et al., 2021). Hence, science on the economic and social pillar of sustainability is represented less by this WC. Furthermore, a disadvantage of using a WC as delineation is that they are assigned to journals, not to individual articles. This means that articles in sustainability science, which are published in multi- or interdisciplinary journals with a much broader scope and without a classification in GSST, are excluded.

Despite these limitations, this research uses GSST as operationalization of sustainability science, since the benefit of the strong relation of the WC to sustainability science outweighs its limitations. Moreover, the disadvantages of other available methods are deemed to be more critical. Using "sustainability" or "sustainable" as search terms can lead to many false positives, since it is an ambiguous concept that can be used in a broader sense than how it is used in sustainability science (Bautista-Puig et al., 2021). Furthermore, operationalizations limiting the field to articles *on* "sustainability science" in fact seem to exclude most of sustainability science.

---

[1] Information on the launch of this WC: http://wokinfo.com/media/pdf/wos5- 22-1-external-release-notes.pdf. Accessed on February 3rd, 2021.

**Table 2** Overview of operationalizations of sustainability scien*ce* used in previous studies

| **Article** | **Operationalization of the field** | **Period** | **Nr. of publications** |
|---|---|---|---|
| (Bautista-Puig et al., 2021) | Articles in the Web of Science category “Green & Sustainable Science & Technology” | 2014-2018 | 57.227 |
| (Bautista Puig et al., 2020) | Publications in the WoS databases containing<br>a) “economic sustainab*”<br>b) “environmental sustainab*”<br>c) “social sustainab*”<br>in title, abstract or keywords | 1993-2017 | a) 1683 (economic)<br>b) 1302 (social)<br>c) 6107 (environmental) |
| (Fang et al., 2018) | Articles in the WoS databases containing “sustainability science”, “science for sustainability” or “science of sustainability” in title, abstract or keywords | Up to 2017 | 832 |
| (Olawumi & Chan, 2018) | Articles in WoS core collection found using search string “sustainability* AND sustainable development”, excluding research in research areas not related to the built environment | 1991-2016 | 2094 |
| (Pandiella-Dominique et al., 2018) | Articles in the Web of Science category “Green & Sustainable Science & Technology” | 1994-2016 | 49.065 |
| (Fernandes & Philippi, 2017) | a) Articles found in the WoS and Scopus using search term “sustainable” OR “sustainability”<br>b) Articles found in the WoS and Scopus using search term “sustainability science” | Up to April 2016 | a) 299.000 (Scopus), 240.000 (WoS)<br>b) 776 (Scopus), 639 (WoS) |
| (Kajikawa et al., 2014) | Articles citing at least one other article in a set of articles found in the WoS using search query “sustainab*” | Up to May 2013 | 51.390 |
| (Buter & Van Raan, 2013) | Articles in the WoS containing “sustainab” in their title | 1999-2008 | 10.594 |

| | | | |
|---|---|---|---|
| (Rosulnik, 2012) | Articles in the WoS containing "sustainability" in title, abstract or keywords | 1991-2011 | 24.487 |
| (Schoolman et al., 2012) | Articles in Scopus containing "sustainability" in title, abstract or keywords | 1996-2009 | 17.226 |
| (Bettencourt & Kaur, 2011) | Articles in WoS containing "sustainability" in title, abstract or keywords | Up to 2009 | 20.376 |

## 3.3 Data collection

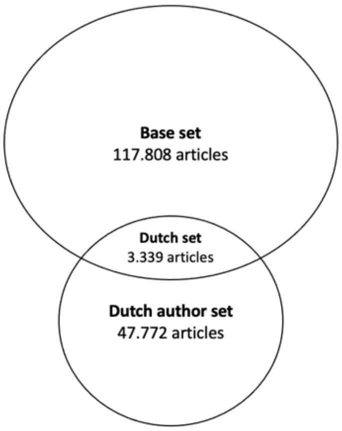

**Figure 7** The sets of bibliographic records retrieved from the Web of Science.

See Table 1 for an overview of the data sources per variable. Bibliographic records of articles published globally in sustainability science are retrieved from the Web of Science core collection[2]. This set of records will be called the *base set*. The assessment of interdisciplinarity in a set of articles published by sustainability *scientists* and the measurement of the age at and number of publications before entry requires the identification of authors in sustainability science. Since the process of author disambiguation is time consuming, this is done from a subset of articles published by an author with a Dutch address. This subset will be called the *Dutch set*. Furthermore, a set of records containing articles published by the identified authors in *any* discipline will be called the *Dutch author set* (see Figure 7).

The base set is retrieved from the Web of Science on May 3rd, 2021. The following query is used: "WC=GSST, DT=Article, Language=English, TS=2001-2020", meaning that the

---

[2] The Web of Science core collection consists of the Science Citation Index Expanded (SCI-EXPANDED), the Social Sciences Citation Index (SSCI), the Arts & Humanities Citation Index (A&HCI) and the Emerging Sources Citation Index (ESCI).

time span of publication is limited to the years 2001-2020, the document type to article and the language to English. The base set consists of 117.808 articles. The Dutch set is retrieved by adding “CO=NETHERLANDS” to the query, resulting in 3.339 records (see Figure 7). Records downloaded from the WoS consist of 69 fields, containing bibliographic information such as the title (field tag “TI”), addresses of the authors (field tag “C1”) or cited references (field tag “CR”) of a publication.

In order to retrieve the *Dutch author set*, 4.594 unique Dutch authors (i.e. authors with a Dutch address) are identified from the “C1” field of the *Dutch set*. Publicly available profiles of authors on *LinkedIn,* the WoS, Scopus, orcid.org and university websites are used for manual author disambiguation. If available, the authors are linked to their OrcidID, which is a unique identification number. The OrcidIDs are needed to retrieve the *Dutch author set*, since due to author disambiguation issues, using a large number of author names in a WoS search query leads to a large amount of false positives. Thus, the query to retrieve the *Dutch author set* contains the 1.438 available OrcidIDs of the identified authors. The set is limited to articles written in English and retrieved from the WoS core collection. It contains 47.772 records.

Additionally, the number of publications in GSST before 2001 is retrieved in order to calculate the CAGR. Furthermore, the distribution of WCs per year in the base set is required to compute its diversity over time. These distributions can be found under the “Analyze” tab in the WoS interface and are downloaded separately for each year of publication. Computation of the disparity within the distributions required data on the cognitive distances between WCs. Leydesdorff et al., (2013) computed the cosine measures of these distances as part of the development of a global map of science and made them available for research. The most recent

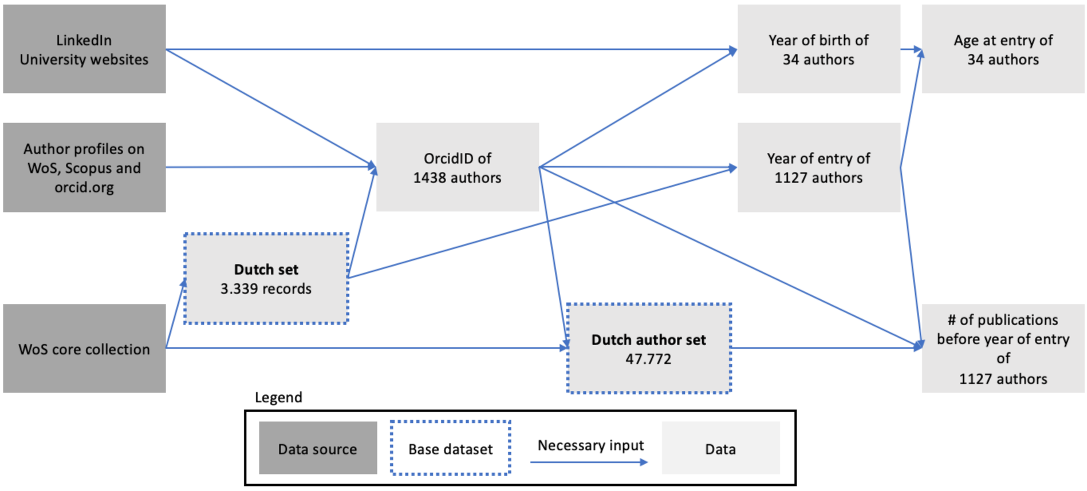

**Figure 8** Schematic overview of data collection for the variables age at entry and number of publications before entry.

computation was done in 2019. Data on the distances are downloaded from http://www.leydesdorff.net/wc15/wc19.

To be able to compute the ages at entry, publicly available data from author profiles on *LinkedIn* and university websites are used to retrieve the years of births of the identified authors. Since this is a time consuming process, this is done for a randomly generated sample of two hundred authors. However, the birthyears of most authors was not available directly. If possible, they were inferred from the years they started and/or finished primary and/or secondary school, since deviation from the usual ages associated with those moments is considered to be unlikely. This leads to the identification of the birthyears of 34 authors. Furthermore, the OrcidIDs are used to identify the first publication in GSST of each author. The publication year of this article is considered to be the year of entry of the author. In the case of 302 authors, their OrcidID did not appear in all of their records, reducing the reliability of the automatic identification of their year of entry. The record of the first publication of nine authors did not contain a year of publication. Those authors are excluded from the analysis (see Figure 8).

### 3.4 Data analysis

See Table 1 for an overview of the methods of analysis per variable. The sets of bibliographic records are imported into *R*Studio using the *Bibliometrix* package (Aria & Cuccurullo, 2017; R Core Team, 2020). The function *biblioAnalysis* in this package is used to conduct a basic bibliometric analysis of the sets. The output of the function includes the number of new publications per year and the team sizes per article. The CAGR is calculated using the total number of publications in GSST up until 2000 and 2020.

Diversity is measured in the distribution of WCs occurring in 1) a set of articles published globally in sustainability science (the *base set*), 2) a set of articles published by Dutch sustainability *scientists* (the *Dutch author set*) and 3) the cited references of individual articles in Dutch sustainability science (the *Dutch* set). For the measurement of diversity, software available for research from http://www.leydesdorff/net is used to compute DIV* and its contributing factors variety, balance (1-Gini-coefficient) and disparity. The software uses the formula for DIV* described in the Theory section and the cosine measures of distances between WCs to compute disparity.

The diversity of WCs in the *base set* and the *Dutch author set* is computed using *wc19.exe,* a routine that computes diversity values of distributions of WCs (Leydesdorff et al., 2019b, 2019a). To analyze the development over time, the distributions *per year of publication* are used as input to the routine. The diversity of WCs in the *cited references of articles in the Dutch set* is computed using the routines *jcitnetw.exe* and *mode2div.exe* and the network analysis software *Pajek* (Leydesdorff et al., 2019b, 2019a). Those routines compute the diversity values of the cited references *per article*. The development over time of this indicator is assessed by calculating the average diversity value *per year of publication.* The technical limits of those routines do not allow for computation of diversity in the cited references of all articles in the *base set*.

The ages of the cited references in the *base set* are computed by subtracting the year of publication of an article from the year of publication of each cited reference in that article. 120 records have no information on their cited references and the publication year of 646 records is missing, leaving 117.038 records to analyze. While the relative age of references in principle refers to the *average* age of references in a publication, the use of the *median* age is preferred to minimize the risk of bias produced by outliers (Jarić et al., 2014). Hence, the median age is computed. Furthermore, the Price Index is computed per article by dividing the number of references younger than 6 years by the total number of references. Time series of the relative age and Price Index are constructed by computing their averages *per year of publication*.

Title and abstract length are measured by counting the number of words in the “TI” and “AB” fields respectively. The number of keywords and references per article are measured by counting the number of separators (“;”) in the “DE” and “CR” fields respectively. 12.111 records do not contain keywords. The number of pages per article are available directly from the “PG” field of the *base set*. Time series of these indicators are constructed and visualized by calculating the averages per year. To control for the influence of team size on the indicators, their averages are also calculated and visualized for team sizes varying from one to five authors.

The number of publications before entry of 1127 authors is derived by counting the appearances of their OrcidID in the *Dutch author set* in records published before their year of entry. To reduce bias produced by outliers, the time series of this indicator is constructed using the median value per year of entry. The age at entry of 34 authors is calculated by subtracting their years of birth from their years of entry. Following Schweitzer & Brendel (2019) and Jones (2009), an age window in which people tend to be most productive is chosen to eliminate outliers. Therefore, ages at entry outside the range of 25 to 45 are excluded from the analysis.

### 3.5 Validity and reliability

The collection of a large number of records enhances the reliability of the results for most of the indicators. Moreover, the robustness of the results concerning interdisciplinarity is increased by measuring diversity on multiple levels. However, in case of the indicators that could only be measured for the *Dutch set,* the results should be approached with more caution. In particular, the reliability of the results concerning the development over time of the age of entry is limited, since retrieval of the year of birth of an author was successful in only 34 cases.

The necessary use of OrcidIDs to retrieve the *Dutch author set* significantly limits the share of identified authors that can be used. A bias towards a certain type of author that is more likely to have an OrcidID might be introduced. Furthermore, even though the use of OrcidIDs in large WoS search queries is preferred over using names, OrcidIDs are not perfectly integrated in the databases yet. Not all publications of an author are always linked to their OrcidID and in rare cases an OrcidID is linked to a publication not written by that author. Therefore, it should be taken into account that the *Dutch author set* does not contain the complete publication histories of the authors and may include falsely identified records.

The use of a WC as delineation of sustainability science may limit the validity of the results. Since WCs determine the knowledge domains of journals and not of individual articles, the classification suffers from limited specificity (Hu et al., 2020). Moreover, the adequacy of the definition of the WCs is debated (Leydesdorff & Bornmann, 2016). Thus, the operationalization of sustainability science as GSST excludes parts of the field. As mentioned above, GSST has a bias towards environmental sustainability (Bautista Puig et al., 2020). However, since the definition and delineation of sustainability science is not clear-cut and debated by scholars, a pragmatic approach is deemed justified.

The development over time of the indicators related to the burden of knowledge may be influenced by other factors, reducing their reliability. Increasing team size may be influenced by the changing preferences of a new generation of scientists. Besides, incentivization of publication may trigger authors without a substantial contribution to be added to teams. This is illustrated by hyperauthorship in fields such as physics, in which case sometimes more than a thousand authors are responsible for a publication (Schweitzer & Brendel, 2020).

The incentivization of citation may also influence some of the indicators. While studies into the relationship between the length of an abstract and the number of citations an article receives have found contradicting results (Letchford et al., 2016; Weinberger et al., 2015), the possibility of authors increasing the length of their abstract for strategic reasons needs to be taken into account (Brendel, 2018). There are more obvious strategic reasons for increasing the number of keywords in order to receive more citations. Articles with more keywords are found more often by other researchers. This needs to be taken into account when interpreting the results of this indicator. Next to incentivization, it needs to be noted that technological advancements make it easier to find, access and cite scientific knowledge, which is likely to cause an increase in the number of cited references (Schweitzer & Brendel, 2020).

# 4. Results

## 4.1 Growth

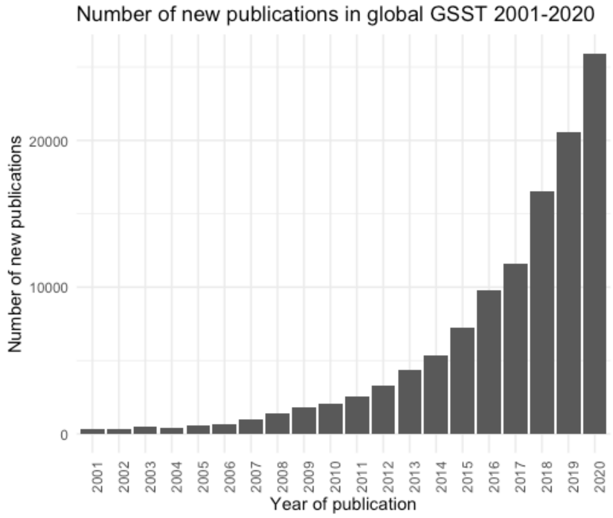

**Figure 9** New publications in the WC Green & Sustainable Science & Technology.

Figure 9 displays the number of new publications per year in global sustainability science. The figure shows that the field has been growing exponentially until 2020. In 2020, more than 25.933 new articles were published, against 2.025 in 2010 and 324 in 2001. A stagnation as suggested by Fang et al. (2018) is not visible. If there is a burden of knowledge in sustainability science, it does not (yet) influence the quantitative output of the field as a whole. The CAGR of the field is 25,9%, which is significantly higher than the 4,3% growth rate of science overall as estimated by Price (1963). This means that the number of publications in sustainability science doubles every three years, compared to ten to fifteen years in science in general. This suggests that at least in terms of growth, sustainability science is not a 'normal' science.

## 4.1 Interdisciplinarity

### 4.1.1 Diversity of WCs in global GSST

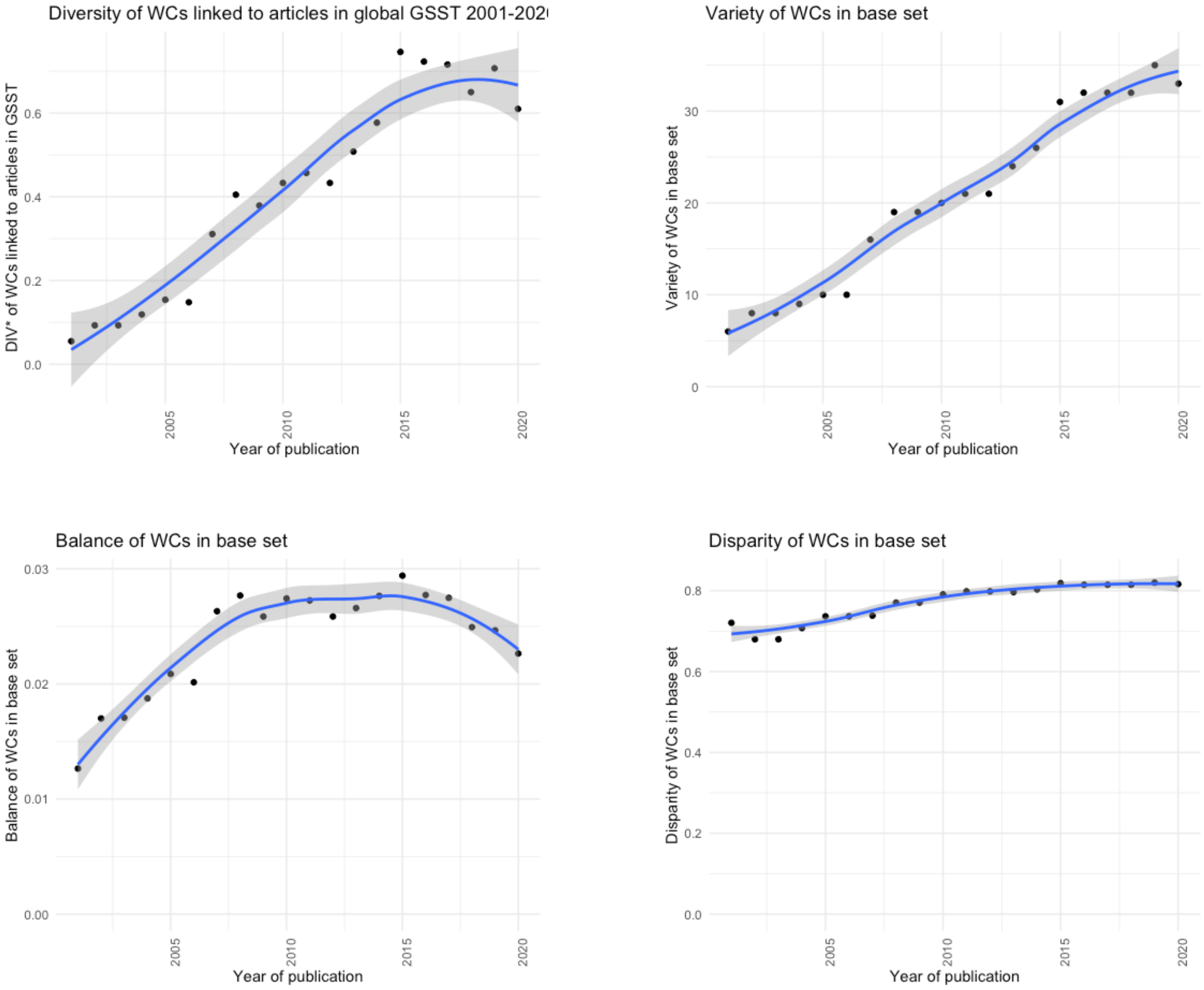

**Figure 10** Diversity (DIV*) in the distribution of WCs in the *base set* and its contributing factors variety, balance and disparity. Including loess trend line.

Figure 10 shows the diversity in the distribution of WCs in the *base set* over time, along with its contributing factors variety, balance and disparity. The development is characterized by a slight increase between 2001 and 2006, followed by a leap and then a steeper increase between 2012 and 2015. After 2015, the increase stagnates and a slight decreasing trend begins. The increase is mainly driven by an increase in variety and up to 2007 also by an increase in balance and disparity. The latter two stagnate or start to decrease after that year. The trends in variety and disparity in the context of the observed steep growth indicate that the subject sustainability is spreading through the scientific landscape. Since the *base set* consists only of journals classified as GSST, the increase in variety means that an increasing number of journals are classified as GSST *together* with other WCs. The stagnation of disparity, i.e. the cognitive distance between disciplines, makes sense in the context of increasing variety: after a certain point, ‘new’ WCs are more likely to be close to other WCs occurring in the set.

The stagnation and decrease from 2015 onwards in balance indicates that one or more WCs in the distribution are occurring relatively more frequent than others, i.e. those WCs are becoming increasingly dominant. WCs occurring frequently in combination with GSST are ‘Environmental Sciences’ (ESc), ‘Environmental Engineering’ (EE) and ‘Environmental Studies’ (ESt). This underlines the dominance of environmental sustainability in this WC already found by Bautista-Puig (2020). In 2020, 60% of GSST-journals were simultaneously classified as ESc, against 27% in 2010. Thus, while the topic of sustainability is spreading into an increasing number of disciplines, the largest share of the growth is occurring in journals related to environmental science. This is line with the observation made by Bautista-Puig et al. (2020) that environmental sustainability science is growing faster than economic and social sustainability science. Moreover, it could indicate that the consolidation of the field as described by Fang et al. (2018) and others, is mainly occurring in the environmental branch of sustainability science, while simultaneously an increasing number of other disciplines is involved in the creation of new interdisciplinary knowledge on sustainability. Within sustainability science overall, there seems to be a centripetal force of coalescence as well as a centrifugal force diverging the subject across the scientific landscape.

Variation in the degree of interdisciplinarity does not only occur between the ‘branches’ of the sustainability science, but also between journals, as was already found by Bautista-Puig et al. (2021). Twelve journals in the *base set* are classified as GSST *only*. While the absolute number of new articles in those journals increased from 182 in 2015 to 535 in 2020, the relative share of GSST-only-articles decreased from 2,5% in 2015 to 2,0% in 2020. This supports the observation that there is a growing part of sustainability science that is mature and relatively autonomous, while at the same time the boundaries of the field are pushed into new interdisciplinary territory.

### 4.1.2 Diversity of WCs in *Dutch author set*

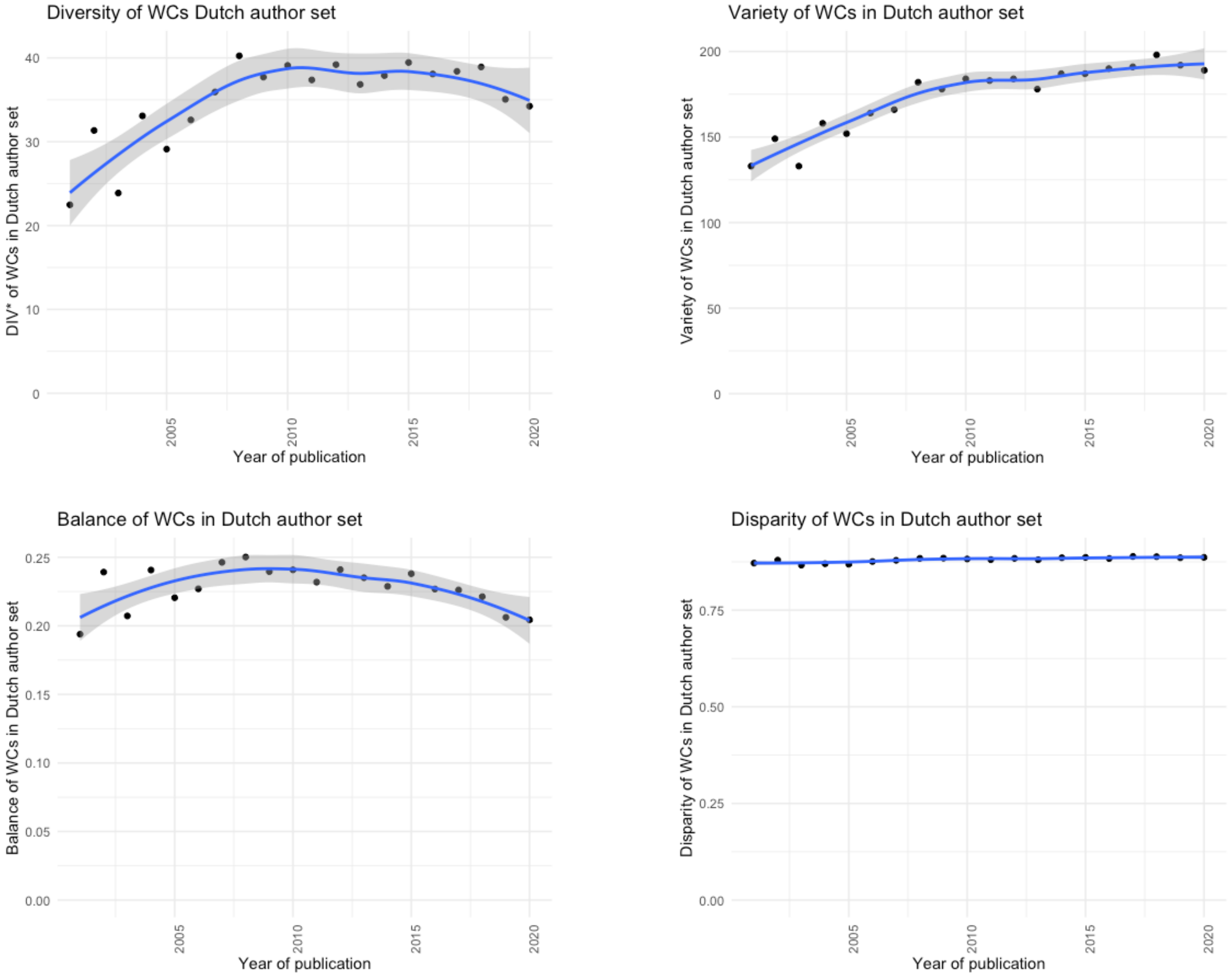

**Figure 11** Diversity (DIV*) in the distribution of WCs in the Dutch author set and its contributing factors variety, balance and disparity. Including loess trend line.

See Figure ***11*** for the development over time of diversity in the distribution of WCs in the *Dutch author set* and its contributing factors. Diversity in this set increases until 2010, then stagnates and starts to decline in 2018. The increase is driven by increases in all three factors until 2010. Variety keeps increasing after that, albeit less steeply, while disparity stabilizes. This means that authors from an increasing variety of disciplinary backgrounds publish in sustainability science. The stagnation and decline in diversity is driven by an increasingly steep decline in balance starting in 2010. This means that a few WCs are becoming dominant in the distribution. The dominating WCs in 2020 are ESc (20,3%), ESt (12,6%) and GSST (12,3%). This supports the observation made by Bautista-Puig et al. (2020) that environmental sustainability science is growing faster than social and economic sustainability science.

### 4.1.3 Diversity in cited references

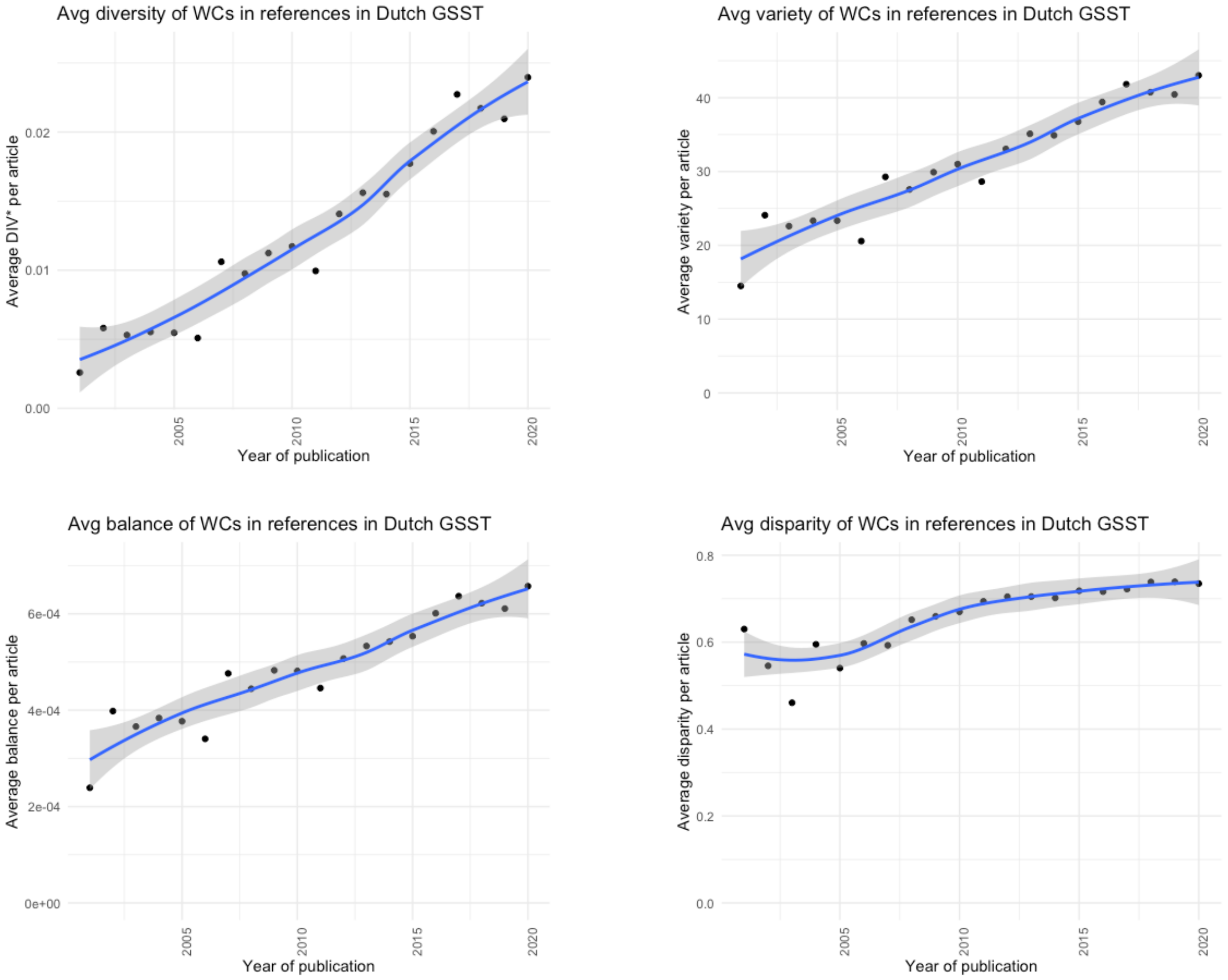

**Figure 12** Average diversity of WCs in the cited references of articles in the Dutch set and its contributing factors average variety, balance and disparity. Including loess trend line.

Figure 12 shows the development of diversity in the cited references of articles in the *Dutch set*. Diversity in cited references is a more specific indicator of knowledge integration than the diversity values presented above. The diversity in the references of articles in Dutch GSST show a clear linear increasing trend, which is driven by increases of all three contributing factors. The pattern resembles the development of diversity in the distribution of WCs in the *base set*, showing a bigger leap in 2007 and a steeper increase from 2012 to 2017, except there is no sign of a beginning decline in the most recent years. The increase in disparity is less steep than the increase in variety and balance, but no stagnation is visible in either one of the factors.

This suggests that sustainability science is still becoming increasingly interdisciplinary, continuing the trend identified by Rosulnik (2012) and Schoolman (2012), as it is integrating knowledge components from an increasingly diverse knowledge base. Compared to the diversity indicators discussed above, the absence of a decline or even stagnation in the development of balance is striking, since one might expect that the environmental WCs would also start to dominate in cited references. The continuous increase suggests that sustainability science keeps drawing on knowledge from a diversity of other domains, instead of becoming increasingly self-sustaining. Hence, in terms of balance, the development of diversity in cited references points in the other direction than the development of diversity in the distribution of WCs assigned to journals.

## 4.2 Cumulativeness of knowledge

### 4.2.1 Median age of references

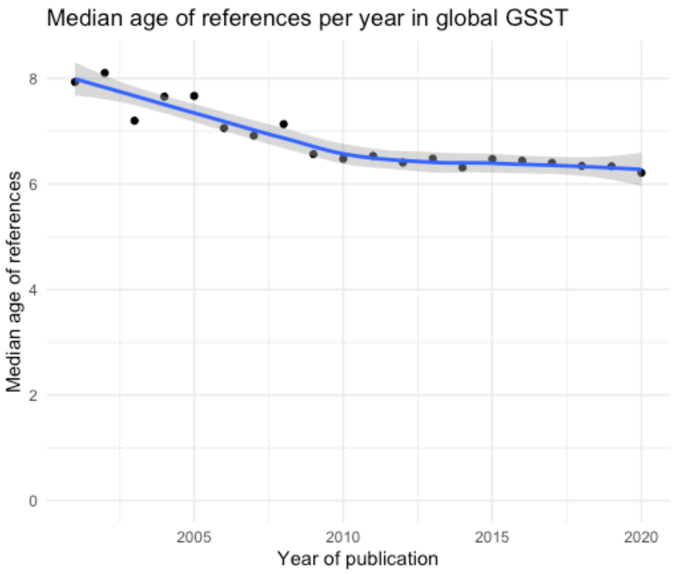

**Figure 13** Median age of references in the base set. Including loess trend line.

Figure 13 shows the development of the median age of references per year in the *base set*. There is a clear decreasing trend in the first ten years, after which an inflection point marks the beginning of a less steep decrease until 2020. In 2001 the median age of references in the *base set* is 7,9 years, against 6,5 years in 2010 and 6,2 years in 2020. This result is in line with theory suggesting that an emerging field draws from older literature at first and then the age of references drops when the field picks up momentum (González-Alcaide et al., 2016). The ongoing downward trend is not in line with the expectation based on observations in science in general, where the age of references increases over time. If references would be equally distributed among publications, the exponential growth of the field would lead to an increasing trend in the age of references (Egghe, 2010). Therefore, the decreasing trend suggests that there is a strong inclination to cite relatively young papers. This is an indication that the field is becoming more tightly connected and that knowledge is becoming increasingly cumulative. In other words, there is a stronger paradigm with a clearer research front.

### 4.2.2 Price-Index

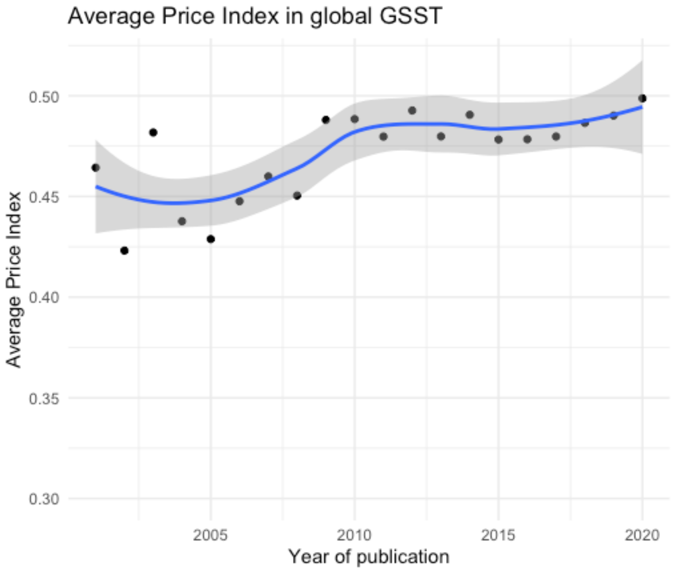

**Figure 14** Average Price Index per year in the base set. Including loess trend line.

Figure 14 displays the development over time of the average Price Index in the *base set*. Naturally, the trend is more or less the opposite to the median age of references: if younger references are cited, the Price Index increases, as is the case between 2001 and 2010. In the latter year there is an inflection point, after which the Price Index stabilizes around 48% and slightly increases again from 2017 onwards. The Price Index of sustainability science is a little higher than the 42% to 46% found by Price for the social sciences (Price, 1970). Note however, that there may be differences between subfields. Green chemistry, for example, can be expected to be a 'harder' subfield of sustainability science than research on social sustainability. Overall, however, the development of the Price Index indicates increasing cumulativeness of knowledge in sustainability science.

## 4.3 Collaboration in knowledge production

### 4.3.1 Team size

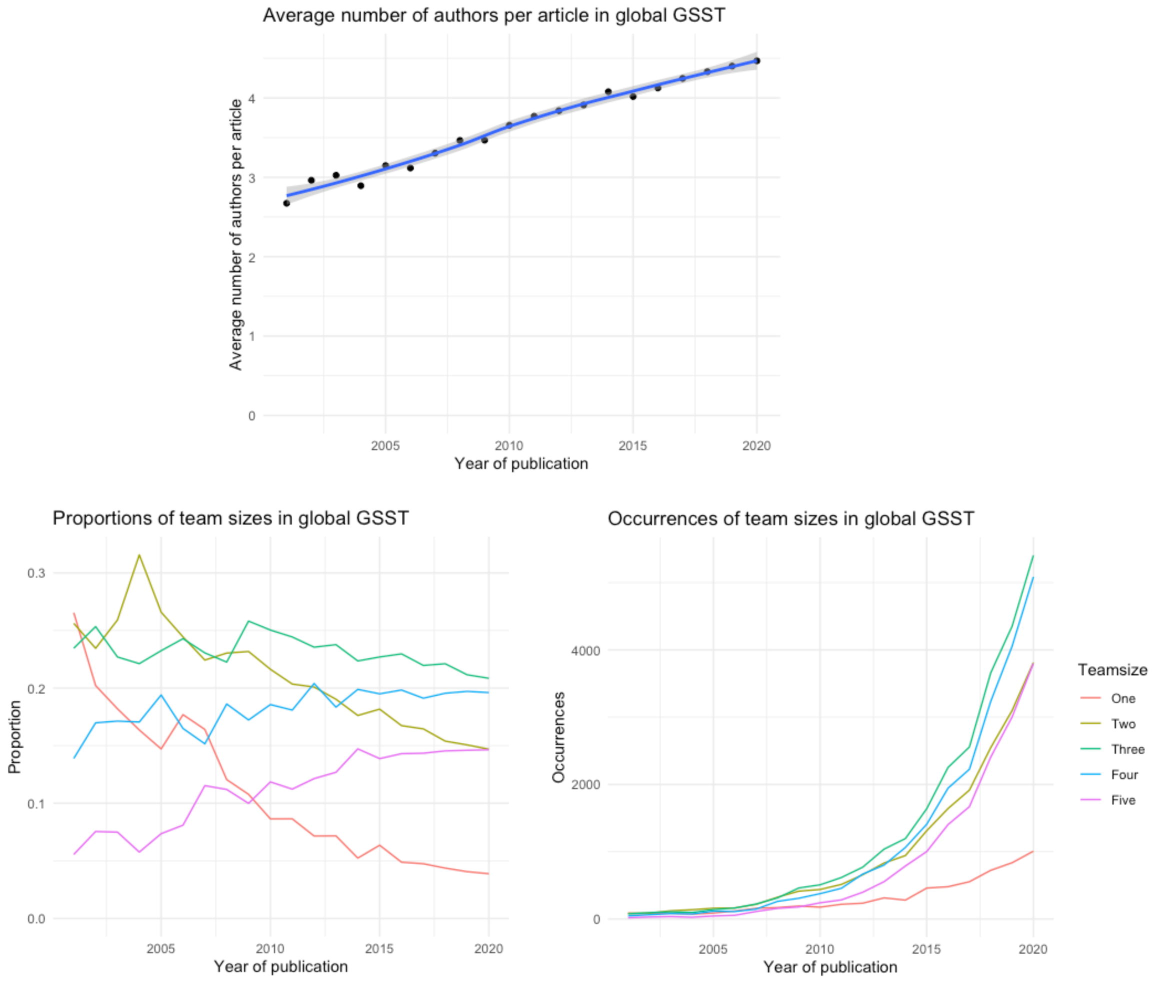

**Figure 15** Top: average team size per year in the base set. Including loess trend line. Bottom: proportions and occurrences of team sizes one to five.

Figure 15 shows a linear increasing trend in the average team size of articles in sustainability science. *Hypothesis 1* is therefore accepted. In 2001, the average team size was 2,7, against 3,7 in 2010 and 4,7 in 2020. Thus, on average, every decade one author is added to teams in sustainability science. Furthermore, the shares of teams consisting of one, two or three authors show a decreasing trend starting between 2004 and 2009. The shares of teams consisting of four and five authors show an increasing trend. These findings are in line with the general trend in science towards more collaboration. Besides, they may be related to the increasing interdisciplinarity of articles in sustainability science. Concerning a potential burden of knowledge, an increase in team size can be regarded as a proxy for a higher degree of knowledge input, specialization of individual authors and division of labor per publication. Hence, it indicates the existence of a knowledge burden. However, a strong conclusion cannot be drawn from this indication alone, since there is multitude of confounding factors potentially influencing team size.

## 4.4 Complexity of the produced knowledge

### 4.4.1 Number of words in title and abstract

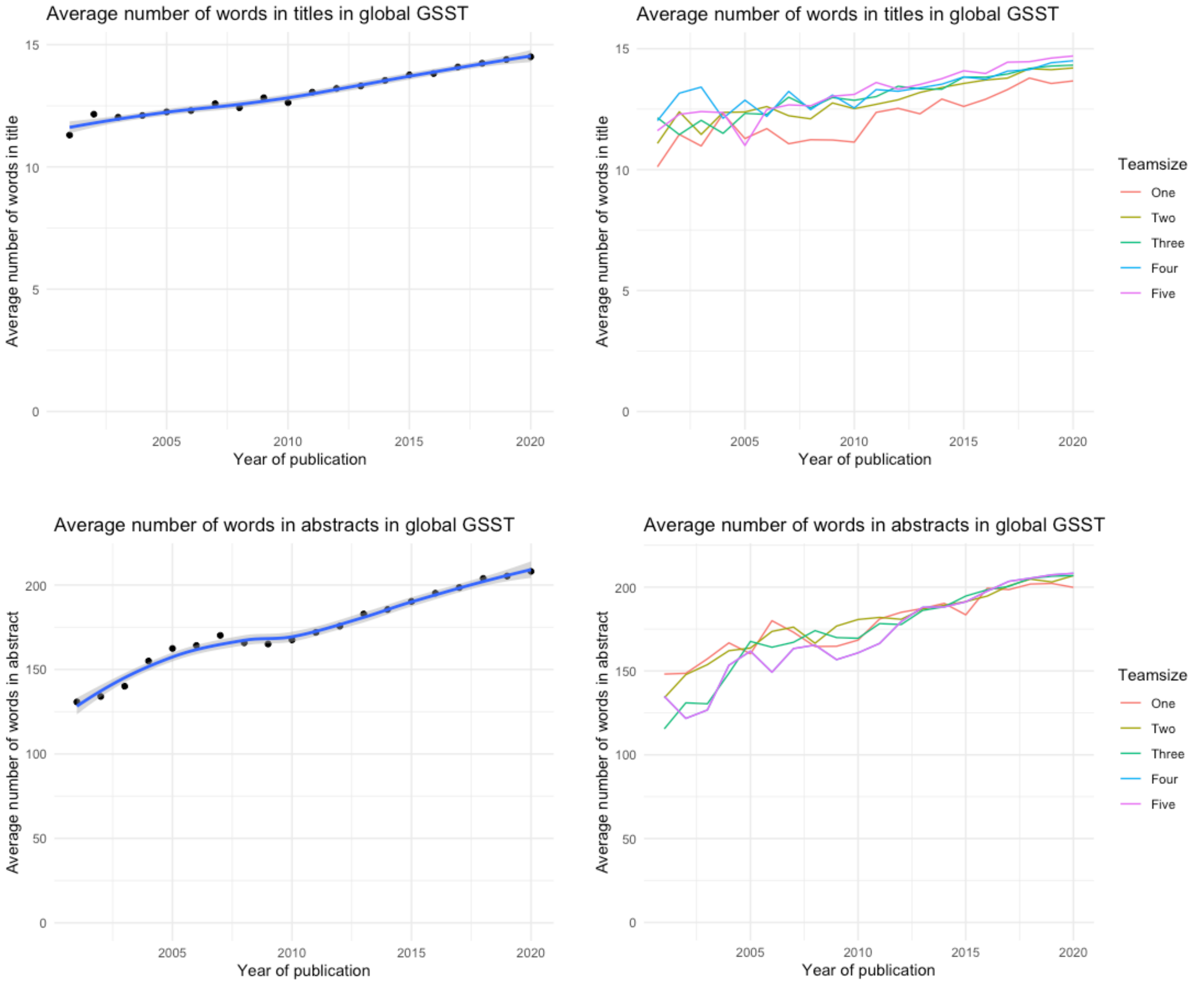

**Figure 16** Average number of words in titles and abstracts per year in the base set, overall (including loess trend line) and per team sizes one to five.

Figure 16 shows an increase in the number of words used in both titles and abstracts of articles in sustainability science. In 2001 titles on average consisted of 11,3 words, against 12,6 in 2010 and 14,5 in 2020. Abstracts increased in length from 131,8 to 167,5 in 2010 and 208,0 words in 2020. Furthermore, both title and abstract length increases regardless of team size, indicating that titles and abstracts are not merely becoming longer because a larger number of authors is working on articles. These findings can be interpreted as newly produced knowledge in sustainability science becoming increasingly complex, and thus indicate the existence of a burden of knowledge for individual researchers. Note further that, as in the case of the ages of references, there is an inflection point around 2010 in the development of abstract length, at which a linear increase begins. Moreover, the title and abstract lengths of articles of various team sizes start to converge at this point.

### 4.4.2 Number of keywords and pages per article

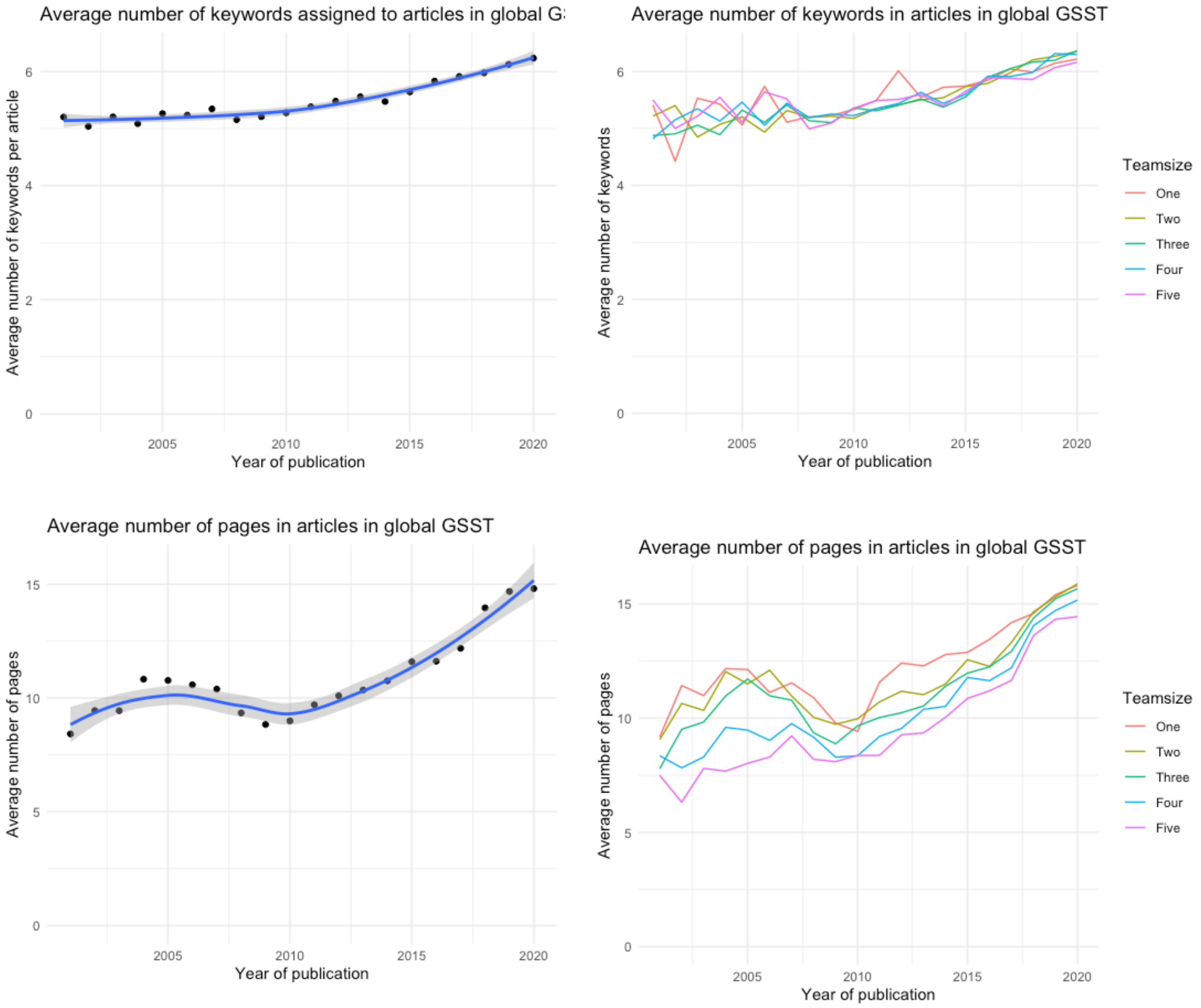

**Figure 17** Average number keywords and pages per year in the base set, overall (including loess trend line) and per team sizes one to five.

Figure 17 shows the development over time of the number of keywords and pages per article in sustainability science. The number of keywords follow a continuously increasing trend over the entire period, whereas the number of pages fluctuates until 2009 and then starts to increase linearly. These trends are similar for various team sizes. In 2001, articles on average were characterized by 5,2 keywords, against 5,3 in 2010 and 6,2 in 2020. The average number of pages increased from 8,4 in 2001 to 9,0 in 2010 and 16,8 in 2020. Together with the development of title and abstract length, these findings indicate an increasing level of complexity of newly produced knowledge in sustainability science. *Hypothesis 2* is therefore accepted. Again, especially concerning the number of pages, the year 2010 marks the beginning of a strong upward trend and convergence of the trends for different team sizes. Remarkably, while single-authored papers on average have the shortest title, they are among the longest regarding the number of pages.

## 4.5 Reaching the threshold of knowledge production

### 4.5.1 Number of references

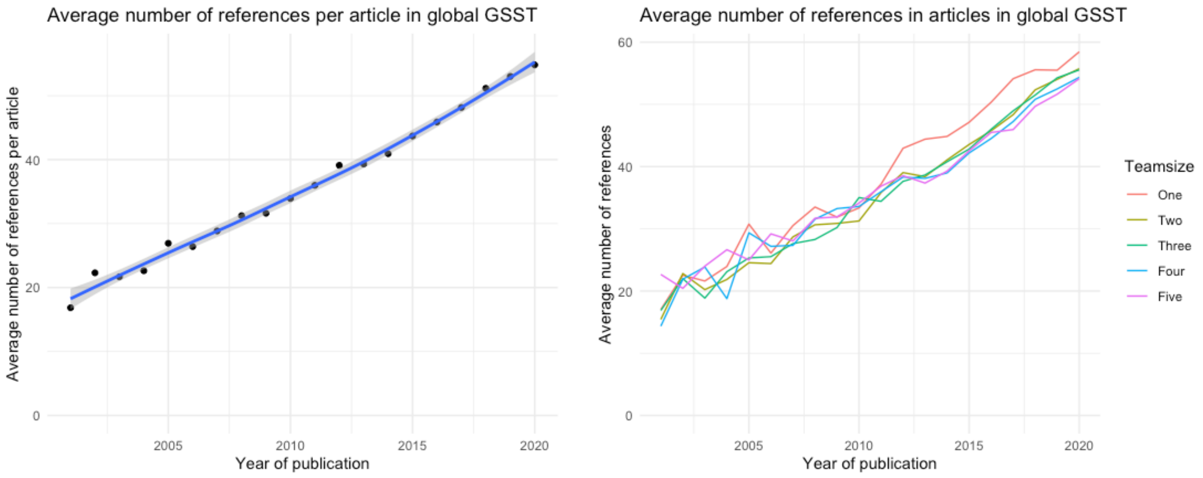

**Figure 18** Average number of references per year in the base set, overall (including loess trend line) and per team sizes one to five.

Figure 18 displays an almost continuous increase in the number of references of articles in sustainability science, regardless of team size. *Hypothesis 3a* is therefore accepted. The increase of this variable is particularly strong. The average number of references *triples* from 16,8 in 2001 to 54,8 in 2020. Since the number of references is a proxy for the amount of preceding knowledge necessary to create new knowledge, this finding is an indicator of the existence of a burden of knowledge. Strategic reasons and the accessibility of scientific knowledge, however, are likely to be a factor in the observed increase as well.

### 4.5.2 Age at and number of publications before entry

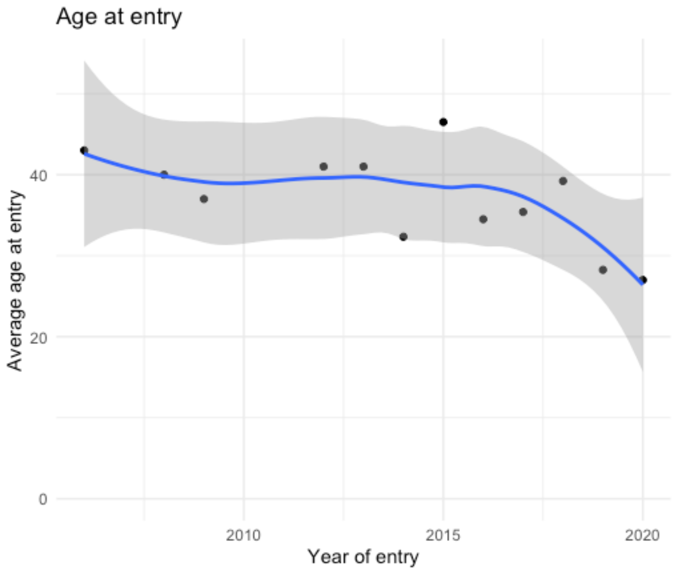

**Figure 19** Average age at entry of sustainability scientists per year. Including loess trend line.

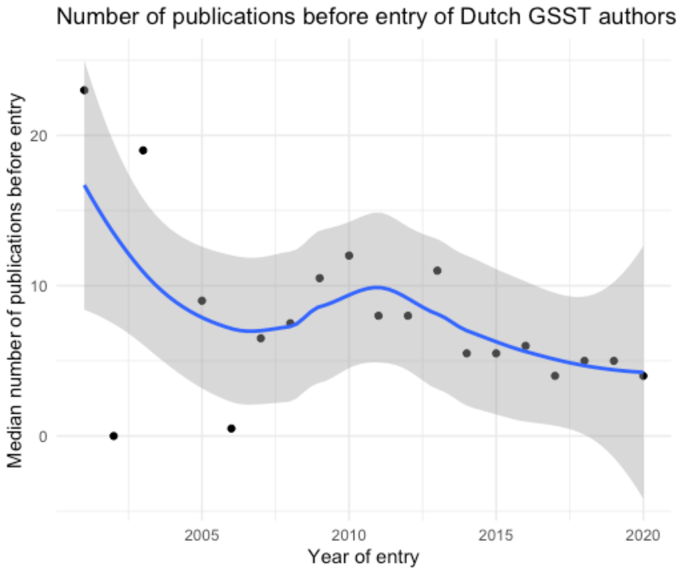

**Figure 20** Average number of publications before entry of sustainability scientists per year. Including loess trend line.

Figure 19 shows a slightly decreasing trend in the age at entry of sustainability scientists. Note, however, that the number of available birthyears limits the amount of ages analyzed to 29. Figure 20 displays the average number of publications before entry of sustainability scientists that entered the field between 2001 and 2020. While the observed values differ greatly until 2011, from that point on there seems to be a decreasing trend. *Hypothesis 3b* is therefore declined. A possible explanation is that in the early emerging phase of a field, experienced researchers are more capable of developing new concepts and methods, and that once these have been developed and refined, they can be used easily to quickly produce large amounts of new knowledge. In other words: first someone has to figure out how to build a ladder, before others can use it to easily pick the lowest-hanging fruit. The decreasing age at entry points in the same direction. It could be explained by the increasing availability of educational programs specifically aimed at sustainability science. Researchers that have participated in such interdisciplinary programs may be better suited to reach the threshold of knowledge production relatively quickly. This explanation would align with the theory suggesting that agreement on shared methods and concepts in the emerging stage of a field leads to an acceleration of knowledge production. Once there is agreement, educational programs that are created during the emerging stage are able to transfer the relevant knowledge efficiently.

**Table 3** Overview of the results

| Variable | Operationalization | Result |
|---|---|---|
| What kind of science is sustainability science? | | |
| Growth | Number of new publications | **Exponential growth** – no stagnation visible. |
| | Cumulative Average Growth Rate (CAGR) | **25,9%** |
| Interdisciplinarity | Diversity of WCs in base set | Increasing diversity because of **spread of sustainability through the scientific landscape** |
| | Diversity of WCs in Dutch author set | Stagnation of diversity driven by decline in balance because of **increasing dominance of researchers of environmental sustainability** |
| | Diversity of WCs in cited references of Dutch set | Increasing diversity driven by all three factors because of **increasing interdisciplinary knowledge integration** |
| Cumulativeness of knowledge | Median age of references | Decreasing age of references indicates **increasing cumulativeness of knowledge** |
| | Price Index | Increasing Price Index indicates **increasing cumulativeness of knowledge** |
| Is there a burden of knowledge in sustainability science? | | |
| Collaboration in the production of knowledge | Number of authors per publication (team size) | Increasing team size indicates **increasing collaboration among researchers** (H1 accepted) |
| | Number of words in title per publication | |

| | | |
|---|---|---|
| Complexity of the produced knowledge | Number of words in abstract per publication | Increasing trends in all indicators because of **increasing complexity of newly produced knowledge** (H2 accepted) |
| | Number of pages per publication | |
| | Number of keywords per publication | |
| Threshold of knowledge production | Number of references per publication | Increasing number of references indicate **increasing threshold to produce a new piece of knowledge** (H3a accepted) |
| | Age of author in year of first publication in GSST (Age at entry) | Decreasing trends since 2010 indicate that the **threshold of researchers to start producing to the knowledge base is decreasing** (H3b declined) |
| | Number of publications of Dutch authors in other WCs before first publication in GSST (Number of publications before entry) | |

# 5. Discussion

This study has two objectives. First, to assess what kind of science sustainability science is in terms of growth, interdisciplinarity and cumulativeness of knowledge. The results show that the field grew rapidly and became more interdisciplinary between 2001 and 2020. Cumulativeness of knowledge increased, with a steeper increase until 2010 than in the years thereafter. The second objective is to detect patterns indicating the existence of a burden of knowledge. Such patterns are found in trends regarding collaboration among researchers and complexity of newly produced knowledge, as well as in the threshold to produce a new piece of knowledge. Meanwhile, the threshold for individual researchers to start contributing to the knowledge base decreases from 2010 onwards. This section discusses these findings in relation to the literature examined in the Theory. Besides, the limitations of the deployed methods are discussed and several avenues for further research suggested.

## 5.1 Growth, interdisciplinarity and cumulativeness

Regarding the nature and development of sustainability science, the findings offer an empirical substantiation of some existing theories, while contradicting others. The increasingly steep growth of publications in sustainability science shows that a stagnation as observed by Fang et al. (2018) is not occurring. On the contrary, the field is growing more rapidly than a few years ago, since a higher CAGR was found in this study compared to the rate found by Bautista-Puig et al. (2020) in data up to 2017. Signs of a knowledge burden are therefore not yet visible in the quantitative output of the field.

The results further show that the trend of increasing interdisciplinarity identified by Rosulnik (2012) and Schoolman et al. (2012) continues until 2020. Besides, the increasing dominance of research related to environmental science confirms that this branch of sustainability science is growing significantly faster than other parts of the field (Bautista Puig et al., 2020; Schoolman et al., 2012). When painting a picture of sustainability science, the environmental pillar would appear as the centerpiece, attracting most of the attention. Note, however, that choosing GSST as operationalization of sustainability science may have introduced a bias towards research on environmental sustainability (Bautista Puig et al., 2020). If a ‘true’ delineation of sustainability would be possible, the proportion of the social and economic pillar might be larger, although other operationalizations also found a dominance of the environmental pillar (Kajikawa et al., 2014; Schoolman et al., 2012).

Increasing diversity in cited references indicates that sustainability science is integrating knowledge from an increasingly diverse area of the scientific landscape. This means that the field is not becoming self-sustaining and remains dependent on knowledge from other disciplines. Therefore, the field is not developing towards transdisciplinarity as defined by Buter and Van Raan (2013). Neither does the field seem to reach an equilibrium or turn into ‘normal’ science as expected by Pacheco et al. (2017) – at least in terms of interdisciplinarity. This could simply mean that the field is not ‘there’ yet, that it remains in an interdisciplinary stage of development, but nevertheless will ultimately converge into a relatively autonomous discipline. However, it is more likely that the results are a reflection of sustainability science being a different, ‘post-normal’, kind of science (Spangenberg, 2011). Moreover, as Klein (2020) and Fernandes and Philippi (2017) argue, interdisciplinarity does not necessarily lead to the creation of yet another discipline. The findings of this study suggest that their interpretation of sustainability science as an umbrella term for a collection of interdisciplinary subfields of existing disciplines is more adequate.

The relation between interdisciplinarity and collaboration already found by Wuchty et al. (2007) is supported by the results. Following Fontana et al.’s (2020) reasoning, increasing diversity in the cited references of papers also indicates increasing novelty. This can be interpreted as an indication of the existence of a burden of knowledge. If many ideas have already been found, researchers need to search for increasingly novel ideas, to which end they increasingly collaborate across disciplinary boundaries.

A decreasing median age of references and an increasing Price Index indicate that cumulativeness of knowledge in sustainability science is increasing. These results are in line with the expectation regarding an emerging field (González-Alcaide et al., 2016): first older references are cited, then the age declines and cumulativeness increases as the field picks up momentum between 2001 and 2010. The continuing increase after the inflection point in 2010 suggests that the research paradigm in sustainability science is gaining in strength, i.e. the field is becoming ‘harder’. The Price Index of nearly 50% suggests that the field finds itself between the social and natural sciences in terms of hardness (Price, 1970). Considering the diverse nature of the field, this does not mean that the field is unifying under a single paradigm. Research on green chemistry, for example, is part of a different paradigm than research on sustainable business models. Both paradigms, however, could be gaining in strength. The indicators of cumulativeness merely show an *aggregate* increase.

Connecting the findings regarding interdisciplinarity and cumulativeness, one could say that under the umbrella of sustainability science, various research fronts have emerged. While the field as a whole is not an autonomous discipline, separate subfields may have an increasingly integrated knowledge structure. Separate analysis of the growth, interdisciplinarity and cumulativeness of knowledge per subfield based on keyword clusters or journals would be valuable for a better understanding of the different knowledge dynamics *within* sustainability science, and is therefore a suggestion for further research.

## 5.2 Patterns of a knowledge burden

The exponential growth in the quantitative output of sustainability science seems to confirm the theoretical expectation that increasing cumulativeness and a strong paradigm causes an acceleration of knowledge production. The consolidation of the field and agreement on shared methods and concepts enables researchers to recombine knowledge components more easily (Cole et al., 1978). Based on the theory, it is expected that this accelerating effect of cumulativeness eventually fades away, at which point the burden of knowledge mechanism starts to influence research productivity. Early signs of the existence of such burden are already visible in the majority of the indicators assessed.

The results show that newly produced knowledge in sustainability science is increasingly complex. According to the Jones (2009) and Brendel (2018), this is an indication of the existence of a burden of knowledge. The combination of measurement of cumulativeness and complexity of produced knowledge yields an innovative and valuable contribution to the theory. The steeper increase of the indicators of knowledge complexity from 2010 onwards suggests that the rate at which newly produced knowledge becomes more complex is related to the cumulativeness of knowledge. Once the paradigm(s) in sustainability science is firmly established in 2010 – as indicated by the relatively steep increase in cumulativeness until the inflection point in that year – all indicators of complexity begin an unambiguous linear increase. In other words, the burden of knowledge increases more rapidly within a stronger paradigm. Future research could deepen these insights by performing statistical analysis of the indicators and investigate the potential correlations between indicators of complexity and cumulativeness of knowledge.

The threshold of producing a new piece of knowledge, i.e. a journal article, in sustainability science also increased between 2001 and 2020, as indicated by a linear increase in the number of references. The increase in team size can be seen as a logical counterpart to this development: if the threshold to produce a piece of new knowledge is higher, more authors may be needed to climb over it. These findings are in line with the burden of knowledge hypothesis and the expectation based on the studies of Jones (2009) and Schweitzer & Brendel

(2020) in other domains of knowledge creation. Rival explanations for the detected patterns are discussed below in section 5.3.

On the level of the individual researcher's career, increasing team size lowers the threshold of knowledge production: if more authors cooperate, each individual's share decreases or – at least – does not increase. This may be one of the reasons why the indicators of the height of the threshold of knowledge production in researcher's careers are stable or show a decrease. The rejection of the hypotheses related to the threshold therefore does not imply that a burden of knowledge does not exist. Rather, it implies that increasing collaboration seems to suffice as a strategy to deal with a burden of knowledge, while the burden does not yet influence the age at and number of publications before entry.

Another explanation of the decrease in the number of new publications and age at entry is that newly established educational programs are able to transfer knowledge of common concepts and methods more efficiently. The finding of a decreasing trend in the number of publications before entry *beginning in 2010* supports this hypothesis. That year seems to mark a turning point in the historical development of sustainability science. The emerging phase, during which educational programs and common concepts and methods have been established, ends, and in the years thereafter these tools enable researchers to quickly produce a large amount of new knowledge. In other words, maturity of the field in the sense of better organized education contributes to dealing with the burden of knowledge. This would explain why the results regarding the threshold in researchers' careers differ from the findings of Schweitzer and Brendel (2020), who find an increasing age at first publication for researchers in the long-established field of economics. The number of publications before entry is used for the first time as an indicator in this study and can be regarded as an extension of the Jones' (2009) burden of knowledge model. The discussion above can be a starting point for future research to include it as a measure as well.

### 5.3 Limitations

There are two limitations resulting from the operationalization of disciplinary categories as Web of Science categories. First, the use of a Web of Science category as delineation of sustainability science introduces a bias towards research on environmental sustainability and neglects papers published in multidisciplinary journals such as *Nature* or *Science*. Nevertheless, the large number of identified articles and resulting clear trends in the indicators suggest robustness of the results. Therefore, it is safe to assume that the findings of this study are valid for the broader field of sustainability science. A more specific analysis of the indicators in separate subfields would result in a sharper picture of the field and is thus suggested as an avenue of further research.

The second limitation concerns the measurement of diversity of WCs occurring the *base set* and *Dutch author set*. Since WCs are assigned to journals instead of individual articles, the accuracy of the analysis is limited. Furthermore, increasing number of WCs over time and the possibility of journals being assigned multiple categories, introduces the possibility that variety increases because of a database effect. Methods for accurate classification of a single disciplinary category on article level have recently become available (Milojević, 2020). Future research could benefit from the use of such methods.

The methods regarding the indicators of the threshold of knowledge production in researcher's careers have two limitations. First, the use of OrcidIDs to retrieve authors' publication histories and identify their first publication may introduce an unknown bias towards a certain type of author and limits the number of authors for which the indicator can be measured. Furthermore, the limited availability of public data on birthdates reduces the validity of the results regarding age of entry.

It needs to be noted that there are other possible explanations for the observed trends in the indicators of the burden of knowledge. Collaboration, for example, is incentivized as it increases the chance of research being funded (Schweitzer & Brendel, 2020). Besides, the costs of collaboration have decreased significantly, thanks to the advancement of information- and communication technologies. Those technologies also enable researchers to find and include references more easily, influencing the trend in this indicator. Furthermore, strategic reasons might play a role in the increasing number of references and keywords, as well as title and abstract length. These rival explanations cannot be easily separated from the influence of the burden of knowledge on the indicators. However, the identified relation between the level of cumulativeness and the rate of change of knowledge complexity can only be explained by the existence of a knowledge burden. Moreover, looking at all indicators together, their trends are convincingly consistent with the burden of knowledge hypothesis. Future research could attempt to add control variables and conduct a more elaborate statistical analysis to confirm the identified patterns and deepen the insights.

## 5.4 Implications for policy and society

This study argues that once sustainability science matures further and the accelerating effect of cumulativeness fades away, the burden of knowledge could start to significantly influence researchers' productivity. Therefore, a further increase in collaboration is expected to be necessary in order to deal with increasing complexity and processing of knowledge, which implies that policies aimed at the organization of the field should facilitate and encourage such collaboration. Furthermore, the burden of knowledge could be alleviated by transferring knowledge more efficiently. The further improvement of educational programs and effective use of information and communication technologies in academic research could therefore contribute to minimizing the effect of such a burden. The most straightforward way to deal with declining research productivity, however, is to increase the number of researchers. Therefore, the overarching implication of this research for policy and society is that unless a new transformational technology or paradigm shift causes the burden of knowledge decrease starkly, the cost of new green ideas could start to increase rapidly over the course of the next decades.

# 6. Conclusion

This study asked whether new green ideas are getting harder to find due to a burden of knowledge. First, the growth, interdisciplinarity and cumulativeness of knowledge in sustainability science were assessed to understand the knowledge dynamics in the field. The results show that sustainability science is growing rapidly and integrating knowledge from an increasing area of the scientific landscape. Furthermore, knowledge has rapidly become more cumulative until 2010. Since then the increase continued at a lower rate. Sustainability science should thus be regarded as an umbrella term for a collection of highly interdisciplinary research, with multiple strengthening paradigms accelerating knowledge production.

Second, eight indicators related to a burden of knowledge were measured to test three conceptual hypotheses derived from Jones' (2009) model. Collaboration in knowledge production, the complexity of newly produced knowledge and the threshold to produce a new piece of knowledge showed unambiguously increasing trends. The threshold for individual researchers to start contributing to the knowledge base decreased, which suggests that the accelerating effect of cumulativeness of knowledge and the efficient transfer of knowledge by educational programs are outweighing the effect of the knowledge burden.

The results of this study therefore imply that while a burden of knowledge exists in sustainability science, the influence on individual researchers and the rate of knowledge production is still limited. However, it can be expected that when the field matures, the research paradigm is refined and knowledge complexity increases further, dealing with the burden of knowledge will come at greater cost and new green ideas will become harder to find.

# 7. Acknowledgements

I would like to thank my supervisors Gaston and Thomas for their guidance and inspiration. Furthermore, I express my sincere gratitude to Claudia, Jörg and Johanna and all others who made valuable suggestions for improvements.

# 8. References

Arbesman, S. (2011). Quantifying the ease of scientific discovery. *Scientometrics*. https://doi.org/10.1007/s11192-010-0232-6

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*. https://doi.org/10.1016/j.joi.2017.08.007

Astebro, T. B., Braguinsky, S., & Ding, Y. (2020). Declining Business Dynamism Among Our Best Opportunities: The Role of the Burden of Knowledge. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3684945

Bautista-Puig, N., Mañana-Rodríguez, J., & Serrano-López, A. E. (2021). Role taxonomy of green and sustainable science and technology journals: exportation, importation, specialization and interdisciplinarity. *Scientometrics*, *126*(5), 3871–3892. https://doi.org/10.1007/s11192-021-03939-6

Bautista Puig, N., Sanz Casado, E., & Mauleón, E. (2020). Analysis of Social, Environmental and Economic Sustainability Core: A Bibliometric Overview. *International Journal of Innovation and Sustainable Development*, *1*(1), 1. https://doi.org/10.1504/ijisd.2020.10026529

Bettencourt, L. M. A., & Kaur, J. (2011). Evolution and structure of sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1102712108

Bloom, N., Jones, C. I., van Reenen, J., & Webb, M. (2020). Are ideas getting harder to find?†. *American Economic Review*. https://doi.org/10.1257/aer.20180338

Bornmann, L., & Mutz, R. (2015). Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references. *Journal of the Association for Information Science and Technology*, *66*(11). https://doi.org/10.1002/asi.23329

Brendel, J. (2018). *Die Last des Wissens. Eine Analyse von Publikations- und Autorendaten*. Universität Bayreuth.

Buter, R. K., & Van Raan, A. F. J. (2013). Identification and analysis of the highly cited knowledge base of sustainability science. *Sustainability Science*. https://doi.org/10.1007/s11625-012-0185-1

Cole, S., Cole, J. R., & Dietrich, L. (1978). Measuring the cognitive state of scientific disciplines. In *Toward a metric of science: The advent of scientific indicators*.

Cummings, J. N., & Kiesler, S. (2014). Organization Theory and the Changing Nature of Science. *Journal of Organization Design*, *3*(3), 1–16. https://doi.org/10.7146/jod.18596

Diener, R. A. V. (1984). Informational dynamics of journal article titles. *Journal of the American Society for Information Science*, *35*(4). https://doi.org/10.1002/asi.4630350405

Diodato, V. (1982). The occurence of title words in parts of research papers: variations among disciplines. *Journal of Documentation*, *38*(3), 192–206.

Egghe, L. (2010). A model showing the increase in time of the average and median reference age and the decrease in time of the Price Index. *Scientometrics*, *82*(2), 243–248. https://doi.org/10.1007/s11192-009-0057-3

Fang, X., Zhou, B., Tu, X., Ma, Q., & Wu, J. (2018). "What kind of a science is sustainability science?" An evidence-based reexamination. *Sustainability (Switzerland)*. https://doi.org/10.3390/su10051478

Fernandes, V., & Philippi, A. (2017). Sustainability sciences: Political and epistemological approaches. In *The Oxford Handbook of Interdisciplinarity.* (p. 21).

Fontana, M., Iori, M., Montobbio, F., & Sinatra, R. (2020). New and atypical combinations: An assessment of novelty and interdisciplinarity. *Research Policy*. https://doi.org/10.1016/j.respol.2020.104063

Franssen, T., & Wouters, P. (2019). Science and its significant other: Representing the humanities in bibliometric scholarship. *Journal of the Association for Information Science and Technology*, *70*(10), 1124–1137. https://doi.org/10.1002/asi.24206

González-Alcaide, G., Llorente, P., & Ramos, J. M. (2016). Bibliometric indicators to identify emerging research fields: publications on mass gatherings. *Scientometrics*, *109*(2), 1283–1298. https://doi.org/10.1007/s11192-016-2083-2

González-Márquez, I., & Toledo, V. M. (2020). Sustainability science: A paradigm in crisis? In *Sustainability (Switzerland)*. https://doi.org/10.3390/su12072802

Gordon, R. J. (2016). The rise and fall of American growth: The U.S. standard of living since the Civil War. In *The Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War*. https://doi.org/10.1093/jahist/jaw576

Haeussler, C., & Sauermann, H. (2020). Division of labor in collaborative knowledge production: The role of team size and interdisciplinarity. *Research Policy*, *49*(6), 103987. https://doi.org/10.1016/j.respol.2020.103987

Haider, L. J., Hentati-Sundberg, J., Giusti, M., Goodness, J., Hamann, M., Masterson, V. A., Meacham, M., Merrie, A., Ospina, D., Schill, C., & Sinare, H. (2018). The undisciplinary journey: early-career perspectives in sustainability science. *Sustainability Science*. https://doi.org/10.1007/s11625-017-0445-1

Hu, X., Li, X., Rousseau, R., & Rousseau, R. (2020). Describing Citations as a Function of Time. *Journal of Data and Information Science*, *5*(2), 1–12. https://doi.org/10.2478/jdis-2020-0011

Irwin, E. G., Culligan, P. J., Fischer-Kowalski, M., Law, K. L., Murtugudde, R., & Pfirman, S. (2018). Bridging barriers to advance global sustainability. In *Nature Sustainability*. https://doi.org/10.1038/s41893-018-0085-1

Jarić, I., Knežević-Jarić, J., & Lenhardt, M. (2014). Relative age of references as a tool to identify emerging research fields with an application to the field of ecology and environmental sciences. *Scientometrics*, *100*(2), 519–529. https://doi.org/10.1007/s11192-014-1268-9

Jones, B. F. (2009). The burden of knowledge and the “death of the renaissance man”: Is innovation getting harder? *Review of Economic Studies*. https://doi.org/10.1111/j.1467-937X.2008.00531.x

Jung, T., & Ejermo, O. (2014). Demographic patterns and trends in patenting: Gender, age, and education of inventors. *Technological Forecasting and Social Change*. https://doi.org/10.1016/j.techfore.2013.08.023

Kajikawa, Y., Tacoa, F., & Yamaguchi, K. (2014). Sustainability science: the changing landscape of sustainability research. *Sustainability Science*. https://doi.org/10.1007/s11625-014-0244-x

Kates, R. W. (2011). What kind of a science is sustainability science? In *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1116097108

Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., McCarthy, J. J., Schellnhuber, H. J., Bolin, B., Dickson, N. M., Faucheux, S., Gallopin, G. C., Grübler, A., Huntley, B., Jäger, J., Jodha, N. S., Kasperson, R. E., Mabogunje, A., Matson, P., … Svedin, U. (2001). Environment and development: Sustainability science. In *Science* (Vol. 292, Issue 5517). https://doi.org/10.1126/science.1059386

Klein, J. T. (2020). Sustainability and collaboration: Crossdisciplinary and cross-sector horizons. *Sustainability (Switzerland)*. https://doi.org/10.3390/su12041515

Kuhn, T. S. (1970). The Structure of Scientific Revolutions Second Edition, Enlarged. In *International Encyclopedia of Unified Science*.

Letchford, A., Preis, T., & Moat, H. S. (2016). The advantage of simple paper abstracts. *Journal of Informetrics*, *10*(1). https://doi.org/10.1016/j.joi.2015.11.001

Leydesdorff, L., & Bornmann, L. (2016). The operationalization of "fields" as WoS subject categories (WCs) in evaluative bibliometrics: The cases of "library and information science" and "science & technology studies." *Journal of the Association for Information Science and Technology*, *67*(3). https://doi.org/10.1002/asi.23408

Leydesdorff, L., Carley, S., & Rafols, I. (2013). Global maps of science based on the new Web-of-Science categories. *Scientometrics*, *94*(2). https://doi.org/10.1007/s11192-012-0784-8

Leydesdorff, L., & Rafols, I. (2011). Indicators of the interdisciplinarity of journals: Diversity, centrality, and citations. *Journal of Informetrics*, *5*(1), 87–100. https://doi.org/10.1016/j.joi.2010.09.002

Leydesdorff, L., Wagner, C. S., & Bornmann, L. (2019a). Diversity measurement: Steps towards the measurement of interdisciplinarity? *Journal of Informetrics*, *13*(3), 904–905. https://doi.org/10.1016/j.joi.2019.03.016

Leydesdorff, L., Wagner, C. S., & Bornmann, L. (2019b). Interdisciplinarity as diversity in citation patterns among journals: Rao-Stirling diversity, relative variety, and the Gini coefficient. *Journal of Informetrics*. https://doi.org/10.1016/j.joi.2018.12.006

Milojević, S. (2020). Practical method to reclassify Web of Science articles into unique subject categories and broad disciplines. *Quantitative Science Studies*, *1*(1), 183–206. https://doi.org/10.1162/qss_a_00014

Olawumi, T. O., & Chan, D. W. M. (2018). A scientometric review of global research on sustainability and sustainable development. In *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2018.02.162

Pacheco, R. C. S., Manhães, M., Maldonado, M. U., & Frodeman, R. (2017). Innovation, Interdisciplinarity, and Creative Destruction. In *Oxford Handbooks Online*. https://doi.org/10.1093/oxfordhb/9780198733522.013.25

Pandiella-Dominique, A., Bautista-Puig, N., & Filippo, D. De. (2018). Mapping growth and trends in the category 'Green and Sustainable Science and Technology.' *23rd International Conference on Science and Technology Indicators All*.

Perez, C. (2015). 11. Capitalism, Technology and a Green Global Golden Age: The Role of History in Helping to Shape the Future. *Political Quarterly*. https://doi.org/10.1111/1467-923X.12240

Porter, A. L., & Rafols, I. (2009). Is science becoming more interdisciplinary? Measuring and mapping six research fields over time. *Scientometrics*. https://doi.org/10.1007/s11192-008-2197-2

Price, D. (1963). *Little science, big science ...and beyond*. New York: Columbia University Press.

Price, D. (1965). Networks of scientific papers. *Science*, *149*(3683), 510–515.

Price, D. (1970). Citation measures of hard science, soft science, technology and non-science. In C. Nelson & D. Pollock (Eds.), *Communication amongst scientists and engineers* (pp. 3–22). Lexington, KY: Heath Lexington.

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/

Rao, C. R. (1982). Diversity: Its Measurement, Decomposition, Apportionment and Analysis. *Sankhyā: The Indian Journal of Statistics, Series A*, *44*(1), 1–22.

Rath, K., & Wohlrabe, K. (2016). Recent trends in co-authorship in economics: evidence from RePEc. *Applied Economics Letters*, *23*(12). https://doi.org/10.1080/13504851.2015.1119783

Rosulnik, M. (2012). Is sustainability science becoming more interdisciplinary over time? *Acta Geographica Slovenica*. https://doi.org/10.3986/AGS52109

Schoolman, E. D., Guest, J. S., Bush, K. F., & Bell, A. R. (2012). How interdisciplinary is sustainability research? Analyzing the structure of an emerging scientific field. *Sustainability Science*. https://doi.org/10.1007/s11625-011-0139-z

Schweitzer, S., & Brendel, J. (2020). A burden of knowledge creation in academic research: evidence from publication data. *Industry and Innovation*. https://doi.org/10.1080/13662716.2020.1716693

Spangenberg, J. H. (2011). Sustainability science: A review, an analysis and some empirical lessons. *Environmental Conservation*. https://doi.org/10.1017/S0376892911000270

Stacey, A. G. (2021). Ages of cited references and growth of scientific knowledge: an explication of the gamma distribution in business and management disciplines. *Scientometrics*, *126*(1), 619–640. https://doi.org/10.1007/s11192-020-03761-6

Stirling, A. (2007). A general framework for analysing diversity in science, technology and society. *Journal of the Royal Society Interface*, *4*(15), 707–719. https://doi.org/10.1098/rsif.2007.0213

Weinberger, C. J., Evans, J. A., & Allesina, S. (2015). Ten simple (Empirical) rules for writing science. In *PLoS Computational Biology* (Vol. 11, Issue 4). https://doi.org/10.1371/journal.pcbi.1004205

White, A., & Hernandez, N. R. (1991). Increasing field complexity revealed through article title analyses. *Journal of the American Society for Information Science*, *42*(10). https://doi.org/10.1002/(SICI)1097-4571(199112)42:10<731::AID-ASI6>3.0.CO;2-W

World Commission on Environment and Development. (1987). *Our common future*. Oxford: Oxford University Press.

Wuchty, S., Jones, B. F., & Uzzi, B. (2007). The increasing dominance of teams in production of knowledge. *Science*, *316*(5827). https://doi.org/10.1126/science.1136099

Zhang, L., Rousseau, R., & Glänzel, W. (2016). Diversity of references as an indicator for interdisciplinarity of journals: Taking similarity between subject fields into account. *Journal of the Association for Information Science and Technology*, *67*(5), 1257–1265. https://doi.org/http://dx.doi.org/10.1002/asi.23487