Mapping Hypotheses and Evidence in Urban Ecology: A Perspective on Knowledge Synthesis with a Focus on Biotic Homogenization

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Sophie Lokatis-Reichert

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DECLARATION

The scientific work presented in this thesis was conducted from March 2019 to November 2022, with an interruption of 6 months between April 2019 and October 2019, at Freie Universität Berlin and at the Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB). The work was supervised by Prof. Dr. Jonathan M. Jeschke, head of the Ecological Novelty group. Prof. Dr. Jens Rolff, Professor at Freie Universität Berlin, was co-supervisor.

1. Gutachter: Prof. Dr. Jonathan Jeschke
2. Gutachter: Prof. Dr. Jens Rolff

Disputation am: 9.2.2023

I hereby declare that this dissertation was written and prepared by me independently. Furthermore, no sources and aids other than those indicated have been used. Intellectual property of other authors has been marked accordingly. I also declare that I have not submitted the dissertation in this or any other form to any other institution as a dissertation.

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LIST OF PUBLICATIONS WITH AUTHOR CONTRIBUTIONS

Author of this dissertation: Sophie Lokatis-Reichert

Note: In all articles included in this thesis I use the shorter version S. Lokatis as author name.

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THESIS OUTLINE

The dissertation consists of a General Introduction, four separate chapters and a General Discussion. The General Introduction describes the background and purpose of the studies and defines the research objectives. Each of the following chapters represents an independent manuscript and follows the conventional structure of research papers, with subsections for the Introduction, Material and Methods, Results and Discussion. All manuscripts have either been published (Chapters 1, 3 and 4), or have been accepted in a peer-reviewed journal (Chapter 2). In the last section, the thesis' main themes are discussed in a broader context.

SUMMARY

A city is a highly complex, anthropogenically constructed system – an urban ecosystem. Researchers that study this system come from very different academic fields, bringing with them their own methods and research questions. From the perspective of (biological) urban ecology, this thesis first takes a step back, and focuses on knowledge production in general academia (chapter 1). The concept knowledge in the dark, or short: dark knowledge, describes the gap between potential and actual knowledge. In chapter 1, several potential reasons for dark knowledge in general are discussed. Focusing on the acasemic system, these are for example loss of academic freedom, research and publication biases, a lack of reproducibility, financial interests and barriers in understanding each other among disciplines and different areas of society. We also discuss potential solutions. One important aspect is rethinking and improving research synthesis and finding ways to bridge language and information barriers both within and beyond the academic system.

Chapters 2, 3 and 4 then take up a main theme from chapter 1: research synthesis, and within the setting of urban ecology show how different approaches to synthesis can help bridge communication between researchers within and beyond one discipline (biological urban ecology), identify biases and knowledge gaps, and visualize and summarize available knowledge. The chapters proceed from a very broad perspective on urban ecology to the topic of urban biotic homogenization, and then a very specific aspect within urban biodiversity research: the influence of mowing of urban lawns on arthropods, which is one specific cause of biotic homogenization in cities.

In Chapter 2, together with a group of urban ecologists predominantly based in Berlin, I collected 62 research hypotheses from urban ecology. In a second step, my co-authors and I present a first map of these hypotheses in a structured, bipartite network. As urban ecology is a multi-disciplinary field that is of high interest to urban planners and administrations, knowledge transfer between different stakeholders is particularly important. The network we propose consists of four distinct clusters, into which the hypotheses we previously identified can be grouped: (i) *Urban species traits & evolution*, (ii) *Urban communities*, (iii) *Urban habitats* and (iv) *Urban ecosystems*. This work is intended to grow, and as an invitation to researchers, practitioners and others interested in urban ecology to contribute to collecting additional hypotheses, jointly fill the network (or rather the underlying Wikidata project) with empirical data. Chapter 2 is thus intended as a first step towards an open and community curated knowledge base for urban ecology.

Chapter 3 focuses on one of the hypotheses from our network: urban biotic homogenization (UBH). Urbanization, which is restructuring ecosystems at an unprecedented pace, is hypothesized to cause the homogenization of urban species communities. This idea has also been applied to other biodiversity levels like genetic diversity, behavioural diversity, functional diversity, and the like. There is, however, good reason to also formulate a hypothesis predicting the opposite effect: biotic diversification, that predicts species communities (and other levels of biodiversity) to become biologically more diverse because of ongoing urbanization. In chapter 3, I disentangle the different connotations, scales and "auxiliary hypotheses", i.e., hypotheses that often unspokenly accompany a tested research hypothesis, which have been applied in the research literature on urban biotic

homogenization and diversification. Applying the hierarchy-of-hypotheses approach, I systematically map and structure the comprehensive body of literature on UBH, comprising 225 individual tests of the hypothesis from 145 publications. Interestingly, UBH is generally used with two very different connotations in relation to scale (i.e., homogenization *across cities* versus *within cities*). There are several strong research biases, for example in relation to taxonomic focus, scale, and study systems. We visualize support and biases in an evidence gap map and provide a bibliographic network of the field.

Chapter 4 is a meta-analysis of the impact of reduced mowing frequencies on the abundance and diversity of arthropods on urban grassland sites. It is based on 46 datasets on arthropod abundance and 23 datasets on taxa richness, respectively. As in chapter 3, we report severe geographical biases. While we find a medium positive effect (effect size: $g = 0.54$) of reduced mowing on arthropod abundance, the effect that reduced mowing has on urban arthropod taxa richness is larger ($g = 1.25$). Some functional groups benefit more from reduced mowing, especially winged insects, and perceived non-pest species.

In the final, General Discussion, I try to connect several points that can be traced to all four chapters and discuss them in the context of urban ecology. These are: knowledge gaps and biases, with a brief discussion of how the concept of dark knowledge can (and should) be relevant to researchers from urban ecology, and research and knowledge synthesis. I finish my thesis by reflecting on how these are important in the context of urban ecological knowledge in the Anthropocene, and how they should be extended in the face of planetary crisis.

Keywords: Anthropocene, dark knowledge, Knowledge synthesis, research biases, research maps, Urban ecology

ZUSAMMENFASSUNG

Eine Stadt ist ein hochkomplexes, von Menschen geschaffenes System - ein urbanes Ökosystem. Wissenschaftler, die dieses System untersuchen, kommen aus sehr unterschiedlichen akademischen Bereichen und bringen ihre eigenen Methoden und Forschungsfragen mit. Aus der Perspektive der (biologischen) Stadtökologie untersucht diese Arbeit verschiedene Aspekte der Wissenssynthese. Dabei beginnt sie mit einem allgemeinen Kapitel zu Wissensproduktion in der Wissenschaft (Kapitel 1). Der Begriff ‚knowledge in the dark', oder kurz: ‚dark knowledge' beschreibt die Kluft zwischen potenziellem und tatsächlichem Wissen. In Kapitel 1 werden mehrere mögliche Ursachen für dark knowledge diskutiert, zum Beispiel ‚biases' in Forschung und bei Veröffentlichungen, Probleme bei der Reproduzierbarkeit, finanzielle Interessen und Verständnisbarrieren zwischen Disziplinen und der Öffentlichkeit. Wir schlagen mehrere Ansatzpunkte zur Verbesserung unseres Wissenschaftlssystems vor. Ein wichtiger Aspekt ist die Reformierung von Wissenssynthese und die Verbesserung bei der Überwindung von Sprach- und Informationsbarrieren sowohl innerhalb als auch außerhalb des Wissenschaftssystems.

Die Kapitel 2, 3 und 4 greifen ein Hauptthema aus Kapitel 1 auf: die Wissenssynthese, und zeigen am Beispiel der Stadtökologie, wie verschiedene Syntheseansätze dazu beitragen können, die Kommunikation zwischen Forschern innerhalb und außerhalb einer Disziplin (biologische Stadtökologie) zu verbessern, ‚biases' und Wissenslücken zu identifizieren, und das verfügbare Wissen zu visualisieren und zusammenzufassen. Kapitel 2 beginnt mit einer sehr weiten Perspektive auf die Stadtökologie, es folgt Kapitel 3 zum Thema der biotischen Homogenisierung in Städten, und zum Abschluss mit Kapitel 4 ein sehr spezifischer Aspekt innerhalb der städtischen Biodiversitätsforschung: der Einfluss der Mahd städtischen Rasenflächen auf Arthropoden - eine ausgewählte Ursache für die biotische Homogenisierung, welche in Kapitel 3 untersucht wird.

In Kapitel 2 habe ich gemeinsam mit einer Gruppe von Stadtökolog*innen, welche überwiegend in Berlin angebunden sind, 62 Forschungshypothesen aus der Stadtökologie zusammengetragen. Aus diesen Hypothesen haben meine Mitautoren und ich eine erste Karte in Form eines strukturierten, bipartiten Netzwerks erstellt. Da es sich bei der Stadtökologie um ein sehr interdisziplinäres Gebiet handelt, das aus für Stadtplaner und -verwaltungen außerhalb der Wissenschaft von großem Interesse ist, ist der Wissenstransfer zwischen den verschiedenen Akteur*innen besonders wichtig. Das von uns vorgeschlagene Netzwerk besteht aus vier verschiedenen Clustern, zu denen die zuvor ermittelten Hypothesen zugeordnet werden können: *Urban species traits & evolution*, *Urban communities*, (iii) *Urban habitats* und (iv) *Urban ecosystems*. Dieses Netzwerk soll in Zukunft größer werden. Das Kapitel ist eine Einladung an Wissenschaftler*innen und Akteur*innen außerhalb des Wissenschaftssystems, weitere Hypothesen zu sammeln und das Netzwerk (bzw. das zugrunde liegende Wikidata-Projekt) mit empirischen Daten zu füllen. Kapitel 2 ist als erster Schritt in Richtung einer offen und gemeinschaftlich kuratierten Wissensplattform für die Stadtökologie gedacht.

Kapitel 3 untersucht eine der Hypothesen die in Kapitel 2 gesammelt wurden: die biotische Homogenisierung in Städten (urban biotic homogenization, UBH). Urbanisierung wird häufig als Ursache der Homogenisierung von Artengemeinschaften aufgeführt. Diese Homogenisierung lässt sich auch auf andere Ebenen der biologischen Vielfalt übertragen, wie genetische Vielfalt,

Verhaltensvielfalt und funktionale Vielfalt. Andererseits gibt es auch den gegenteiligen Effekt: die biotische Diversifizierung in urbanen Gebieten. Artengemeinschaften (und andere Ebenen der biologischen Vielfalt) können aufgrund der fortschreitenden Urbanisierung auch biologisch vielfältiger werden. In Kapitel 3 untersuche ich die verschiedenen Konnotationen, geographischen Skalen und "Hilfshypothesen", d. h. Hypothesen, die eine wissenschaftliche Hypothese, oft unausgesprochen, begleiten, welche in der Forschungsliteratur zu UBH verwendet wurden. Mithilfe einer Hypothesenhierarchie (hierarchy-of-hypotheses approach) strukturiere ich 225 Einzelstudien aus 145 Veröffentlichungen zur UBH. Interessanterweise wird UBH im Allgemeinen mit zwei sehr unterschiedlichen Konnotationen in Bezug auf den Maßstab verwendet (Homogenisierung zwischen verschiedenen Städtes und biotische Homogenisierung innerhalb einer Stadt). Es gibt mehrere ‚biases', z. B. in Bezug auf die taxonomischen Gruppen welche untersucht werden, den untersuchten Maßstab und die Systeme welche untersucht werden. ‚Biases' und Evidenz innerhalb der Literatur zur UBG werden in einer ‚evidence gap map' sichtbar gemacht, und ein bibliografisches Netzwerk des Forschungsfelds erstellt.

Kapitel 4 ist eine Meta-Analyse der Auswirkungen einer reduzierten Mahd auf die Abundanz und Diversität von Arthropoden auf städtischen Grünflachen. Sie basiert auf 46 Datensätzen zur Häufigkeit bzw. 23 Datensätzen zur Diversität von Arthropodem. Wie in Kapitel 3 beschreiben wir auch in diesem Kapitel starke geografische ‚biases'. Während wir einen mittleren positiven Effekt (Effektgröße: $g = 0{,}54$) einer Mahdreduktion auf die Häufigkeit von Arthropoden feststellen, ist der Effekt, den eine Reduktion der Mahd auf die Diversität von Arthropoden in Städten hat größer ($g = 1{,}25$). Einige funktionelle Gruppen profitieren stärker von einer reduzierten Mahd, insbesondere geflügelte Insekten und Gruppen, die nicht als Schädlinge wahrgenommen werden.

In der abschließenden, allgemeinen Diskussion versuche ich mehrere Punkte, die sich aus den vier Kapiteln ergeben, miteinander zu verbinden und sie im Kontext der Stadtökologie zu diskutieren. Dabei stehen Wissenslücken und ‚biases' im Zentrum einer kurzen Diskussion darüber, on und in welcher Form das Konzept ‚dark knowledge' für Stadtökolog*innen relevant sein kann (und vielleicht sogar sollte). Ich schließe meine Arbeit mit einer allgemeinen Überlegung, wie die zuvor diskutierten Themen für stadtökologisches Wissen im Anthropozän wichtig sind, und wie diese im Kontext der planetaren Krise erweitert werden sollten.

Schlüsselwörter: Anthropozän, dark knowledge, wissenschaftliche „Landkarte", Forschungs-„biases", Stadtökologie, Wissenssynthese

General Introduction

Figure I.1 Australian kestrel looking over Melbourne. CC BY Jes (mugley on Flickr)

Bird's eye view

The structure of this thesis can be paraphrased with a kestrel's steep descent from the sky. Circling its territory, it is aware of the winds that carry it, and carefully scans the landscape below. Knowledge is the overarching theme of the present thesis, and the realm where the urban kestrel starts its flight. In chapter one, the term knowledge in the dark, in short: *dark knowledge*, is introduced. It captures the gap between potential knowledge and actual knowledge, implying a number of potential causes for this gap. Much like the airborne kestrel, the first chapter is not yet concerned with the upcoming descent, but instead takes a very general stance at science – or more concretely – the limits and flaws of knowledge production and research synthesis in academia. It is, of course, an urban kestrel, so the landscape below it comprises skyscrapers and turbulent roads, which it navigates with ease. Navigating the landscape of urban ecology as a scientific discipline, the second chapter presents a map of concepts and hypotheses, which were identified collectively by me and my co-authors, most of them with backgrounds in urban ecology. This chapter is concerned with building a "common knowledge base" for urban ecologists, by gathering and mapping important concepts and hypotheses in the field, with the aim to capture research trends and help both researchers from within the field, and outsiders, to navigate among them. The third chapter, where our kestrel finally swoops down on its prey, takes into view one of the identified hypotheses: Urban Biotic Homogenization. It analyses knowledge gaps, trends and conflicting terminology by combining literature review and bibliometrics (an approach termed 'research weaving') connected to this concept in urban ecology. The fourth and final chapter looks at one potential cause of urban biotic homogenization: wide-spread, tidy mowed lawns. Kestrels will find little prey here, but our meta-analysis shows how previously sterile urban lawns can recover when adapting a wildlife-friendly mowing regime and foster an abundance of insects and other many-legged creatures. This final chapter adds to the broader perspective of scientific knowledge, and research synthesis, that spans the thesis, with a very practical example: A tasty locust in its beak, the falcon returns to its nest high up, taking a final gaze over its hunting ground.

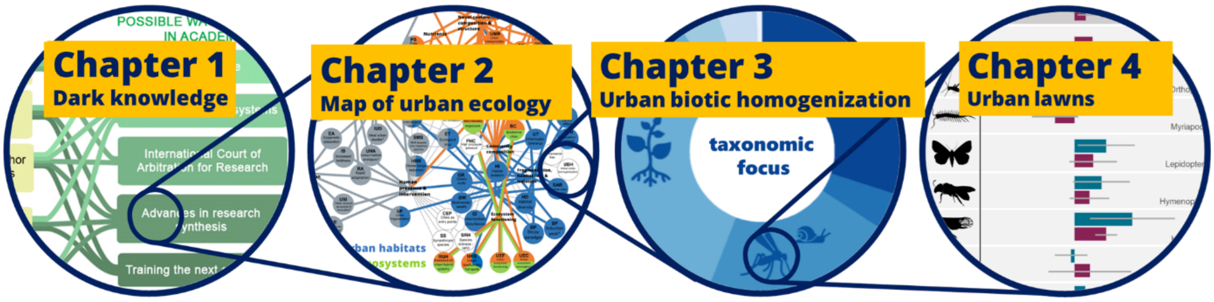

Figure I.2 The four chapters of this thesis are hierarchically connected to each other. Each consequent chapter takes up a topic raised in the previous one.

Knowledge: a multifaceted term

As a scientist trained in ecology, I can say that ecologists only rarely have the time to step back from their mostly empirical or theoretical (e.g., modelling) work to dwell in epistemological debates and look at their research from the perspective of philosophers of science, the humanities, or social sciences. They *produce* knowledge, with increasing societal importance, and naturally care about truth and the relevance of their findings. Ecologists are part of a network of a larger research infrastructure and increasingly work – *produce knowledge* – with the premise that their contributions are 'meaningful' and address societal challenges. They are active parts of the so-called "knowledge society". While the scientific method is rooted in the innate human striving towards knowledge and understanding of the natural world, "independent [...] from immediate practical purposes" (Renn 2018, p. 15), our society has in the last century become dependent on the manufacturing and distribution of intentionally produced knowledge[1]. This realization gives us scientists a pressing reason to step back and reflect on our role and the knowledge we produce.

Approaching all chapters of this thesis from an overarching perspective on knowledge, and our role as ecologists within the wider knowledge society, will be a recurrent theme throughout the thesis, and hopefully offer some insightful thoughts beyond the findings of each separate chapter.

But what is knowledge? The most traditional definition of (relational) knowledge is knowledge as justified true belief. Knowledge, in this view, arises when three conditions are met: a belief is formed, that belief is justified and epistemically true[2]. Understanding knowledge as justified true belief is rooted in ancient philosophy and can be traced through the history of all civilizations. While scholars

[1]"Nobody could have anticipated that human societies would eventually become dependent on such knowledge, a challenge made even greater by the intrinsically uncertain nature of scientific knowledge" (Renn 2018, p. 15)

[2]A premise that has kept generations of philosophers, and later sociologists of science, occupied.

have raised serious philosophical concerns about this concept in the past 60 years (Dutant 2015), it remains the foundation of arguments in epistemology, the branch of philosophy that studies the nature of knowledge. For example, Nagel (2014) defines knowledge in its simplest form as "the epistemic link between an individual human being and a fact". But having put 'relational' in parentheses a couple of sentences earlier gives away that there are other forms of knowledge[3]: acquaintance knowledge (knowledge-who) and practical knowledge (knowledge-how) are the most common distinction of knowledge types in epistemology beyond relational knowledge (knowledge-that, Davidson 1991, McCain 2016a). Acquaintance knowledge describes the knowledge of something, or someone, that a person is familiar, or acquainted with. It is different from relational knowledge in that, even though one might know all the facts about a given object or person or experience, a true knowledge of these can only arise through acquaintance. This dilemma has been famously illustrated by Frank Jackson's "knowledge argument"[4]. Knowledge-how, practical, or procedural knowledge is the knowledge of performing tasks, mostly gained by experience. Although scientific knowledge is often subsumed under relational knowledge in epistemology (McCain 2016b), it is built in large parts on acquaintance, as well as practical knowledge (Renn 2020). But the situation gets even more complicated when approaching knowledge from a broader, interdisciplinary perspective. Knowledge turns out to be a multifaceted concept, with very different emphases, when being approached from the perspective of history (Ricoeur 1978, Perkins 1984, Elliott 2003, Nekhamkin 2015), sociology (Shapin 1995, McCarthy 2005, Weingart 2010), anthropology (Crick 1982, Barth 2002), linguistics (Keesing 1972, Gordon & Hendrick 1997, Van Dijk 2011), cognitive science (Starmans 2012), or information science (Farradane 1980, McInerney 2002, Bates 2005, Cheng et al. 2018).

Although it is beyond the scope of this thesis to present an exhaustive overview of the many different approaches to knowledge, I will briefly introduce two issues surrounding the concept of knowledge raised by developmental psychology and the social sciences. Broadening our perspective on knowledge (and the role of knowledge in our 'knowledge society') will be central to the discussion at the end of the thesis, where I try to review all chapters in the light of knowledge in the context of global uncertainty and crises. Please note that in our article on 'dark knowledge', which refers to the gap between potential and actual knowledge, we explicitly "focus on knowledge of individual people rather than collective knowledge", and that dark knowledge is not restricted to scientific knowledge, but "applies to various knowledge definitions". How these choices impact, and possibly restrain, our own argument and the concept of dark knowledge, will also be discussed at the end.

[3]other terms for relational knowledge are descriptive knowledge, knowing-that, or declarative knowledge

[4]The Knowledge argument, or „Mary's room", is a thought experiment by philosopher Frank Cameron Jackson published in 1982. He places Mary, a brilliant scientist, into a black-white room. Mary supposedly learns every possible scientific fact about colours and colour vision. Would she still learn something new, when she left the room, now experiencing colours for the first time?

Knowledge and culture

Where epistemologists had approached knowledge from an abstract, logical, and presumably universal (i.e. detached from social, historical, and developmental influences) perspective, different research disciplines arose in the beginning of the 20th century that studied the concept of knowledge from different angles (Renn 2018, pp 42). Sociologists have been especially active in pointing out that knowledge arises from social networks, and that scientific knowledge, which had long been regarded as being largely impartial and independent from social influences (Maasen 2009), should not be treated as an exception in this regard. According to Randall Collins (1998, p. 879), "Sociologists of science have away the idealizations with which scientists have traditionally presented their results, hiding their actual investigation and negotiation, as if they produced scientific truths untouched by human hands [...]. [S]ocial construction per se does not necessarily undermine truth, for there is no other way that true statements could arise than by the activities of social networks."

Research from developmental psychology added an equally constructivist, but very different perspective on knowledge by stressing that the mental capabilities that enable us to gain knowledge, and even knowledge about objects and causal relationships themselves, arise from a series of cross-cultural, though genetically determined, interactions with reality. Human infants build their knowledge by trial and error, and by repeatedly experiencing the consequences of their actions. Children pass several milestones on their active (though unconscious) path to epistemology[5], on which they gain the mental capacity to make logical inferences and hypothetical deductions. They do not find knowledge (and abstract concepts) in the "lofty realms of science and philosophy" (borrowing a phrase from Renn 2018, p 47), but simply as a direct consequence of profound and experience-based interactions with physical reality (Piaget, 1977). Knowledge, consequentially (and this has also been studied intensely in anthropology and linguistics) is highly interrelated with culture, as language and previously obtained knowledge profoundly shape how we conceptualize the world, and in turn also how that new knowledge is acquired and interpreted.

The realization that knowledge, or "epistemic intuition", depends on context and culture has had a wide impact on several disciplines engaged in studying different aspects of knowledge[6] and led to a need for more interdisciplinary collaboration (Maasen 2009, Cohen 2010). It has, at least in part, also led to non-scientific forms of knowledge being taken more seriously (see section 'Knowledge in the Anthropocene' in this Introduction). Let me, however, first turn towards scientific knowledge, and recent developments in metascience that have shaken science from within. This will set the context for the four chapters because each of them is concerned with aspects of (barriers to) scientific knowledge production and distribution, although at very different scales.

[5]The knowledge infants obtain includes object permanence (i.e. knowing that an object or a person continues to exist outside the personal field of attention), the acquisition of symbols and language, and finally operational thinking.

[6]Anthropologists, for example define knowledge as "cultural belief" (Crick 1982, Pelto & Pelto 1997), and sociologists are studying "whatever passes for 'knowledge' in a society, regardless of the ultimate validity or invalidity (by whatever criteria) of such 'knowledge'" (Berger & Luckmann 1966, p. 15).

Scientific knowledge in jeopardy: the reproducibility crisis

> *"Science, the discipline in which we should find the harshest scepticism, the most pin-sharp rationality and the hardest-headed empiricism, has become home to a dizzying array of incompetence, delusion, lies and self-deception. In the process, the central purpose of science – to find our way ever closer to the truth – is being undermined."* – Stuart Richie 2020, p.7

In general, scientists seem to have found a way to bridge the barriers of language, culture, and disciplines, as they "collaborate on a massive scale in generating shared knowledge, and they also build on one another's results and engage in constructive debate" (Kukla 2015, p. 203). And even though scientists themselves are social beings that can be biased or driven by ideology or cultural beliefs, science as a whole is supposed to be a self-correcting system, that can, in principle, produce objective knowledge (Longino, 1998). One way to ensure scientific quality is peer review (at least in theory, see Lee et al. 2013). During publication, peer review ensures that only high-quality and sound findings are released into the sphere of scientific knowledge. With its rigorous approach to knowledge inquiry, science has rebuilt our understanding of nature and reality, outstretching into society, culture, and belief. Scientific knowledge is generally perceived by most to be more trustworthy than other forms of knowledge (Hendriks et al. 2016), and the information technology and infrastructure that we are embedded in is a constant reminder that the system works.

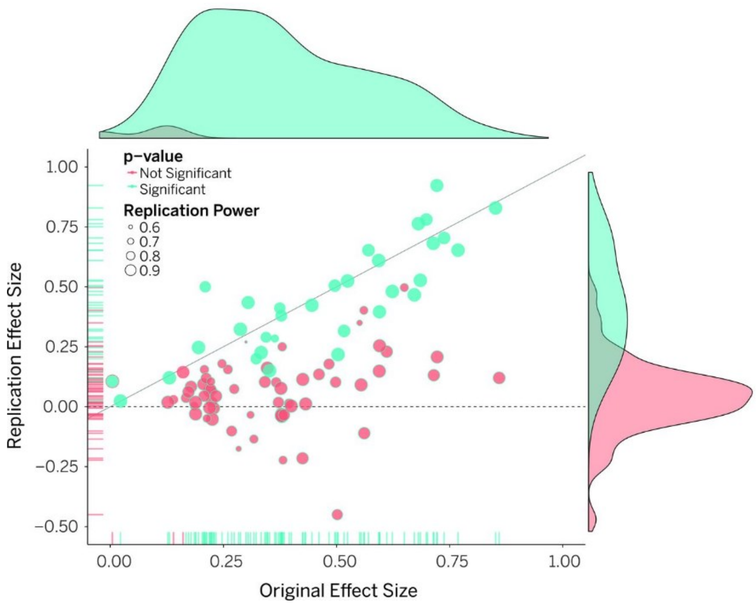

Figure I.3 This figure from the report of a wide-scale replication attempt, published 2015 in Science, captures the essence of the replication crisis: Only 39% of all 100 studies in psychology could be replicated successfully (Open Science Collaboration 2015). Similarly, an attempt to replicate 53 'landmark studies' in cancer-research found that only 11% could be reproduced (Begley and Ellis 2012).

One of the cornerstones of scientific objectivity is replicability: only if research findings can be replicated by other researchers, do they outlast. If not, they are discarded. But this built-in safeguard system ran hot with the start of the so-called reproducibility crisis in 2011, leaving a stain on the view of science as a source of infallible, ultimately objective truth. The replication crisis brought to light systematic fraud, cases of deception, widespread scientific misconduct, and, most importantly, inherent flaws within the scientific system as it is currently set up.

A peek into the abyss science had steered itself into had been published a couple of years earlier under the not very reassuring title "Why most published research findings are false" (Ioannidis 2005). Following the outrage within the science community after the exposure of several highly problematic studies in psychology in 2011 (especially Bem 2011, Stapel &

Lindenberg 2011, retracted), hundreds of researchers from psychology joined the Open Science Collaboration, a concerted replication project that aimed to reproduce the findings of 100 randomly selected studies from 2008 (Open Science Collaboration 2015). As it turned out, many of these published research findings could not be replicated (see Fig. I.3).

Other disciplines followed in cross-examining their own scientific output, with similar results and new problems surfacing: a large proportion of results could not be reproduced, even when using the exact same dataset (e.g. Chang & Li 2015, Konkol et al. 2019), or replication attempts failed because the original articles did not include enough information on the experiments performed (Errington et al. 2021). In some cases, data had been entirely invented (e.g. Fanelli 2009, a practice that will let you end up in the innermost circle of scientific hell[7]), but in many cases, the work was either done carelessly (Casadevall et al. 2016) or the results were overinterpreted (e.g. by presenting random findings as primary results, see HARKing, Kerr 1998). "Overall, the replication crisis seems […] to have wiped about half of all psychology research off the map" (Ritchie 2020, p. 31). And even though the exact amount of untrustworthy research findings in other disciplines remains mostly unknown, there is little doubt that the scientific system has a very profound problem, stretching to many research fields and disciplines (Pashler et al. 2012, Baker 2016). Ecology is certainly no exception, with Fraser et al. (2018) concluding that "[t]he rates of QRPs [questionable research practices] found in this study [on ecology and evolution] are comparable with the rates seen in psychology, indicating that the reproducibility problems discovered in psychology are also likely to be present in ecology and evolution[8].

The replication crisis was the result of a deeply flawed publication system that favoured positive results over negative ones (Fanelli 2010, 2012), rarely published replication studies (as the results would be considered boring, and not promise anything new, Evanschitzky et al. 2007), and incentivized scientists to publish as many important findings as possible, or else be lost in academic vacuity ("publish or perish", leading among others to a practice termed "salami slicing", which describes the publication of results in several articles that could have been combined, Van Dalen & Henkens 2012, Brischoux & Angelier 2015). The newly born scepticism towards the reliability of research findings from within the scientific community has led to intense debates, and several promising reforms of the scientific system. It even led to the formation of a new discipline: metascience.

[7]„Here, Satan himself lies trapped forever in a block of solid ice alongside the worst sinners of all. Frozen in front of their eyes is a paper explaining very convincingly that water cannot freeze in the environmental conditions of this part of Hell. Unfortunately, the data were made up."

[8]In fact, some well-established ecological hypotheses and concepts, that have been taught to generations of undergraduate students (and many continue to be taught), like domestication syndrome (Lord et al. 2020), the island rule (Meiri et al. 2008, Lokatis & Jeschke 2018), r/K selection (Jeschke & Kokko 2009) or the intermediate disturbance hypothesis (Fox 2013), have been shown to be at least overstated (see given references), if not entirely refuted or built on biased or forged data. Ecologist Jeremy Fox even used the term zombie hypotheses for all those ideas that are "intuitively appealing" and "tend to persist", regardless of contradictory, or inconclusive evidence (Fox 2011, building on Quiggin 2010).

Science from a bird's eye view: Metascience

As scientists, we only rarely take on an eagle's perspective – or here: that of an urban kestrel – on our discipline. Scientific work typically involves "systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses" (Oxford English Dictionary 2022). It does, as I have indicated above, also have a social dimension, that requires scientists to "work in teams, […] give lectures and conference speeches, debate each other in seminars, form scientific societies to share research and […] publish their results in peer-reviewed journals" (Ritchie 2020, p.14). But, and this has been shown repeatedly by social scientists and science historians, along with the meta-scientific analyses that followed the reproducibility crisis: science has some very influential systemic flaws that are shaped by funding agencies, science policies, and political agendas (see for example Oreskes & Conway 2010, Nosek et al. 2012, Csiszar 2016, Smaldino & McElreath 2016, Munafò et al. 2017). As mentioned above, science has the innate potential to correct itself, provided that the biases, errors, misrepresentations, and manipulations are disclosed and made public at a wide scale. This is where metascience, or meta research, has come in.

Metascience studies scientific research using the methods of science, with the aim to identify problems, and improve the scientific system. The widescale replication attempt by the Open Science Collaboration is a (laborious) form of metascience. The methods and findings of metascience are not new[9], but as a consequence of the publication crisis, metascience has gained enormously in importance. Meta-scientific research targets the scientific system at all levels: research methods and study design, data analysis, management and reporting, peer review, and institutional and social incentives. Several recommendations, especially the call for open data and open science, have been adopted in the past years: research institutes like the Center for Open Science and METRIC (Meta-Research Innovation Center) were founded (both in 2013), scientists and research institutions joined national and international networks for reproducibility and open science, and a number of publishers have adopted new guidelines on data quality and transparency, with several journals having been founded that are specialized on open science or on reporting negative results (see also Ioannidis et al. 2015). Metascience relies heavily on scientometrics and bibliometrics, as well as information science (Sugimoto & Larivière 2018). What it rarely does is reflecting on the role of science in the face of environmental collapse.

Knowledge in the Anthropocene

With the onset of the new millennium at plain sight, Lubchenco (1997) writes: „the roles of science – to discover, communicate, and use knowledge and train the next generation of scientists – have not changed, but the needs of society have been altered dramatically. The current and growing extent of human dominance of the planet will require new kinds of knowledge and applications from science— knowledge to reduce the rate at which we alter the Earth systems, knowledge to understand Earth's ecosystems and how they interact with the numerous components of human-

[9]See e.g. Schor & Karten 1966, Carver 1978 and Kerr 1998, as well as the discourse surrounding meta-analyses (Rosenthal & DiMatteo 2001, de Vrieze 2018).

caused global change and knowledge to manage the planet". With ever accelerating environmental deterioration and societal crises (e.g. Dixson-Declève et al. 2022), the need for science to tackle the sustainability crises has been echoed repeatedly (e.g. Raven 2002, Cash et al. 2003, Sarewitz & Pielke 2007, Holdren 2008, Dilling et al. 2011, Schneider et al. 2019).

At the same time, scientific knowledge, finds itself in a companion position. The cause of this downgrade is neither rooted in the postmodernist critique culminating in the so called "science war" (see Segerstrale 2000), nor a lost in public trust following the reproducibility crisis, but instead born out of: (1) the development in western democratic societies towards a public and academic system that takes questions of equity and colonial crimes seriously (Gadgil et al. 1993, Berkes et al. 2000, Berkes et al. 2017, Nielsen et al. 2017, Nielsen et al. 2018, Norström et al. 2020); and (2) a state of shock in the face of multiple planetary crises, along with the urgent need to act (Hoppe 1999, Adger 2010, Van der Hel 2016, Kettle et al. 2017, Harvey et al. 2019, Knapp et al. 2019, Nightingale et al. 2019, Moallemi et al. 2020, Woroniecki et al. 2020)[10].

An urban ecology perspective on knowledge: outline of this thesis

The present thesis is situated within urban ecology, with a focus on knowledge production and research synthesis. Humans started to live in cities at least 5000 years ago (Childe 1950), but the 21st century will take urbanization to a new level, with mega cities spanning across national borders, and cities being disproportionally more vulnerable to the unfolding climate catastrophe, resource scarcity, and social unrest than other systems[11]. It has been predicted that between 2000 and 2030, urban areas will triple in size (Seto et al. 2012), and as cities expand, so does the pressure they exert on nature (McKinney 2002; Ives et al. 2016). Urbanization has become one of the most critical environmental issues (Pauleit et al. 2016). Resulting climate alterations, pollution, and habitat fragmentation are known to contribute to species endangerment and the homogenization of biotic communities (McKinney 2002). Parallel to the growth of human cities, research on cities and urbanization has grown. Urban ecologists are joined by evolutionary biologists, climatologists, geologists, medical scientists, and information scientists, by social scientists like geographers, anthropologists and political scientists as well as historians and cultural researchers - even architecture and the fine arts join the common aim to understand the fabric of cities, and finding sustainable and equitable solutions to urban development.

The birth of urban ecology as a scientific discipline can be dated to the second half of the 20th century. Researchers with a background in ecology typically ask "How, and why, do urban organisms differ from their counterparts in other, typically natural, environments?", "In what way does urbanization influence ecology, evolution, or behaviour of organisms?" and "Do urban and non-

[10]The discourse on the role and objectives of the IPBES, the Intergovernmental Panel on Biodiversity and Ecosystem Services, illustrates this twofold turn in knowledge policy: [The IPBES "aims to incorporate knowledge from a variety of sources, including not only the natural, social, and engineering sciences but also indigenous and local knowledge (ILK). The inclusion of ILK is not only a matter of equity but also a source of knowledge that we can no longer afford to ignore" (Diaz et al. 2015b).

[11]Cities are disproportionally more threatened from climate change and environmental deterioration than other land use types (Grimm 2008, Kumar 2021).

urban areas differ in biodiversity and/or species abundance?" (Grimm et al. 2000, Ouyang et al. 2018). But even answering even these explicitly ecological questions requires to look beyond the discipline: "A wealth of research from a diversity of disciplines (e.g., political ecology, cultural anthropology, sociology) has revealed the ubiquity of complex interactions between human society and nature through millennia and across geographic regions [see ref. therein]. This research has laid the groundwork for studying the interactions among social, ecological, and evolutionary dynamics in cities." (Des Roches et al. 2021). As a recent example, Schell et al. (2020) studied the interaction between urban wildlife and systemic racism and social injustice, concluding that "incorporating environmental justice principles into how we perform and interpret urban ecology and evolution research will be essential, with restorative and environmental justice serving as the foundation for effective ecological restoration and conservation."

In cities, human culture and social life agglomerate, and any ecologist that wants to study urban nature naturally must include the human perspective, or employ research methods, of other disciplines. This is why urban ecology has been an interdisciplinary endeavour since its beginnings in the 1970s[12] (Kowarik 2020).

Consequently, research on cities can get very complex[13]. Thinking about knowledge in an urban context is important, or rather: the opposite of knowledge – uncertainty and the unknown – are important for urban ecology. This argument was brought up by Marina Alberti, who dedicates an entire chapter of her book "Cities that think like planets" (2016, chapter 8) to 'incomplete knowledge, uncertainty, and surprises'. Only if we fully embrace the inherent incompleteness and uncertainty of our knowledge on urban systems, she argues, can urban planning meet the unprecedented challenges and hazards that cities face under global crises and climate emergency (ibid.). Alberti's argument builds on those limitations of knowledge that stem from incomplete knowledge, uncertainty, and surprise. Including these in models and planning strategies is of paramount importance, but apart from missing, and uncertain knowledge, there are also barriers, biases and erroneous information, which further complicate the situation.

Illuminating these is subject of **Chapter 1 – "Knowledge in the Dark: Scientific challenges and ways forward."** Chapter 1 introduces 'knowlede in the dark', which describes the gap between potential and actual knowledge. Focusing on the academic system, several issues that potentially cause dark knowledge are described. Chapter 1 concludes with possible way forwards, with the aim to reduce the amount of dark knowledge and improving our academic system. Even though Chapter 1 does not take an urban perspective itself, I will return to Alberti's argument in the general discussion at the end of this thesis and discuss her argument in the light of the thesis' main chapters, as well as in the broader context of the role of knowledge in the Anthropocene. This opposite side of what is generally perceived as valid, well established, and certain knowledge that Alberti addresses has

[12]The reverse is not necessarily true, but the interest in nature, urban wilderness, and the work of evolutionary biologists and ecologists in urban areas has been increasing among other disciplines, not least in course of the COVID-19 pandemic.

[13]As a matter of fact the idea of„wicked problems" can be traced back to urban planning theory and the impossibility to find one-size-fits-all solutions that satisfy all aspects of a problem (Rittel & Webber 1973).

recently grown into an emerging research discipline: agnotology, or ignorance studies (Somin, 2006; Croissand 2014, Gross, M., & McGoey, 2015; Slater, 2019). Even though chapter one was not written for urban ecology, I will discuss it in that context at the end of the thesis and show both limitations and merits in looking at dark knowledge from an urban perspective. I argue that it is crucial to also consider causes and extents for ‘ignorance’, and that doing so will even strengthen Alberti’s case.

Chapter 2, “Hypotheses in urban ecology: building a common knowledge base”, takes on the problem of knowledge and research synthesis in urban ecology, offering a potential way forward by circumventing some of the problems of the scientific publication system raised above. Given the high inter- and even intradisciplinarity of urban ecology, one crucial issue regarding knowledge in urban ecology is knowledge exchange, both between the different disciplines involved as well as crossing the academic frontier by including city planners, administrators, and citizens (e.g. Hagemeier-Klose et al. 2014, Seydel & Huning 2022). Unfortunately, as I have argued above, it is not even unambiguous what all these different groups mean when they use the term ‘knowledge’. What they have in common, though, is a mutual striving to understand and improve life in cities. The map of hypotheses in urban ecology, even though drawn exclusively from the perspective of ecologists, is intended to grow into other disciplines, and, by building on the principles of open science and self-correction, provide some urgently needed orientation and cross-checking for the field.

After having introduced the concept of dark knowledge in chapter one and a conceptual map of urban ecology in Chapter 2, in **Chapter 3, “Urban biotic homogenization: approaches and knowledge gaps”**, the focus lies on one selected hypothesis from urban ecology, urban biotic homogenization. The urban biotic homogenization hypothesis predicts an increase in the compositional similarity of urban biomes. According to this hypothesis, similar processes are increasingly occurring in urban areas around the globe: urban areas provide dispersal pathways that are of lesser importance in less human-influenced areas, leading to the spread of non-native species, selective immigration of urban-tolerant generalists (urban exploiters, Lowry et al. 2013), and the extinction of specialized species (Devictor et al. 2008). Hypotheses and concepts in ecology, and this holds true for the urban biotic homogenization hypothesis as we will show in this chapter, are (often unconsciously) broken down into sub-hypotheses, which are then tested in experiments or observational studies. The overarching hypothesis may be accepted as generally valid, whereas in reality, there is only empirical evidence for one or some of the sub-hypotheses (Heger and Jeschke 2018). A powerful tool to identify research gaps and conflicting usage of concepts and hypotheses is the hierarchy-of-hypothesis approach (ibid., Jeschke et al. 2012, Heger et al. 2021). In combination with complementing approaches from metascience, Chapter 3 is about identifying gaps and biases in knowledge production related to biotic homogenization in urban settings, but also about researchers being ambiguous about how they use widespread concepts.

The gold standard of meta-scientific research are meta-analyses[14], so here it is: a meta-analysis on the **"Impact of mowing frequency on arthropod abundance and diversity in urban habitats" (Chapter 4).** Regularly mowed lawns are a symbol of worldwide biotic homogenization and seen as one direct cause for it (Polsky et al. 2014, Wheeler et al. 2017), and so Chapter 4 can be regarded as specific aspect of the UBH hypothesis. The theme of knowledge gaps and biases reoccurs in chapter 4. This chapter will also allow me to discuss issues surrounding meta-analyses in general at the end of the thesis, and return to the overarching theme of knowledge in the Anthropocene. For now, the main questions are: are there biases in research on urban lawn management? How big is the impact of giving urban lawns back to nature, at least to some degree? And: What types of arthropods will our urban kestrel find there, before returning to its lookout?

[14]Receiving reviews peppered with phrases like "why didn't you do a meta-analysis?" or "a meta-analysis seems more appropriate!", seems to be a common response to synthesis articles that do not apply meta-analytic techniques (personal experience, and pers. comm. with several of my colleagues).

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Chapter 1 | Knowledge in the dark: scientific challenges and ways forward

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Abstract

A key dimension of our current era is Big Data, the rapid rise in produced data and information; a key frustration is that we are nonetheless living in an age of ignorance, as the real knowledge and understanding of people does not seem to be substantially increasing. This development has critical consequences, for example it limits the ability to find and apply effective solutions to pressing environmental and socioeconomic challenges. Here, we propose the concept of "knowledge in the dark"—or short: Dark Knowledge—and outline how it can help clarify key reasons for this development: (*i*) production of biased, erroneous, or fabricated data and information; (*ii*) inaccessibility and (*iii*) incomprehensibility of data and information; and (*iv*) loss of previous knowledge. Even in the academic realm, where financial interests are less pronounced than in the private sector, several factors lead to Dark Knowledge, that is they inhibit a more substantial increase in knowledge and understanding. We highlight four of these factors—loss of academic freedom, research biases, lack of reproducibility, and the Scientific tower of Babel—and offer ways to tackle them, for example establishing an international court of arbitration for research and developing advanced tools for research synthesis.

Introduction

The quote from John Naisbitt, "we are drowning in information but starved for knowledge" (Naisbitt 1982, p. 24), is more applicable today than ever before. Thanks to smartphones and similar devices, we have instant access to enormous amounts of data and information. At the same time, we seem to lack the capacity to transform available information into knowledge that would allow us to make important decisions in our daily lives on topics such as health care or economic investments (Ungar 2008). Evidence suggests that the general knowledge of individuals has not increased in the way that overall information and data have increased—a phenomenon termed the knowledge–ignorance paradox (Putnam 2000; Ungar 2008; Schulz et al. 2010; Schulz 2012; Millgram 2015). Proctor (2016) has called the current era the "age of ignorance"; conspiracy theories and rumors thrive in the World Wide Web's echo chambers (Butter 2018), and today's societies are increasingly seen as "post-truth societies" in which truth has partly lost its value and importance to people (Higgins 2016; Viner 2016).

There are different perspectives and definitions about "knowledge" and related terms such as "reality" (Boghossian 2007; Rowley 2007; Moon and Blackman 2014; Nagel 2014). Assuming that an objective reality exists, our usage of the term knowledge follows the knowledge pyramid where data are on the bottom, information is in the middle, and knowledge and understanding are on top (cf. Ackoff 1989; Rowley 2007). Different versions of this pyramid exist, for example "understanding" is sometimes left out or included in knowledge. We use knowledge in the broad sense here, including understanding. We avoid a narrow definition of knowledge, as indeed the concept of "knowledge in the dark" outlined below applies to various knowledge definitions. However, we focus on knowledge of individual people rather than collective knowledge. Of course, individual and collective knowledge are interrelated, and key points outlined below also apply to collective knowledge, yet a detailed comparison of individual versus collective knowledge is beyond the scope of the current article.

As illustrated in the knowledge pyramid, knowledge requires the reflection and interpretation of data and information, i.e., it is evidence based. This is not restricted to scientific evidence, but includes data and information generated in other professions or domains, as well as experience of indigenous people or other local residents (cf. Wynne 1992; Funtowicz and Ravetz 1993; Kleinman and Suryanarayanan 2012; Yeh 2016). When reflecting on and interpreting data and information about a given topic, people can become knowledgeable about this topic. Such knowledge enables them to, for instance, better predict the consequences of important decisions related to this topic—and act accordingly, for example during elections. This is not the case for data and information per se. The latter are only truly useful if people can transform them into knowledge. Here, we focus on desirable knowledge, as humans do not want to know everything (e.g., Gigerenzer and Garcia-Retamero 2017).

The observation that we are living in a time where data and information, and thus potential knowledge, keep accumulating, but where the real knowledge of people does not keep up, is frustrating. Science's primary goal is to advance knowledge; thus we are currently falling short of our mission. At the same time, we are facing a sizable risk that science is losing trust, and thus its role as a counselor for evidence-based decision-making (Pielke 2007) in societies across the globe (Kitcher 2011). Indeed, we observe an increasing gap between evidence and people's judgment (Funk and Rainie 2015) partly for economic and ideological reasons.

We, the authors of this article, are natural scientists who have discussed this topic in depth with colleagues from various disciplines and put it into a broader context. Based on these discussions and reflections, we have developed the concept of knowledge in the dark that we consider useful for stimulating discussions about the pivotal role science plays in our societies, and it may help improve our ability to make effective decisions that are important for us as individuals and societies. Here, we outline this concept and then apply it to the academic realm. Various aspects of this broader topic have already been extensively dealt with; see for example the existing body of literature on ignorance studies (also known as agnotology; Gross 2007; Proctor and Schiebinger 2008; Kleinman and Suryanarayanan 2012; Gross and McGoey 2015); the relation between knowledge and uncertainty (post-normal science, e.g., Funtowicz and Ravetz 1993; Mode 2 science, e.g., Nowotny et al. 2003); and public understanding of science, public communication of science and technology, and related fields (e.g., Bucchi and Trench 2008; Nisbet and Scheufele 2009; Groffman et al. 2010; McNeil 2013 and references therein). These studies are highly relevant, but in the interest of brevity we do not provide a comprehensive review of them here. Instead, we highlight complementary ideas that have emerged during our discussions over the past years that should be particularly interesting and accessible to natural scientists who form the primary target readership of this article.

In the next section, we provide a conceptual overview of knowledge in the dark with a focus on both laypeople and experts, where we will also clarify in which way this concept builds upon and extends existing terms, concepts, and frameworks. This section will be followed by reasons for knowledge in the dark in academia, while the final section will suggest ways forward to cope with this phenomenon.

Knowledge in the dark

Let us go back to the above-described conundrum that we are living in a time when data and information, and thus potential knowledge, keep accumulating, while the real knowledge of people does not keep up. What we call knowledge in the dark—or short: dark knowledge—is the gap between real and potential knowledge (Fig. 1.1). This gap can be seen as a lost opportunity and seems to have widened through time. It is a major challenge of our current era and particularly pronounced for inter- and transdisciplinary topics, as knowledge is often trapped in disciplinary silos and professions (Campbell 1969; Ungar 2008; Millgram 2015). At the same time, pivotal environmental, social, and economic challenges urgently need inter- and transdisciplinary solutions.

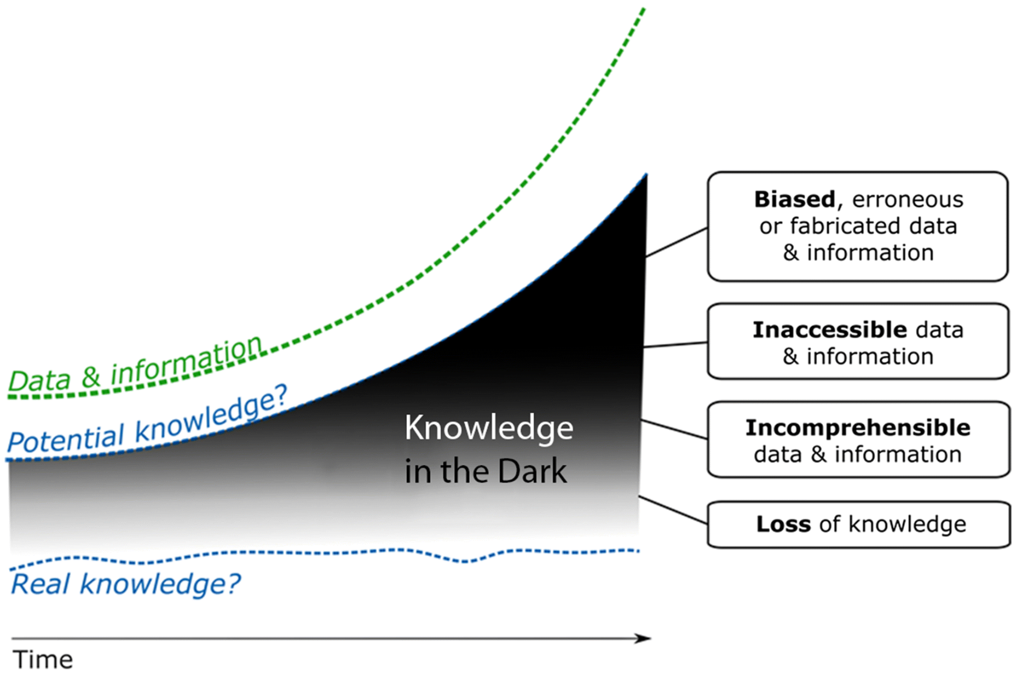

Figure 1.1 Left side: Knowledge in the dark is the gap between real and potential knowledge. The latter represents an idealized scenario assuming that knowledge increases if the amount of data and information increase (cf. Fig. 1.2). The size of the gap between real and potential knowledge is currently unknown and so are the shapes and absolute positions of the lines drawn. We thus added question marks in the graph. There is no y-axis, emphasizing that the graph cannot be quantitatively read. Instead, the relative positions of the lines to each other are important. The curve for potential knowledge is below the one for data and information, as it is not possible to translate all data and information into knowledge (e.g., Ackoff 1989; Rowley 2007). Right side: selected key reasons for knowledge in the dark.

Our use of the term dark knowledge was inspired by "dark matter" in physics and "dark diversity" in biodiversity research. The former is probably well-known to most readers, and the latter describes the gap between potential and actual biodiversity in a given region (Pärtel et al. 2011).

Table 1.1 Key terms and previous concepts in the context of knowledge in the dark, and how we define them here.

Term	Definition	Selected reference(s)
Dark knowledge	Short for **knowledge in the dark**	This article (Fig. 1.1)
Evidence	Data and information, either scientific or generated in other professions or domains, as well as experience of indigenous people or other local residents.	Wynne 1992; Funtowicz and Ravetz 1993; Kleinman and Suryanarayanan 2012
Ignorance	The lack of **knowledge**; includes **knowledge in the dark**. Please note that this colloquial meaning differs from how social scientists sometimes use ignorance: it can also mean knowledge about the limits of knowledge.	Gross 2007; http://wordnet.princeton.edu
Ignorance studies	Also known as agnotology. Social science field focusing on **ignorance**.	Proctor and Schiebinger 2008; Gross and McGoey 2015
Knowledge	Knowledge (includes understanding) requires the reflection and interpretation of data and information, i.e., it is based on **evidence** (following the knowledge pyramid). For instance, knowledge allows to better predict the consequences of important decisions and to act accordingly. We here focus on desirable knowledge, as humans do not want to know everything.	Ackoff 1989; Rowley 2007; Gigerenzer and Garcia-Retamero 2017
Knowledge-ignorance paradox	The general **knowledge** of individuals has not increased in the way that overall information and data have increased.	Naisbitt 1982; Ungar 2008
Knowledge in the dark	The gap between real and potential **knowledge**. It is limited to those dimensions of **ignorance** that humans (a) can in principle and (b) want to reduce (humans cannot and do not want to know everything).	Pinker 1997; Gigerenzer and Garcia-Retamero 2017; this article (Fig. 1.1)

Note: Bold text refers to other terms defined in the table.

The terms knowledge in the dark or dark knowledge have not yet been applied in the emerging social science field agnotology (Proctor and Schiebinger 2008); only ignorance (the lack of knowledge, cf. Table 1) has been widely used, however, with different meanings (see Gross 2007 for standard terms used in this field). It seems useful to discriminate the different dimensions of ignorance. Dark knowledge includes those dimensions of ignorance that can in principle be reduced. It does not include ignorance that cannot be reduced: we humans cannot know everything. In Pinker's (1997, p. 561) words: "We are organisms, not angels, and our minds are organs, not pipelines to truth. Our minds evolved by natural selection to solve problems that were life-and-death matters to our ancestors, not … to answer any question we are capable of asking." Similarly, we humans do not want to know everything (e.g., Gigerenzer and Garcia-Retamero 2017); hence, the concept of dark knowledge focuses on desirable knowledge.

Thus, dark knowledge is a particular part of ignorance for which a specific term (and definition) has been lacking thus far. Indeed, it is of high practical relevance, as it focuses on those dimensions of ignorance that humans both can (in principle) and want to reduce (Table 1). In this way, the concept might be of interest for researchers in the field of agnotology. It should also be useful for the fields of public understanding of science, public communication of science and technology, and related areas. Relevant works here have shown that engaging with the public, which includes an open dialogue between scientists and other stakeholders, is much more effective than a one-way communication effort from scientists to the public (e.g., engagement vs. deficit model; Nisbet and Scheufele 2009; Groffman et al. 2010; McNeil 2013; Smith et al. 2013). Dark knowledge can only be tackled thanks to such insights. Important measures in addition to engaging with the public are outlined in the section on ways forward. Some mechanisms leading to dark knowledge are related to uncertainty, which is key for post-normal science and Mode 2 science (Funtowicz and Ravetz 1993; Nowotny et al. 2003).

	Amount of data and information	Knowledge of … researchers and other experts in the same institution	researchers and other experts in the same discipline	researchers and other experts in a similar discipline	non-experts (i.e. the public)
Idealized scenario	↑	↑	↑	↑	↑
Biased, erroneous or fabricated data & information	↑	→↓[1]	↓[1]	↓[1]	↓[1]
Inaccessible data & information	↑	↑[2]	↑→[2]	↑→[2]	→[2]
Incomprehensible information	↑	↑[3]	↑[3]	↑→[3]	→[3]
Loss of knowledge	→[4]	Gone[4]	Gone[4]	↓[4]	↓[4]

Figure 1.2 How different key reasons underlying knowledge in the dark affect (i) the amount of data and information and (ii) real knowledge of different focal groups, in comparison to an idealized reference scenario assuming that knowledge increases if the amount of data and information increase (cf. potential knowledge in Fig. 1.1). The intensity of the effect on the knowledge of the different focal groups is indicated in grey where dark grey represents a strong effect (i.e., a large gap between potential and real knowledge), and light grey represents a weak effect (i.e., a narrow gap between potential and real knowledge). Note: [1]Researchers and other experts in the institution where data and information were generated might be aware of potential biases and errors in the data and information, hence they can ignore them in such cases, and their knowledge is not reduced by such data and information. Others will not be aware of biases and errors and will thus be misled, which reduces their knowledge on the topic. [2]Data and information are typically accessible for researchers and other experts in the institution where they were generated; for researchers and other experts in the same or a similar discipline, profession or knowledge domain, the data and information might be accessible (e.g., if their colleagues from the institution are willing to share them), but nonexperts have typically no access (an exception would be if the researchers producing the data and information follow an open science model). [3]Incomprehensibility is particularly severe for nonexperts, but might already affect researchers and experts from a similar discipline or profession than the one within which the data and information were generated. [4]The loss of knowledge is illustrated for the case of a discipline that disappeared where the knowledge of researchers and other experts in the discipline is gone; the knowledge of researchers in similar disciplines and of nonexperts is reduced as well, as they cannot benefit from the experts' knowledge anymore. The amount of data and information themselves are not reduced in this case, although of course they are not fully comprehensible anymore.

The concept of dark knowledge also highly benefits from other points put forward by social scientists, for example the importance of considering research biases (see below for details) or that science has no monopoly on evidence, as data and information stemming from outside of science can be crucial as well (Wynne 1992; Funtowicz and Ravetz 1993; Kleinman and Suryanarayanan 2012; Yeh 2016); further examples are provided below.

As scientists, we need to be aware of roadblocks for our endeavor to advance knowledge and focus on those we really can and want to remove. The dark knowledge concept may be helpful in this regard, particularly when we consider key mechanisms underlying dark knowledge—these are the roadblocks we should focus on.

We highlight four of these mechanisms here (Fig. 1.1, right). They are aligned with consecutive steps making up the process of knowledge production: how data and information are (*i*) produced or not, (*ii*) made available or not, (*iii*) are comprehensible or not, (*iv*) and are remembered or forgotten. The mechanisms differ in their effects on different focal groups, from (a) researchers and other experts in the institution where specific data and information have been generated, to researchers and other experts outside of this institution, but in the (b) same or a (c) similar discipline or profession, and to (d) nonexperts (Fig. 1.2). In explaining the mechanisms, we draw from findings across various disciplines, e.g., social sciences (including agnotology) or economics.

Biased, erroneous, or fabricated data and information

First, dark knowledge can be caused by biased, erroneous, or fabricated data and information. For instance, the type of data and information produced can be influenced by financial or sociopolitical interests (Kitcher 2011). When "high-stakes" metrics are applied, which assess the performance of people and at the same time strongly influence their future career, there are incentives to "cream" or fabricate the data used for calculating these metrics; creaming is a strategy to maximize a metric by "excluding cases where success is more difficult to achieve" (Muller 2018, p. 24). For example, schools in Florida and Texas have been shown to reclassify weak students as disabled, thus excluding them from calculating average student achievement levels (this is a high-stakes metric for teachers and school principals; Muller 2018, p. 93).

The production of biased, erroneous, or fabricated data and information can be combined with systematic disinformation leading to doubt and uncertainty. This was, for example, done by the tobacco industry, which successfully distorted the public understanding of tobacco health effects (Oreskes and Conway 2010). Similar strategies have been applied in the context of climate change (Oreskes and Conway 2010), by the sugar industry (Kearns et al. 2015), and by pharmaceutical companies that hide information about their products from the public (Kreiß 2015; Crouch 2016). False information can now be actively spread with so-called bots, i.e., software applications running automated tasks (Howard and Kollanyi 2016; Kollanyi et al. 2016).

Producing biased, erroneous, or fabricated data and information leads, of course, to an increase in the amount of data and information (Fig. 1.2). Under ideal circumstances, such an increase would augment the amount of knowledge (see idealized line "potential knowledge" in Fig. 1.1, and idealized scenario in Fig. 1.2). In the case of biased, erroneous, or fabricated data and information, however, such data and information reduce instead of increase knowledge (Fig. 1.2). Only researchers or other experts from the institution that generated the data and information might be aware of critical errors;

other people are not usually aware of them, thus their understanding of the topic will be severely hampered (Fig. 1.2).

Inaccessible data and information

The second reason for dark knowledge is inaccessibility of data and information. For example, findings of secret services, the military, and industry are frequently inaccessible to the public and thus do not increase public knowledge (Resnik 2006; Proctor and Schiebinger 2008; Bozeman and Youtie 2017). Looking at Organisation for Economic Co-operation and Development (OECD) countries (for which more comprehensive and comparable data are available than for other countries), expenditures into research and development by the industry and military combined are about three times higher than governmental expenditures for civil research (OECD 2017). Industry investments are particularly high, and these have been increasing through time, whereas governmental expenditures are—in relative gross domestic product terms (GDP)—lower today than they were in the 1980s (Fig. 1.3). This trend can be called privatization of knowledge. In 2015, Volkswagen had the highest research and development budget of all companies worldwide, which was higher than the United Kingdom's governmental expenditures for civil research (Fig. S1.1). Samsung also trumped the United Kingdom's budget, and Intel and Microsoft trumped Italy's budget.

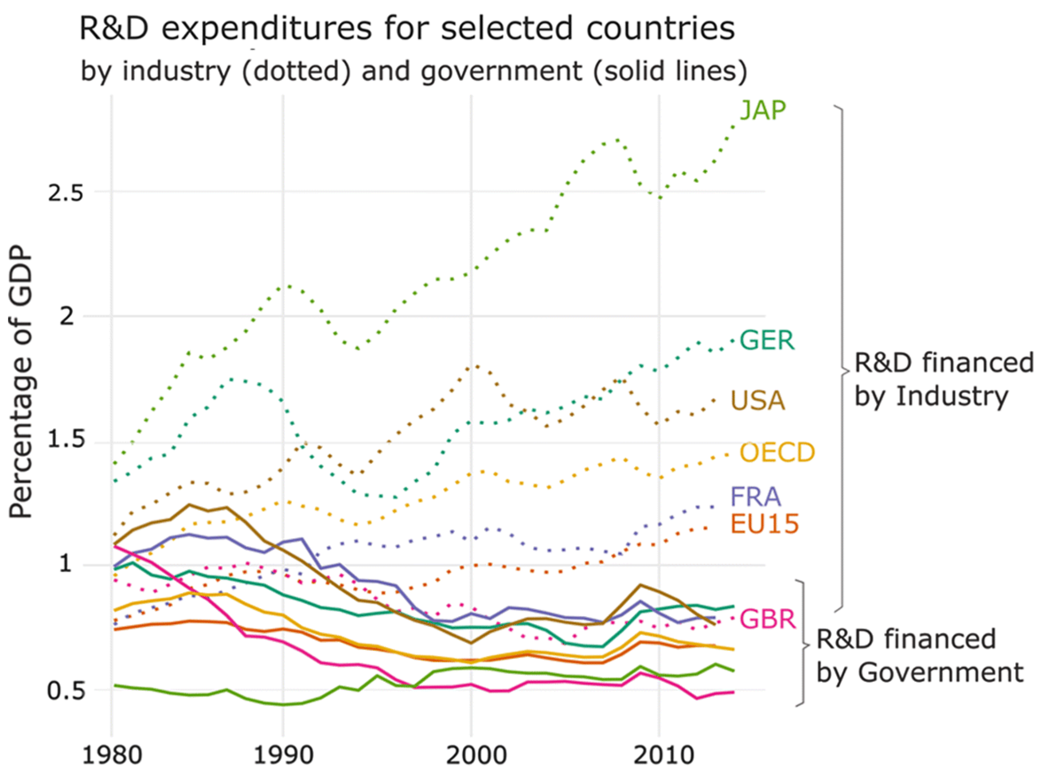

Figure 1.3 Temporal development of relative (as percentage of GDP) industrial and governmental expenditures into R&D in several countries and groups of countries (data from OECD 2017). GDP, gross domestic product; R&D, research and development; JAP, Japan; GER, Germany; USA, United States of America; OECD, Organisation for Economic Co-operation and Development; FRA, France; EU15, the 15 member countries in the European Union prior to 1 May 2004; GBR, Great Britain.

Of course, not all research results from industry, the military or secret services remain hidden from the public. This is, for example, illustrated by the American Department of Defense Congressionally

Directed Medical Research Programs (http://cdmrp.army.mil), which originated in 1992 with a focus on breast cancer research and now includes other medical research areas that are not primarily of military interest, but benefit the general public (Young-McCaughan et al. 2002). Nonetheless, a large fraction of the research results from industry, the military, or secret services remains hidden. Companies intend to become economic leaders in their specific domain, and military supports geopolitical power and protects national interests (see also Resnik 2006). Thus, the results that are made public are often biased or selected, for instance to boost sales (e.g., for pharmaceutical products), to avoid legal restrictions (e.g., for tobacco or sugar) or to shape geopolitical decisions (Hartnett and Stengrim 2004; Oreskes and Conway 2010; Kearns et al. 2015; Kreiß 2015; Crouch 2016).

Incomprehensible data and information

The third reason for dark knowledge is that much information is incomprehensible. Even if information is accessible in principle, it can frequently only be understood by researchers and experts from the same discipline or profession, whereas most people find it incomprehensible, for instance, because they do not understand the logic underlying the data or information, or the technical language in which these are outlined (Fig. 1.2; Millgram 2015; Plavén-Sigray et al. 2017).

Loss of knowledge

Fourth and finally, previous knowledge can be lost. This is, for example, the case when professions or scientific disciplines shrink (e.g., if university positions for this discipline are cut) or completely disappear. Although the literature and other information produced by such disciplines still exist, there is (almost) no one left to make this information fully comprehensible and usable. This mechanism underlying dark knowledge is thus similar to the third; however, there are (almost) no experts anymore who could tap into the literature and information and teach non-experts. Consequently, some of the knowledge that had been produced by these dying disciplines and professions is forever lost. If languages disappear, any related information is similarly lost; and data and information stored in disappearing technologies will also be lost if not transferred to modern technologies. For example, information stored on floppy disks is nowadays increasingly hard to access.

While we outlined general reasons for dark knowledge in this section, we will specify them for academia in the next section and then suggest ways to tackle them. The insights we offer may be transferable to other professions and knowledge domains. Since dark knowledge is a broader societal phenomenon and challenge, we encourage others to join us in advancing the concept of dark knowledge in the future and to apply it in various disciplines and professions.

Knowledge in the dark in academia

We highlight four reasons underlying dark knowledge in academia: loss of academic freedom, research biases, lack of reproducibility, and the Scientific tower of Babel (Fig. 1.4).

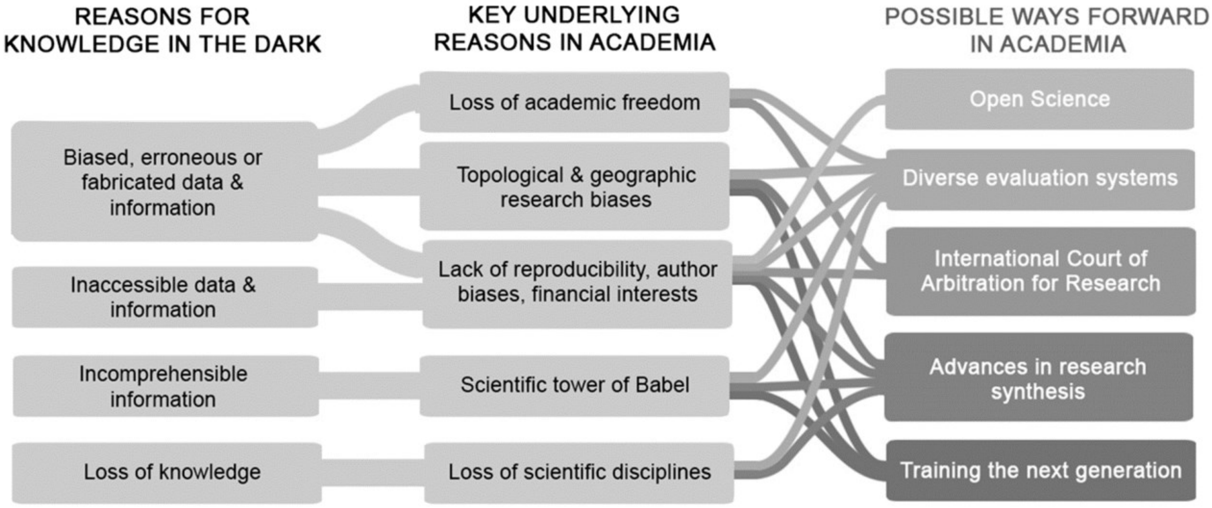

Figure 1.4 Key underlying reasons for knowledge in the dark in academia and possible ways forward. The general dimensions of knowledge in the dark (left section, from Fig. 1.1) are related to key challenges in academia (middle section, linkages are indicated by connecting lines). Possible ways forward to tackle each of these challenges are listed in the right section. Please note that the challenge "Loss of scientific disciplines" is not discussed in detail in the text.

Loss of academic freedom

Academic freedom is pivotal for the functioning of democratic societies, because independent and evidence-based knowledge is necessary if we are to cope with the grand challenges our societies are facing. In reality, however, individual researchers and institutions are not always free in what they investigate and teach, even in democratic societies. Dramatic examples, collected by the Scholars at Risk Network at http://monitoring.academicfreedom.info, include researchers who have lost their position or were prosecuted or imprisoned for political or other reasons.

A more subtle reason for a lack of academic freedom is the overuse of quantitative performance indicators such as the *h*-index, number of publications (in high-impact journals), or amount of grant money obtained. Such metrics have become increasingly popular in evaluating researchers and research institutions (e.g., Weingart 2005; Lawrence 2007; Fischer et al. 2012; Kaushal and Jeschke 2013; Arlinghaus 2014; Hicks et al. 2015; Jeschke et al. 2016; see Muller 2018 for a broader treatment of the topic beyond academia). As a result, researchers focus on topics for which funding is available and that are likely to be published in high-impact journals. This is particularly true if base funding is lacking or if researchers do not have a permanent position. Even in a wealthy country such as Germany, the relative proportion of permanent staff in science and arts at universities was only 17% in 2014 (Buschle and Hähnel 2016).

Moreover, third-party funding is partly steered through politically or economically motivated funding calls, frequently influenced by lobbyists (Kreiß 2015). In addition, private enterprises may exert influence on public research institutions through sponsoring professorships and infrastructure (Kreiß 2015; Crouch 2016), thus potentially further confining academic freedom, independence, and diversity.

Academic research biases

The Matthew effect (Merton 1968) describes the phenomenon that established scientists receive disproportionate credit, whereas lesser known scientists get little credit for their contributions. This "the rich get richer" phenomenon has been corroborated by analyses of scientific collaboration and citation networks (Perc 2014). It favors mainstream research while other topics are being ignored, particularly in a competitive environment with few permanent positions ("undone science", e.g., Kleinman and Suryanarayanan 2012). Countless examples for topical research biases can be found across disciplines. For instance, much of the research on global change and biodiversity loss has focused on climate change, leaving other critical topics, such as effects of synthetic chemicals or the interaction of biodiversity stressors, poorly studied (Bernhardt et al. 2017; Mazor et al. 2018). Kleinman and Suryanarayanan (2012) used the example of the colony collapse disorder in bees to illustrate that the way research topics are addressed is often biased towards reductionist approaches that ignore the real world's complexity. Another example comes from economics which is still largely focused on the neoclassical model, whereas approaches such as ecological economics have remained underexplored (Van den Berg 2014).

Similarly, strong geographic biases can be found across research disciplines, since most research is typically concentrated in affluent countries, particularly in North America and Europe. This has direct and severe consequences for human health in other countries, as research on diseases limited to these regions is critically neglected (Kitcher 2011). Biodiversity research also has strong geographic biases towards North America and Europe, even though biodiversity hotspots are primarily located in the Global South (Bellard and Jeschke 2016; Wilson et al. 2016; Tydecks et al. 2018).

Lack of reproducibility, author biases, financial interests

The first report of the Open Science Collaboration, which has performed extensive replicates of earlier studies in psychology, reported an average reproducibility of only 39% for 97 experiments (Open Science Collaboration 2015; see also Prinz et al. 2011; Ioannidis 2012). A similar phenomenon—which has primarily been reported in psychology, but also in other disciplines such as medicine and biology—is that the strength of evidence (e.g., on the efficacy of a given drug or the empirical support for a scientific hypothesis) frequently declines over time ("decline effect"; Lehrer 2010; Schooler 2011; Jeschke et al. 2012).

Low reproducibility and decline effects can have several underlying reasons. Brian Nosek provides an example: "We interpret observations to fit a particular idea; ... we have already made the decision about what to do or to think, and our "explanation" of our reasoning is really a justification for doing what we wanted to do—or to believe—anyway" (quoted from Ball 2015). Such motivated reasoning is interlinked with temporary fashions in science. For instance, scientists love new hypotheses, as they promise to move a given research field forward. Scientists thus frequently want to find supporting evidence for a new hypothesis, particularly if it was proposed by themselves. Furthermore, studies supporting a new hypothesis are easier to publish than those supporting established hypotheses. For the latter, the opposite tends to be true, as it has become more interesting to publish contradictory evidence. Such publication biases can thus lead to a decline in empirical support for a given hypothesis over time (Jeschke et al. 2012).

Financial interests may also reduce reproducibility, cause decline effects, and prevent access to data and information. For example, there is evidence that the pharmaceutical, tobacco, and sugar industries have strategically manipulated data and information about their products, particularly when they are brand new and need to be sold on the market to balance development costs (Lexchin et al. 2003; Oreskes and Conway 2010; Lexchin 2012; Kearns et al. 2015; Kreiß 2015; Crouch 2016).

The Scientific tower of Babel

Members of scientific disciplines use particular technical terminology – "jargon" – which is hardly understandable by nonspecialists. Some technical terms are clearly identifiable as jargon, especially if they do not exist outside of the discipline. Other technical terms cannot be readily identified, as the same terms exist in everyday language, yet with another meaning, leading to misunderstandings. For example, we are using the term ignorance here as in everyday language, meaning "the lack of knowledge" (e.g., http://wordnet.princeton.edu); however, when social scientists use the technical term ignorance, they frequently mean "knowledge about the limits of knowledge" (Gross 2007, p. 751).

Technical terms are often helpful in accurately and succinctly writing scientific papers. This is particularly true if the target readership is within the boundaries of the same discipline. Jargon can thus reduce dark knowledge within disciplines; however, it hampers inter- and transdisciplinary work. Analyzing 709 577 abstracts published between 1881 and 2015 from 123 scientific journals, Plavén-Sigray et al. (2017) showed that the use of jargon in scientific texts has increased with time, and concurrently the readability of scientific texts has decreased. A total of 22% of scientific abstracts published in 2015 cannot even be considered readable by graduates from English-language colleges.

The rise of technical terminology is one key reason for the knowledge-ignorance paradox outlined above. Today, people have a high level of specialized knowledge but a relatively low level of general understanding. Knowledge becomes increasingly trapped in disciplines, and people outside a given discipline may become "logical aliens", i.e., they do not understand the logic and standards of a specific discipline: "if you are an academic employed by a university, and you want to meet a logical alien, you don't need to walk any further than the other end of the hall – or at most, to an adjacent building on your very own campus" (Millgram 2015, p. 33).

Ways forward in academia

Dark knowledge is a challenge for democratic societies, as these need citizens who can make informed decisions. If people are ill-informed or no longer care about the truth, democracy is at risk and science will basically become irrelevant (Kitcher 2011). To avoid such a pessimistic scenario, what are possible ways forward? We outline five approaches below (summarized in Fig. 1.4).

In these approaches, we do not explicitly mention public engagement of scientists, although it is implicitly included in some of our suggested solutions. Engaging with the public, including an open and active dialogue with stakeholders, is a key task of scientists, and we refer interested readers to publications where these issues have been treated in detail (e.g., Bucchi and Trench 2008; Nisbet and Scheufele 2009; Groffman et al. 2010; McNeil 2013; Smith et al. 2013).

Open science

Key components of open science are open access to scientific publications, open data, open source and open methodology (Kraker et al. 2011). One of its initiatives aims at FAIR – findable, accessible, interoperable, and reusable – data (Wilkinson et al. 2016). Thus, open science directly tackles one of the key reasons underlying dark knowledge, the inaccessibility of data and information. Related to the more specific challenges in academia outlined in the previous section, open science has great potential in improving research reproducibility (e.g., through open methodology) and reducing biases in which data and information can be found, accessed, and reused for research synthesis (e.g., through the FAIR data principles). Open science is clearly an important step forward and helps to build trust into research.

However, there are also important challenges. First, the public availability of data such as health records, behavioral data, or genomic sequencing information poses a threat to citizens on the part of private companies and (future) governments alike. There has been much research on the re-identification of anonymized data, and many examples of past misuse of such data sets exist (Ohm 2009; O'Doherty et al. 2016). In ecology and conservation biology, information about the location of individuals belonging to endangered or newly described rare species can be used by poachers to find them (Lindenmayer and Scheele 2017). Another potential negative effect is that too many nature lovers will try to find particular animals or plants, with possible negative consequences for the whole ecosystem: too many people may destroy the habitat, and harm the species inhabiting it (Lindenmayer and Scheele 2017).

Second, a thorough discussion of how to deal with private companies using data sets of public research institutions is needed. Open public databases are paid by taxpayers and may be an important source of wealth for private companies, which themselves do not typically share their data with the public; when they do, these data are often biased (see above). In other words, open public databases essentially subsidize certain private companies (cf. Mirowski 2018). It is clear that an open science approach alone will not solve the challenges underlying dark knowledge; thus additional approaches are needed (see below).

Diverse evaluation systems

There is an increasing need to revise the performance metrics of researchers and institutions. As briefly outlined above, the application of few quantitative metrics, focusing on money, publications, and citations, constrains academic freedom and favors mainstream rather than outside-of-the-box research, thus promoting research biases (e.g., the Matthew effect) and incentives for authors to predominantly publish what is currently fashionable in science, whereas other research results might remain unpublished (i.e., author publication biases). Furthermore, it may impede inter- or transdisciplinary research, thus contributing to the challenge of the Scientific tower of Babel (cf. Campbell 1969), and even threaten entire disciplines, in which financial interests, overall number of publications, and citations are low.

There is a clear need to diversify evaluation strategies. Researchers should not always be assessed using the same set of metrics, but different metrics should be applied depending on which type of researcher and which skill is needed at an institution (Weingart 2005; Arlinghaus 2014; Hicks et al.

2015; Jeschke et al. 2016). Otherwise, players (i.e., researchers and heads of institutions) focus on "gaming" metrics rather than on their research. Indeed, maximizing metrics has become an end in itself for many researchers, which is not surprising when these metrics are continuously applied for their evaluation (Lawrence 2007; Hicks et al. 2015). For example, many researchers today primarily think about how they can acquire grant money and how they can get into a high-impact journal. If different metrics are applied by different evaluation committees, researchers may be less worried about maximizing certain metrics, as they do not know which metrics will be used in their case. They can then instead focus on actually creating knowledge.

An international court of arbitration for research

Another promising way forward would be to use existing codes of ethics and responsible conduct in science and research (e.g., www.esa.org/esa/about/governance/esa-code-of-ethics; www.icmje.org/recommendations) and turn parts of them into binding rules (cf. Kaushal and Jeschke 2013; Alberts et al. 2015). Any violations of these rules could be dealt with by an international Court of Arbitration for Research (CARe). A similar system exists for sports, where disputes (e.g., doping) can be settled at the international Court of Arbitration for Sport (CAS), which has three courts (in Lausanne, New York, and Sydney). Perhaps it would be worth trying to have at least one for research as well, either in the form of a court or a similar type of entity, such as an international agency of research integrity.

Such an international entity could serve three functions. First, it could assist in setting standards and stimulate a cross-disciplinary discussion of what constitutes scientific misconduct and what does not (cf. Neuroskeptic 2012). Second, for those few countries that have a similar national-level entity (e.g., Austria or Sweden, www.oeawi.at, www.epn.se/en/start/expert-group-for-misconduct-in-research-at-the-central-ethical-review-boardstar), an international entity could handle revisions of cases that are not resolved nationally. Third, it could ensure independent investigations of judgements about possible cases of misconduct. Such independence is not guaranteed if cases are investigated by the research institutions where they occurred or by journals where a study was published. Also, misconduct by scientists often spans across institutions, countries, and journals. After a group of researchers investigated scientific misconduct on the part of the Japanese bone researcher Yoshihoro Sato over a period of several years, focusing on 33 of his more than 200 papers, they concluded that "investigations of this scale should not be handled by journals or institutions" (Kupferschmidt 2018, p. 639).

Of the challenges outlined above, such a court would mainly tackle (*i*) loss of academic freedom and (*ii*) lack of reproducibility, financial interests. Standards and rules can be discussed and implemented to clarify what constitutes misconduct delimiting academic freedom, and potential cases can be handled at the court. Similarly, cases of potential misconduct can be handled that changed the outcome of studies, for example data manipulation, thus making them irreproducible. As outlined above, such misconduct is sometimes driven by financial interests. Of course, the effectiveness of such a court in preventing future cases of misconduct will depend on many factors—a key aspect will be its real power to penalize misconduct.

Advances in research synthesis

The primary goal of research synthesis is to gather, process, and present complex data and information, so that they become more accessible. Indeed, we argue that advances in research synthesis are critical for tackling dark knowledge. For example, systematic reviews and meta-analyses such as those performed by Cochrane (www.cochrane.org) have proven important in synthesizing data and information. However, we need to take further steps (Nakagawa et al. 2019). A promising path forward is an atlas or map of knowledge that will allow people to see where certain research is situated and which lines of research and concepts are (dis-)similar to each other (Bollen et al. 2009; Börner 2010, 2015; Kitcher 2011; Jeschke 2014). Such a map of knowledge will allow nonspecialists to better understand a given discipline and more quickly acquire its knowledge, thus tackling the challenge of the Scientific tower of Babel. Advanced synthesis tools also reveal how data and information delivered by various research fields are important for tackling ecological, social, and economic challenges; they clearly show the need to keep such research fields alive that might be threatened in their existence.

Furthermore, knowledge maps and other synthesis tools can only be successfully developed if scientists of several disciplines and artists work together. For instance, information technologists and statisticians should not only work with experts on the focal research questions, but also with artists or designers who will make sure that the final product (e.g., an online portal) is aesthetically sound and user-friendly. Fortunately, such joint work on advanced research synthesis is increasing, for instance work on visual analytics (Keim et al. 2010), sonification which turns data into sound (Hermann et al. 2011), or the above-mentioned advances in creating knowledge maps (https://hi-knowledge.org). Advanced tools for research synthesis can also help uncover and correct for topological, geographic, or author biases, e.g., by considering potential interests of the funders of a study.

Training the next generation of researchers

Targeted training can also help reduce dark knowledge. Teaching and knowledge centers for data experts and data managers are important (e.g., https://cds.nyu.edu, www.monash.edu/it/our-research/research-centres-and-labs/centre-for-data-science), and we need interdisciplinary training that allows members of different disciplines to talk to and understand each other (Millgram 2015), see for example Campbell's (1969) fish-scale model.

Additional training is required in critically evaluating information and reducing questionable research practices. Specifically, courses could include analyzing different information sources and teaching methods for distinguishing science from pseudoscience (Boudry and Braeckman 2012). They should address questions such as: What constitutes or should constitute our evidence base? What is the role of evidence-based knowledge in society and political decision-making? For example, the course "Calling Bulls**t: Data Reasoning in a Digital World" by Bergstrom and West at the University of Washington, which started in 2017, is a valuable way forward. Its aim is to teach students "how to think critically about the data and models that constitute evidence in the social and natural sciences" (http://callingbulls**t.org).

Training of future researchers should also build awareness that scientists are not immune to biases that influence their work. A profound understanding of what differentiates responsible research from questionable research practices is necessary (Neuroskeptic 2012; Sijtsma 2016). Questionable rearch practices do not necessarily imply intentional fraud but can include "*p*-hacking", as when one repeats an experiment until the desired statistical significance is reached or one ignores outliers in statistical analyses (Neuroskeptic 2012; Head et al. 2015). Such practices of "data cooking" are unfortunately widespread (Fanelli 2009). Importantly, such targeted training needs to benefit future researchers across the globe.

Conclusions

To tackle the challenge of dark knowledge, we need to develop and implement an array of tools. Some of these tools were outlined above with a focus on academia. Additional tools that, for example, increase public engagement and participation in science are clearly needed within and outside of academia to avoid an age of ignorance.

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Chapter 2 | Hypotheses in urban ecology: building a common knowledge base

Currently under revision in Biological Reviews: Sophie Lokatis, Jonathan M. Jeschke, Maud Bernard-Verdier, Sascha Buchholz, Hans-Peter Grossart, Frank Havemann, Franz Hölker, Yuval Itescu, Ingo Kowarik, Stephanie Kramer-Schadt, Camille L. Musseau, Aimara Planillo, Conrad Schittko, Tanja M. Straka, Tina Heger. Hypotheses in urban ecology: building a common knowledge base.

Abstract

Urban ecology is a rapidly growing research field that has to keep pace with the pressing need to tackle the sustainability crisis. As an inherently multi-disciplinary field with close ties to practitioners and administrators, research synthesis and knowledge transfer between those different stakeholders are crucial. Knowledge maps can enhance knowledge transfer and provide orientation to researchers as well as practitioners. A promising option for developing such knowledge maps is to create hypothesis networks, which structure existing hypotheses and help aggregating them according to topics and research aims. Here, we identify 62 research hypotheses used in urban ecology and link them in such a network. Our network clusters hypotheses in urban ecology into four distinct themes: (i) *Urban species traits & evolution*, *(ii) Urban communities*, (iii) *Urban habitats* and (iv) *Urban ecosystems*. We discuss the limitations and potentials of this approach. All information is openly provided as part of an extendable Wikidata project, and we invite researchers, practitioners and others interested in urban ecology to contribute. The hypothesis network and the respective Wikidata project form a first step towards a knowledge base for urban ecology, which can now be expanded and curated to the benefit of both practioners and researchers.

Keywords

Conceptual network, ecological theory, hypotheses in urban ecology, knowledge visualization, map of science, research synthesis, Wikidata

Introduction

> *„to truly advance the discipline of urban ecology requires the creation of new hypotheses and the identification of confirmed generalizations"* Mark McDonnell, History of Urban ecology, 2011, p. 12

Urban ecology is a multifaceted research field that ties together research traditions and methods from a wide range of backgrounds, settings and disciplines. Over the past century, it has been adopted and expanded by researchers from fields as diverse as the social sciences, natural sciences and engineering (Marzluff *et al.*, 2011; McDonnell & Niemelä, 2011; Weiland & Richter, 2011; Wu 2014).

While urban ecology used to be underrepresented in textbooks and journals of ecology (Forman 2016), it meanwhile has become a key research field in tackling the sustainability crisis (Rosenzweig *et al.*, 2010; Sachs *et al.*, 2019; Spiliotopoulou & Roseland, 2020; Tanner *et al.*, 2014). A number of journals cover the intersection of ecology with urban planning, urban biodiversity conservation and urban socio-economy, such as *Landscape and Urban Planning* (1974), *Urban Ecosystems* (1997), *Urban Forestry and Urban Greening* (2002), and *Journal of Urban Ecology* (2015). Urban systems are already dominating resource consumption, with 60-80% of the natural resource consumption happening in cities worldwide (Peter & Swilling, 2012; UN-Habitat, 2017), and substantially impacting every other ecosystem on the globe. While the proportion of humans living in cities is projected to rise from 55% today to more than 2/3 by the middle of this century, resource consumption in areas of urban sprawl is increasing even more strongly (Economic & Affairs, 2018; UN-Habitat 2020).

Urban ecology has different meanings to different researchers and stakeholders, a circumstance that is rooted in the history of the field, the unstandardized use of the term 'urban' (McIntyre, Knowles-Yanez & Hope, 2008; MacGregor-Fors, 2011; McDonnell & Hahs, 2008; Sukopp, 2008) and different meanings of the term 'ecology' (Schwarz & Jax, 2011). Urban ecology has been divided into a solution-oriented branch with a research agenda to make cities more livable and sustainable from the perspective of humans, focusing, e.g., on nature-based solutions and green infrastructure; and a natural-science branch that studies the natural world within cities, including environmental, biological, evolutionary and ecological patterns and processes, and treating human influences as ecological factors (Sukopp, 1998). Both branches are interdisciplinary, the first one with a focus on urban planning, the second one taking the perspective of natural scienists. They have partly been developed in concert, with the Berlin School which provides an example for linking ecological studies with approaches to conserve and develop cities for the benefit of humans (see Kowarik, 2020).

A framework introduced by Grimm *et al.* (2000) differentiates between ecology *of* cities and ecology *in* cities. Here, ecology in cities focuses on the distribution, abundance and interactions of non-human populations in the context of the diverse influences and impacts that urbanization poses on them (Grimm *et al.*, 2000). The ecology of cities has a broader scope: it integrates ecology in cities with research from a social and environmental science perspective, with the aim of studying and understanding cities as ecosystems from an interdisciplinary perspective, including how they "process energy or matter relative to their surroundings" (p. 574). Going even further in developing the urban ecology framework, a "science of cities" has been envisioned by McPhearson and colleagues to:

> *"motivate new and advanced cross-city comparative ecology, to develop more unified conceptual frameworks to advance urban ecology theory, and to synthesize core urban ecology research principles to guide future research in the field" (McPhearson et al., 2016b).*

What researchers mean by urban ecology tends to be shaped by their disciplinary background and the research school they come from (Dooling, Graybill & Greve, 2007). It is a common narrative that urban ecology in Europe focused on what Grimm *et al.* (2000) described as ecology *in* cities, while urban ecology in the anglophone literature was shaped by the sociological adaptation of the term "ecology" to urban settings by the Chicago School of urban ecology in the 1920s (Wu, 2014) , adopting an ecosystem-centered perspective with a focus on humans as key agents from the start (ecology *of* cities). Yet, this view is at least in part the result of barriers in communication. For example, there is a vast amount of urban-wildlife literature in the US (Magle *et al.*, 2012) that even though not explicitly termed urban ecology can be viewed as ecology *in* cities; and there is the holistic ecosystem-centered research in Europe put forward in the late 1960s and culminating in the meticulous analyses of ecosystem flows of the metropolitan region of Brussels (Danneels, 2018; Kowarik, 2020) that can certainly be regarded as ecology *of* cities. International exchange between researchers from different schools of urban ecologiy grew stronger in the 1990s, along with important research schools arising around the globe, with a particular emphasis on research schools in Asia and Australia. Nowadays, research schools from all continents are collaborating with each other (Breuste & Qureshi, 2011), with collaborations spanning continents (e.g. UWIN, the Urban Wildlife Information Network; CURT, the Comparative Urban Research Training network; GLUSEEN, the Global Urban Soil Ecological Education Network) and barriers in communication being less of an issue. Albeit not a new approach (e.g. Stearns & Montag, 1972; Sukopp *et al.*, 1995), researchers all over the world now focus increasingly on combining natural-science urban ecology and solution-focused urban ecology, since a combined, integrative perspective is needed to tackle omnipresent challenges, such as building sustainable cities and conserving biodiversity also outside of nature reserves (Collins *et al.*, 2000; Ramadier, 2004; Wolfram, Frantzeskaki & Maschmeyer, 2016).

However, new barriers to knowledge exchange arise from the increasingly overwhelming amount of research findings being published each year. While research on urban systems is growing rapidly (Bai *et al.*, 2018; Wolfram *et al.*, 2016), the pace of urban growth and the urgency of acting fast demand more intuitive syntheses tools that provide a quick orientation to researchers within and across disciplines, and that enable dynamic, community-based evidence assessment. A rapid extension in literature and data is indicative of urban ecology being a thriving research field. However, this does not automatically lead to a rapid increase in knowledge and understanding (Jeschke *et al.*, 2019). In fact, research in such rapidly expanding fields can become "relatively ineffective and inefficient, as existing evidence is often not found, collaboration opportunities are missed, and research is too often conducted in pursuit of dead ends" (Jeschke *et al.*, 2021). A possible way forward is to create maps of research questions and hypotheses that visually structure complex research fields and can thus guide scientists, policymakers, science writers and others interested in the research field. For the discipline of invasion biology, such conceptual maps were developed by Enders *et al.* (2018, 2020) which were combined with the hierarchy-of-hypotheses approach (Jeschke & Heger, 2018; Heger *et al.*, 2021) to create interactive, zoomable maps of the research field (see http://www.hi-knowledge.org).

Our aim here is to take first steps towards a knowledge base for urban ecology. Specifically, we provide (a) an overview of key hypotheses in the research field and (b) a suggestion for structuring them in a network. While we do not consciously limit ourselves to one of the above-mentioned research schools or branches, we are all researchers based in Germany with a focus on the natural-science aspects of urban ecology. The overview of key hypotheses provided here thus focuses on hypotheses related to the distribution, abundance or interactions of non-human populations in the context of urbanisation. We specifically searched for ecological hypotheses formulated in an urban context. Additionally, we consider ecological hypotheses that have not been developed specifically for urban settings, but have been regularly applied in an urban context, including those from general ecological theory. After presenting and discussing our list and network of hypotheses in urban ecology, we propose and discuss steps towards a community-curated knowledge base for urban ecology, and invite researchers to contribute other relevant hypotheses, thus building a growing and evidence-linked map of urban ecology.

Methods

Collecting Hypotheses

We compiled hypotheses from urban ecology based on expert knowledge within our group and via iterative literature searches in the Web of Science and Google Scholar, including back-tracing literature cited within key references. We cross-compared the identified hypotheses also with the studies by Parris (2018), Forman (2016) and Cadenasso and Pickett (2008; 2017), who previously provided collections of theories, hypotheses and/or principles in urban ecology. Our initial approach was to use a consistent and replicable search string in the Web of Science, but as the term *hypothesis* is (i) often not spelled out when hypotheses are formulated or (ii) is used for statistical- and null-hypothesis testing, this approach was abandoned.

A basic methodological question is what exactly is regarded as a 'hypothesis' in this study. Betts *et al.* (2021) define a hypothesis as "an explanation for an observed phenomenon", and a research question as "a statement about a phenomenon that also includes the potential mechanism or cause of that phenomenon." Scientists often tend to use the term "hypothesis" in a broader way, for ideas or predicted outcomes that can be tested and/or discussed. We therefore decided to define a hypothesis as "an assumption that is based on a formalized or nonformalized theoretical model of the real world and can deliver one or more testable predictions" (Heger *et al.* 2021; after Giere *et al.* 2005). Further, an important question is whether the prediction of a pattern is regarded as hypothesis as well. According to Pickett (2007, Ecological Understanding), it might be. Other authors have a much stricter view and emphasize the explanatory role of hypotheses, stating that predicting a pattern does not provide an explanation (Betts *et al.*, 2021). We here explicitly include non-explanatory, descriptive hypotheses, and suggest that they also contribute to ecological knowledge about cities. The identification of patterns can also lead to valuable predictions and stimulate further research on underlying causal relationships. For example, based on the hypothesis that "urbanization favors non-migratory species", predictions can be derived on how urbanization could drive the loss, or gain, of species with or without migratory behavior.

All collected hypotheses are provided in Table 2.1 (in addition, an extended version of this table is provided in the Appendix, Table S2.1) and as part of an open Wikidata project (wikidata.org/wiki/Wikidata:WikiProject_Ecology/Task_Force_Urban_Ecology), along with a definition and additional information on key literature sources. Where, to our knowledge, no accepted name for a given hypothesis currently exists, we gave it a name. The wiki is a living project and can be adjusted at any time to include more information in the future, e.g. on taxonomic groups hypotheses have been applied to, empirical support of the hypotheses and respective sub-hypotheses.

We discriminate two types of hypotheses based on their content: *explanatory hypotheses* (also *termed research hypotheses*) explicitly refer to a causal mechanism or explanation, while *descriptive hypotheses* are descriptive statements or predictions about expected results (see Betts *et al.*, 2021). Further, we differentiate between (a) hypotheses that are specific for urban environments (i.e. they can only be tested in an urban environment) and have not been derived from more general ecological hypotheses, thus are unique to research in urban ecology; (b) "urbanized" hypotheses that exist in a more general or analogous form outside of urban ecology, but have been adapted to urban systems; and (c) general hypotheses from another research field that have not been specifically adapted to urban systems but are nonetheless highly relevant there (e.g., the street barrier effect, as the high density of streets in cities lead to strong constrains on species' movement).

To structure hypotheses, we noted each hypothesis' focal entity or topic (i.e. whether it addresses species traits, trait evolution, niche shift, species abundance, communities, species interactions, habitat quality, or ecosystem functioning and services), and the hypothesized drivers of change (artificial light at night; anthropogenic noise, climatic change (e.g. heat islands), chemical pollution, nutrients, fragmentation, habitat loss and isolation, invasive alien species and other novel organisms (*sensu* Jeschke *et al.*, 2013), novel community composition and structure, and human presence and intervention). The decision about which attribute to assign to each hypothesis was reached by a consensus approach: each hypothesis was assessed by two authors. If there was no agreement, a third author reassessed the respective hypotheses and consensus was reached via in-depth discussion among these three authors. The attributes assigned in this way were then shared with all other authors for feedback and final consensus.

Network and cluster analysis

The matrix of hypotheses and attributes was used to create a bipartite network; here, every hypothesis is linked to attributes and vice versa, and no information is lost, as opposed to monopartite networks that use dissimilarity matrices of the interconnected nodes and not the connection between hypotheses and attributes themselves.

Typically, clusters are created based on the similarity or connectivity of nodes, here hypotheses and attributes. Nodes are assigned to specific clusters, and each node is attributed to exactly one cluster.

Here, we created a set of 24 clusters based on four regularly used node-based algorithms from R iGraph (GN, Fastgreedy, Walktrap and leading eigenvector). All four algorithms evaluate network partition into disjoint node communities or clusters by calculating modularity (see Newman & Girvan, 2004).

In a second step, these clusters were optimized by a memetic algorithm (PsiMinL) that clusters links instead of nodes and optimizes each cluster separately (Havemann, Gläser & Heinz, 2017; Havemann, 2021) by iteratively adding or removing links. The resulting optimized clusters have the advantage that nodes can be members of more than one cluster (c.f. Enders *et al.*, 2020). Also, resulting clusters will be more robust, as the algorithm does not force nodes into clusters. A detailed description of the network analysis is provided in the Appendix.

Membership of a hypothesis in a cluster is quantified as the percentage of links leading from attributes to the hypothesis, i.e. two out of three links leading to a hypothesis equals a membership of 67% in the respective cluster. A hypothesis (node) can be included in two clusters with 100% if they overlap one another.

Results & Discussion

Hypotheses in urban ecology

We identified 62 hypotheses in urban ecology, including 36 descriptive and 26 explanatory hypotheses (Table 1). Thirty-six hypotheses are uniquely or originally urban; 12 hypotheses stem from related fields like invasion biology or biogeography, but are highly relevant to urban ecology; and 14 hypotheses exist in a general version and, here, are adapted to an urban setting ("urbanized"). This collection of urban hypotheses has a different scope and goes beyond previous compilations that have attempted to structure the field of urban ecology. The approach by Mary L. Cadenasso and Steward T. Pickett is theory-driven, and their five principles are aimed to ground urban ecology within scientific theory and provide suggestions for urban planning and landscape design. These five principles are: (1) "urban areas are ecosystems", (2) "urban ecosystems are diverse", (3) "urban ecosystems are dynamic"; and that (4) "human and natural processes interact in cities" and (5) "ecological processes remain important in cities" (Cadenasso & Pickett 2008). These principles were later extended by the same authors to 13 principles (Pickett & Cadenasso 2012).

In 2016, Richard Forman published a compilation of 90 principles (Forman 2016), based on six reviews on urban ecology. These contain more detailed and case-specific findings and generalizations from research on urban ecosystems. For example, (1) "More buildings and tall structures create both more habitats and hazards for organisms." Kirsten Parris (2018) recently published a collection of theories, paradigms and hypotheses from general ecology that have been shown to apply in urban systems.

Similar to Forman (2016) and Parris (2018), and different from Pickett and Cadenasso (2008 & 2012), we here use a bottom-up approach to structure the field of urban ecology. While there is some overlap between these studies and ours, choosing hypotheses instead of given principles has in our experience two benefits: hypotheses and hypothetical generalizations call by definition to be repeatedly questioned and tested in numerous instances, and can be directly linked to empirical evidence in a future step.

From descriptive to explanatory hypotheses

We chose to differentiate between explanatory or mechanistic hypotheses on the one hand and non-explanatory or descriptive hypotheses on the other hand. While it has been argued that searching for mechanistic explanations can be time-consuming and sometimes even impossible (Quinn & Dunham, 1983; Peters, 1991; Golub, 2010; Houlahan *et al.*, 2017; Nilsen, Bowler & Linnell, 2020), especially in the era of big data (Yang, 2020), several authors have made a strong case for strengthening the use of explanatory hypotheses (Nilsen *et al.*, 2020; Betts *et al.*, 2021; Norberg *et al.*, 2022). According to Betts *et al.* (2021, see also references therein), actively invoking "(1) multiple alternative hypotheses developed *a priori* prevent[s] attachment to a single idea", reduces biases and the prevalence of unsupported or even falsified hypotheses, also called "zombie hypotheses" (Fox, 2011) or "theory tenacity" (Norberg *et al.*, 2022), and "(2) should increase the transferability of findings to new systems".

In many cases, though, especially in a practitioner-oriented field like urban ecology, underlying mechanisms might not be of high interest or seem too complex. *Descriptive hypotheses* can thus be valuable, act as overarching hypotheses and concepts (*sensu* Heger *et al.*, 2021), and invite to generate new, explanatory hypotheses. Sometimes, they implicitly include explanations that might be intuitive for some, but not for other species, or allow predictions in some, but not in other places.

Table 2.1: Sixty-two hypotheses in urban ecology. The provided hypothesis names are either from the literature or, for hypotheses without a previous name, given new names (these are indicated by *asterisks). 'Label' refers to the abbreviation of hypotheses used in Fig. 2.1. 'Cluster' indicates where each hypothesis is located: Cluster I – Urban evolution and traits; II – Urban communities; III – Urban habitats; IV – Urban ecosystems. 'Type' refers to the research field in which a hypothesis was formulated: Urban = urban ecology; Urbanized = hypotheses originally formulated in a related field other than urban ecology, but adapted to urban environments; Related field = research field other than urban ecology. The rightmost column differentiates D = descriptive from E = explanatory or mechanistic hypotheses.

Hypothesis	Label	Cluster	Definition	Key Reference(s)	Type	Descriptive / Explanatory
Acoustic adaptation hypothesis*	AA	I	Animals that communicate acoustically adapt their vocalizations to the local conditions to optimize signal transmission.	Morton 1975	Related field	E
Biodiverse cities*	BC	II, IV	Cities can sustain and promote biodiversity.	Walter 1970, Kühn *et al.* 2004	Urban	D
Biodiversity-wealth*	BW	III	The socio-economic status of urban residents is positively related to the biodiversity in their neighbourhoods.	Kinzig *et al.* 2005	Urban	D
Cities as entry points	CEP		Cities are entry points for introduced non-native species.	Pyšek et al. 2010; Potgieter & Cadotte 2020	Urban	D
Credit card	CC	II	Low variability in resource abundance and reduced predation allow higher population densities in urban areas through the persistence of many weak competitors who remain in poor body condition, are less reproductively successful, and would not otherwise survive.	Shochat 2004	Urban	E
Decay paradigm	DP	III	Species richness declines within patches of remnant native habitat isolated within an urban matrix; habitat-dependent (such as 'forest interior') species are expected to suffer a progressive series of local extinctions over time.	Catterall *et al.* 2010	Urbanized	D
Earlier phenology	EP	I	Seasonal life cycles tend to start earlier in the urban core than in rural surroundings.	Roetzer *et al.* 2000	Urbanized	D
Ecological trap	ET	I, III	Urban ecosystems/habitats can act as ecological traps, i.e. Habitats preferred over other, higher quality habitats that are	Schlaepfer *et al.* 2002; Battin 2004	Related field	E

			low in quality for reproduction or survival and may not sustain a population.			
Enemy release	ER	II	The absence of enemies is a cause of invasion success.	Keane & Crawley 2002	Related field	E
Environmental filter	EF		Urban habitats filter communities as a function of their traits.	Aronson *et al.* 2016	Urbanized	E
Epigenetic adaptation*	EA	I	Epigenetic mechanisms can explain why some organisms are more successful in urban than non-urban areas.	Isaksson 2015	Urbanized	E
Food-web reshaping*	FWR	II	Urban food webs largely lack weak interactions, but the partly disassembled food webs retain a greater density of species interactions (e.g. greater connectance).	Start et al. 2020	Urban	D
Generalists vs. specialists*	GVS		Generalist species are more frequent in urban areas than specialist species.	Sorace & Gustin 2009	Urbanized	D
Genetic signatures*	GS	I	"Genetic signatures of urban eco-evolutionary feedback can be detected across multiple taxa and ecosystem functions." (p. 116 in Alberti 2015)	Alberti 2015	Urban	E
Green roofs	GR	III	Green roofs promote urban biodiversity.	Oberndorfer *et al.* 2007; Williams *et al.* 2014	Urban	E
Habitat diversity	HD	III	Biodiversity in urban areas is high due to habitat diversity.	Pyšek 1989	Urbanized	E
Habitat isolation	HI	III	More isolated habitat islands have lower species richness.	MacArthur & Wilson 1967	Related field	D
Herbivore proliferation*	HP	II	Herbivores may become hyperabundant in urban areas, sometimes leading to pest outbreaks.	Raupp *et al.* 2010	Urban	D
High propagule pressure in cities*	PHC		A higher proportion of alien taxa in captivity and cultivation leads to an increased propagule pressure in cities.	Kühn *et al.* 2017; Potgieter & Cadotte 2020	Urbanized	E
Home range reduction*	HRR	I, III	Many species maintain smaller home ranges in urban areas.	Mannan & Boal 2000; Atwood *et al.* 2004; Wright *et al.* 2012	Urban	D
Human commensalism	HC	I	Species that live in close proximity to humans are more successful in invading new areas than other species.	Jeschke & Strayer 2006	Related field	D
Hyperabundance due to anthropogenic food*	HAF	I, II, III	An increase in the proportion of anthropogenic food with urbanization leads to an increase in the abundance of prey as well as mid-sized animals (e.g. mesopredators).	Fischer et al . 2012	Urban	E
Ideal urban dweller*	IUD	I	There are specific traits that make species successful in urban ecosystems.	Evans *et al.* 2011, Adler & Tanner 2013, pp. 202	Urban	E
Increased boldness	IB	I	Animals tend to become bolder in urban than non-urban areas.	Knight *et al.* 1987; Uchida *et al.* 2019	Urban	D
Intermediate disturbance	ID	III	Biodiversity is high in sites that show intermediate levels of disturbance and decreases with no and high levels of management.	Grime 1973; Connell 1978, p. 1303	Related field	D
Landscape of fear	LOF	II	Animals adjust their behavior and activity to avoid humans spatio-temporally.	Brown *et al.* 1999; Laundré *et al.* 2010; Bleicher 2017	Related field	E
Light at night - social interaction*	LSI	I	Light pollution alters the social interactions and group dynamics of animals.	Kurvers & Hoelker 2015	Related field	E
Matrix species	MS	II, III	Urban habitat remnants are more sensitive to the penetration of matrix species than less disturbed suburban or rural remnants.	Tóthmérész *et al.* 2011	Urban	D
Microbiota exposure	ME	II, IV	Urbanization reduces exposure of humans to environmental microbiota, leading to higher allergy risks and negative effects on immune function.	Ruiz-Calderon *et al.* 2016; Parajuli *et al.* 2018	Urban	E
Non-native species hypothesis* aka Invader species hypothesis	IS		Non-native species richness increases with urbanization.	Sukopp 1969; Kunick 1974; Kowarik 1988; Blair 2001	Urban	D

Non-native substitution hypothesis*	NNS	II	Non-native plants in urban areas can sometimes substitute the loss of resources provided by native plants.	Berthon *et al.* 2021	Urbanized	D
Novel communities	NC	II	Urban environments have novel communities that do not exist in natural environments.	Perring *et al.* 2013	Urban	D
Plant host switching	PHS	I, II	The abundance of alien plants in the urban core encourages native arthropods (herbivores, pollinators) to switch from native to alien host(s).	Shapiro 2002; Raupp *et al.* 2010	Urban	E
Population pressure hypothesis	PPH	III	Urban habitats serve as sinks for rural dispersers. Continuous gene flow between a rural source and an urban sink population prohibits pronounced genetic differentiation.	Gloor *et al.* 2001	Urban	E
Predator proliferation	PP	II	Predator densities and/or predation rates are higher in urban than non-urban areas.	Fischer *et al.* 2012 based on Sorace 2002; Eötvös *et al.* 2018	Urban	D
Predator relaxation	PR	I, II	Predator density, prey mortality and/or prey fearfulness are lower in urban than non-urban areas.	Tomialojc 1982; Gering & Blair 1999	Urban	D
Prey specialization	PS	I, II	"The diet of carnivorous mesopredators will be increasingly dominated by a few species with urbanization. These prey species will be hyperabundant within cities. The predation rate on prey species that are not hyperabundant will decline with urbanization." (p. 816 in Fischer *et al.* 2012)	Fischer *et al.* 2012	Urban	D
Rapid adaptation	RA	I	Rates of evolutionary change are greater in urban systems.	Alberti *et al.* 2017; Johnson & Munshi-South 2017	Urbanized	D
Resilience of urban hybrid systems*	RUH	II, IV	"Resilience in urban ecosystems is a function of the patterns of human activities and natural habitats that control and are controlled by both socio-economic and biophysical processes operating at various scales". (p. 242 in Alberti & Marzluff 2004)	Alberti & Marzluff 2004	Urban	E
Shift toward non-migratory species*	SMS	I	Urbanization favors non-migratory species.	McClure 1989	Urban	E
Species richness - HPD*	SRH		Species richness is positively correlated with human population density.	Luck 2007	Related field	D
Species-area relationship	SAR	III	Species richness and diversity increase with habitat size.	MacArthur & Wilson 1967	Related field	D
Street barrier effect	SBE	III	Streets act as dispersal barriers.	Mader 1984	Related field	E
Street corridor effect	SCE	III	Streets act as dispersal corridors.	Seabrook & Dettmann 1996; James & Stuart-Smith 2000; Von der Lippe *et al.* 2007	Related field	E
Suburban peak*	SP	III	Species richness is highest in sub-urban areas; it is lower in urban centers and the (rural) periphery.	Blair 2001	Urban	D
Synanthropic species	SS		The number of synanthropic species increases along the rural-urban gradient.	Klausnitzer 1987 pp 106; Guetté *et al.* 2017	Urban	D
Thermal tolerance increase	TTI	I	Thermal tolerance increases with urbanization.	Diamond *et al.* 2018	Urban	D
Urban avoiders	UA	I	Urban avoiders have a reduced ability to adapt, compete and/or reproduce in cities.	Blair 1996	Urban	D
Urban biodiversity hot spots*	UHS	II, III, IV	Cities are often located in areas of high biodiversity, and urbanization is disproportionally higher in areas with high biodiversity.	Kühn *et al.* 2004; Luck 2007; Ives *et al.* 2016	Urban	D
Urban biotic homogenization	UBH		Species composition of different cities will become more and more similar as urbanization increases.	Blair 2001; McKinney 2006; Groffman *et al.* 2014	Urbanized	D

Urban core herbivore decline*	UCH	II	The abundance of alien plants in the urban core tends to reduce the richness and abundance of native herbivore insects incapable of using non-native plants.	Raupp *et al.* 2010	Urbanized	E
Urban density-diversity paradox*	UDD		Diversity typically increases as the number of individuals increases in biological communities. Urban environments, however, tend to be characterized by lower biodiversity than wildlands despite high population densities.	Shochat *et al.* 2010; Saari *et al.* 2016	Urban	D
Urban eco-evolutionary mechanisms*	UEE	I	"Through urbanization, humans mediate the interactions and feedbacks between evolution and ecology in subtle ways by introducing changes in habitat, biotic interactions, heterogeneity, novel disturbance, and social interactions." (p. 116 in Alberti 2015)	Alberti 2015	Urban	E
Urban ecosystem convergence	UEC	II, IV	All ecosystems types respond to urban land use in a convergent manner (in other words: urban ecosystems are convergent regardless of the original ecosystem they replaced).	Pouyat *et al.* 2003	Urban	D
Urban ecosystems as source of innovation*	USI	I	"The hybrid nature of urban ecosystems – resulting from co-evolving human and natural systems – is a source of 'innovation' in eco-evolutionary processes. " (p. 117 in Alberti 2015)	Alberti 2015	Urban	E
"Urban effect" on invasion	UEI		The number of non-native species moving through each invasion stage (transport, introduction, establishment, spread) is higher in urban areas than in natural environments.	Potgieter & Cadotte 2020	Urban	D
Urban fragmentation	UF	I, III	Urbanization, [specifically the fragmentation of habitats] leads to a loss of genetic variation within and increased differentiation between populations.	Miles et al. 2019	Urbanized	E
Urban habitat analogues*	UHA	III	Native species can switch to urban habitats.	Thellung 1919; Lundholm & Richardson 2010	Urbanized	D
Urban mesopredator release*	UMR	II	"The abundance of large-bodied predators will decline with urbanization, whereas the abundance of mesopredators will increase." (p. 816 in Fischer *et al.* 2012)	Crooks & Soulé 1999; Fischer *et al.* 2012	Urbanized	D
Urban sexual traits*	UST	I	In urban environments, species show shifts in several traits related to sexual selection (particularly in their coloration, acoustic signals including songs and calls, hormones, pheromones, mating behaviour).	Sepp *et al.* 2020	Urban	D
Urbanization ecosystem functioning*	UEF	II, IV	Urbanization leads to a reduction in ecosystem functions and services.	Grimm *et al.* 2008	Urban	E
Urbanization tolerance	UT	III	Biodiversity loss in cities can be explained by a low tolerance of species to urbanization.	Sol et al. 2014	Urban	D

Are urban hypotheses unique?

Given the unique nature of urban ecosystems, an interesting question is whether general ecological theory can be directly applied to urban ecology (Parris, 2018). Urban ecosystems differ profoundly from natural ones, and ecologists have carved out many differences between urban and non-urban systems, arguing that ecological theory has to be at least adapted (Niemelä, 1999), if not profoundly expanded (Collins *et al.*, 2000; Alberti, 2008; McPhearson *et al.*, 2016a), for urban systems. Still, ecological theory has been repeatedly applied in urban settings (Parris, 2018). Of the 62 hypotheses listed in Table 1, 14 have been adapted from general ecological theory to urban systems (23%), and 12 hypotheses are from related fields (19%). These hypotheses are highly relevant in urban settings, and thus a vital part of urban ecology. Take, for example, the enemy release hypothesis: it is well known in invasion ecology (Enders *et al.*, 2018) and explains the invasion success of species in the absence of (co-evolved) enemies in novel settings. As urban ecosystems have been shown to be rich in non-native species (e.g., Kowarik, 2008; Louvrier *et al.*, 2021), and even hypothesized to act as distribution hubs for species invasions to rural regions (von der Lippe & Kowarik, 2008) as well as to other cities worldwide (Potgieter & Cadotte, 2020), urban ecology and invasion biology are closely connected research fields. As a wide variety (if not most) of general ecological theory can be applied in urban settings (see Parris, 2018), our selection here is far from exhaustive. Accompanying the rapid loss of the untouched, pristine nature (Watson *et al.*, 2016; Potapov *et al.*, 2017) that has been studied by classical ecology (Inkpen, 2017), urban ecosystems are nowadays only one among many strongly transformed ecosystem types, and can even be regarded as trial systems for studying effects of multiple global changes (Lahr *et al.*, 2018). For Johnson & Munshi-South (2017), the global network of cities might even be "the best and largest-scale unintended evolution experiment". So instead of asking if and in what form classical ecological theory can be applied to urban systems, the inverse question might become increasingly important in the future (Forman, 2016): Can research from urban ecology help to understand other anthropogenically shaped ecosystems?

A (first) map of hypotheses in urban ecology

To provide a visualization of theory in urban ecology, we applied a semi-automated approach to map all 62 hypotheses listed in Table 2.1 in a bipartite network, together with 16 assigned attributes (Appendix, Fig. 2.1). Of the seven clusters identified in a network analysis (see Appendix, Table S2.1), the four best separated clusters were retained (clusters I-IV). These clusters were labelled according to the hypotheses and attributes they contain (Figs. 2.1, 2.2), and will be described in detail below. Three clusters were not retained, since cluster VI is the complementary cluster to cluster I, which is thus uninformative, and cluster V and VII are very small and not well separated. Several hypotheses are part of more than one cluster, and nine hypotheses are not part of any of the four clusters, but of the large unnamed cluster VI (Fig. 2.1). Cluster IV is also part of cluster II, and all clusters share overlapping links and nodes (Fig. 2.2).

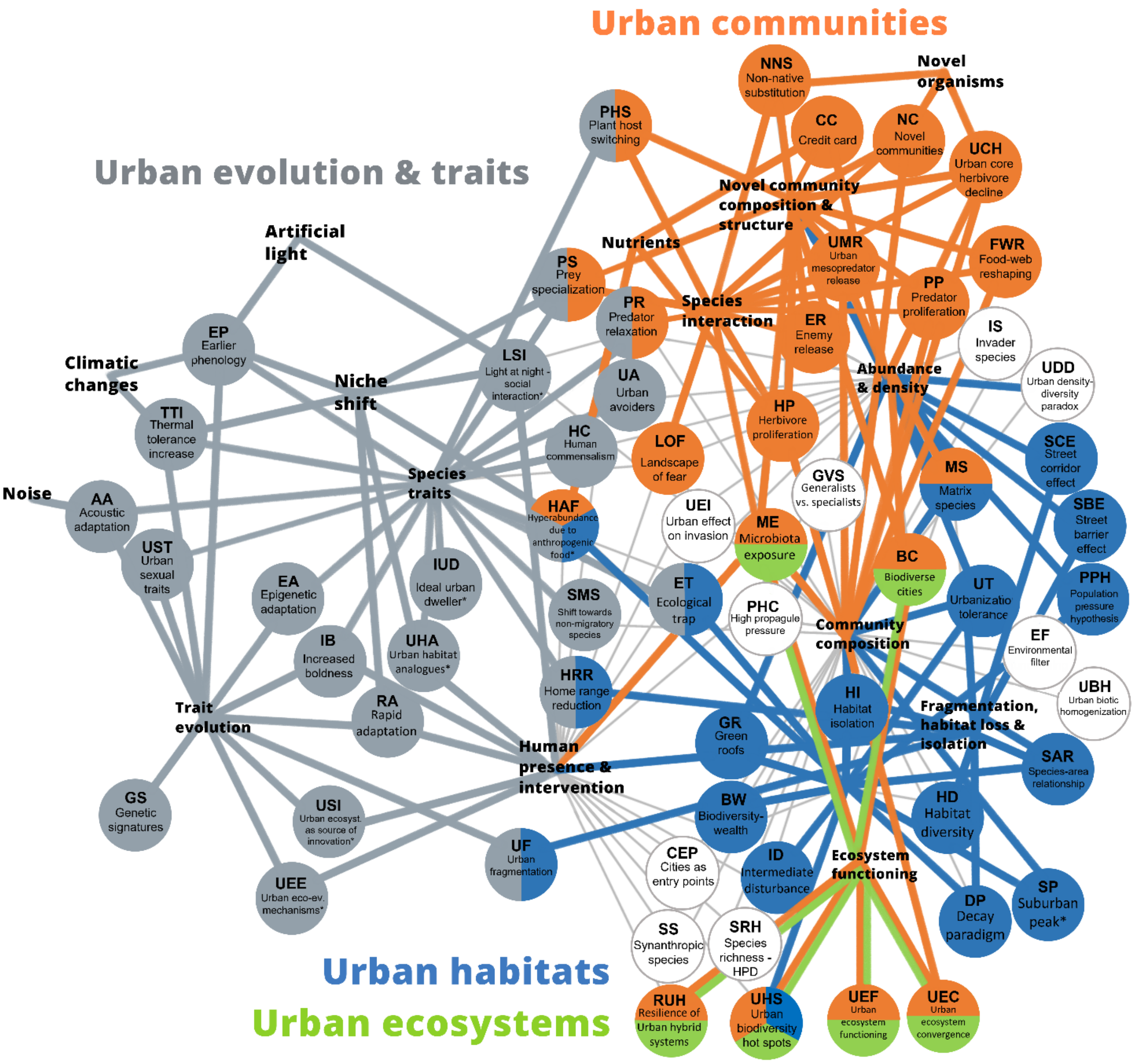


Figure 2.1 Bipartite network of 62 hypotheses (circles) and 15 attributes (hand-written words at the intersection of several links), which were used to characterize and group the hypotheses. Four clusters that emerge when applying a link clustering algorithm are shown. Clusters are named based on prominent hypotheses and traits that they entail: *urban evolution and traits* (grey), *urban communities* (blue), *urban habitats* (green) and *urban ecosystems* (orange). Full circles belong to a single cluster, divided circles indicate that a hypothesis has a shared membership between two or more clusters. Hypotheses embedded within a white circle do not belong to any of the clusters.

Cluster I: Urban species traits & evolution

The cluster on urban species traits and evolution comprises 23 hypotheses; 11 hypotheses have 100% membership and 12 hypotheses have a membership below 50%. Attributes of that cluster are: species traits, trait evolution, niche shift, artificial light, noise, climatic change (all 100% cluster membership) and human presence and intervention (23%). Although the cluster has some overlap with the urban communities and the urban trait cluster, it has the lowest normalized node-cut Psi-value among the identified clusters, which indicates it to be the best separated cluster.

A major focus of the hypotheses in this cluster is to predict and explain which traits characterize species that inhabit urban areas, and how they adapt to urban environments. The study of species that live close to human settlements dates back to studies on birds, mammals and blowflies from the 1950s (see Povolny, 1962; Nuorteva 1963, 1971), and far earlier for plants (Linkola, 1916, reviewed by Sukopp 2008). A central idea in this cluster is the *Ideal urban dweller* hypothesis, which posits that specific traits make species successful in urban ecosystems. This is a very general statement, but we chose to treat it as an overarching hypothesis that can be specified into a range of descriptive hypotheses focusing on a specific taxonomic group or urban setting, and which implicitly assumes that there is a set of traits characterizing an ideal urban dweller (or: an urban avoider). This might be a higher cognitive performance or increased capability to learn (Sol, Lapiedra & Ducatez, 2020); an enhanced movement capacity (Santini *et al.*, 2019); or a more flexible diet (Palacio, 2020; Scholz *et al.*, 2020; Planillo *et al.*, 2021). Hypotheses like *acoustic adaptation*, *earlier phenology*, *increased boldness*, *elevated thermal tolerance* and *shift towards non-migratory species* link evolutionary changes to physical stressors in urban environments or the presence of humans. *Epigenetic adaptation*, *genetic signatures*, *rapid adaptation* and *urban eco-evolutionary mechanisms* are hypotheses about general evolutionary processes that are expected in urban settings.

Cluster II: Urban communities

The urban community cluster includes 13 hypotheses with 100% membership and 9 hypotheses with a membership between 17% and 67%. Attributes within this cluster are: species interactions, ecosystem functioning, nutrients, novel organisms, novel community composition (all 100%) and abundance/density (33%), human presence and interaction (5%) and community composition (3%).

Hypotheses in the community cluster focus on research questions such as: in which respects are urban food webs, communities and species assemblages different from non-urban ones? What characterizes urban species interactions (e.g., predation or competition)? Four hypotheses that are clearly related to abundance and density, as well as community composition as focal entity (i.e. *Invader species*, *Urban density-diversity paradox*, *Urban effect on invasion* and *High propagule pressure in cities*) were not grouped within but in the vicinity of the community-cluster. Nested within the community cluster is the ecosystem cluster outlined below (cluster IV).

Cluster III: Urban habitats

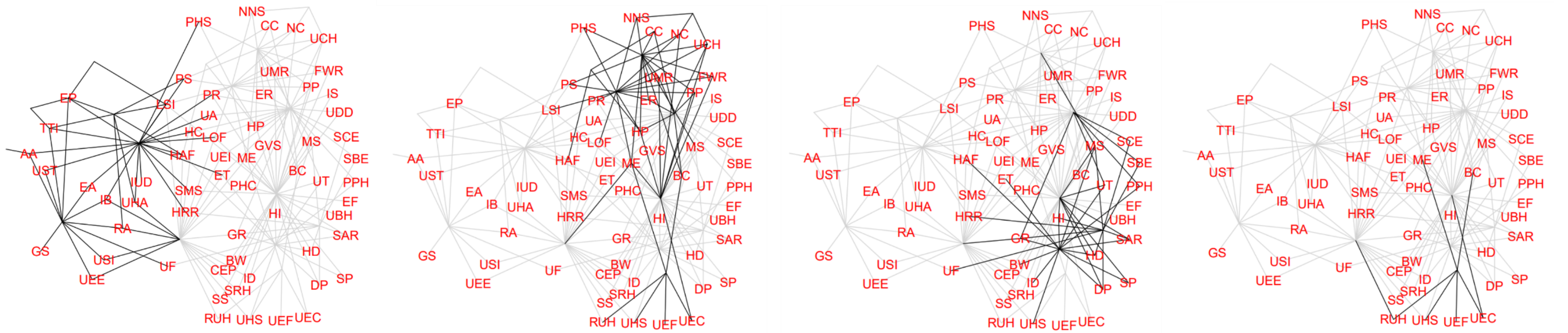
The habitat cluster includes 11 hypotheses with 100% membership and 7 hypotheses with 50% membership and less. The attributes of this cluster are: habitat quality, fragmentation and habitat loss (100%) as well as abundance/density, community composition, novel community composition and human presence and interaction (5-24% membership).

The central question of this cluster is which habitat characteristics influence populations, species and their interaction, and how urban habitats can be characterized. For example, a high diversity of habitats in urban areas has been linked to high overall biodiversity of cities (Pysek, 1989; Sattler *et al.*, 2010; Helden & Leather, 2004), a hypothesis that is very well known but often only implicitly tested. Another example for a hypothesis of the urban habitat - cluster is the *Road barrier effect*, which predicts how traffic routes reduce the mobility of urban wildlife (Rondinini & Doncaster, 2002; Riley *et al.*, 2014), and opposes the *Street corridor effect* (Seabrook & Dettmann, 1996; von der Lippe & Kowarik, 2007; Riley *et al.*, 2014). The habitat cluster contains a large proportion of hypotheses adapted or directly applied to urban systems from other research areas, especially biogeography, population ecology and conservation ecology.

Cluster IV: Urban ecosystems

Taking a broader perspective at patterns and processes on the ecosystem level, the ecosystem cluster comprises only 6 hypotheses, and only three of them with a cluster membership of 100%: *Resilience of urban hybrid systems*, *Urban ecosystem convergence* and *Urban ecosystem functioning*. These hypotheses focus on ecosystem functions or services. Three other hypotheses have a lower affiliation (20-33%). The attributes of this cluster are: ecosystem functioning (100%), human presence and intervention (5%) and community composition (3%).

Not all hypotheses relating to ecosystems are included in this cluster (e.g. *Urban ecosystems as source of innovation* is part of the evolution cluster), but it is still striking that so few of the hypotheses are concerned with ecosystem functions or services (see section "Blind spots in the network"). Thus, while we expect this cluster of the network to be extended in the future, e.g. by including research on microbial urban ecology, it might be



Urban evolution & traits		%
Acoustic adaptation	AA	100
Earlier phenology	EP	100
Epigenetic adaptation	EA	100
Genetic signatures	GS	100
Ideal urban dweller	IUD	100
Increased boldness	IB	100
Rapid adaptation	RA	100
Thermal tolerance increase	TTI	100
Urban eco-evolutionary mechanisms	UEM	100
Urban ecosystems as source of innovation	USI	100
Urban sexual traits	UST	100
Light at night – social interaction	LSI	50
Prey specialization	PS	50
Shift towards non-migratory species	SMS	50
Urban avoiders	UA	50
Urban fragmentation	UF	50
Hyperabundance due to anthropogenic food	HAF	40
Human commensalism	HC	33
Home range reduction	HRR	33
Plant host switching	PHS	33
Ecological trap	ET	25
Predator Relaxation	PR	25
Landscape of fear	LOF	20

Urban communities		%
Biodiverse cities	BC	100
Credit card	CC	100
Enemy release	ER	100
Food web reshaping	FWR	100
Herbivore proliferation	HP	100
Microbiota exposure	ME	100
Non-native substitution	NNS	100
Novel communities	NC	100
Predator proliferation	PP	100
Urban core - herbivore decline	UCH	100
Urban ecosystem convergence	UEC	100
Urban ecosystem function	UEF	100
Plant host switching	PHS	67
Prey specialization	PS	50
Resilience of urban hybrid systems	RUH	50
Urban biodiversity hotspots	UBH	33
Matrix species	MS	25
Predator relaxation	PR	25
Hyperabundance due to anthrop. food	HAF	20
Landscape of fear	LOF	20
Light at night – social interaction	LSI	17

Urban habitats		%
Decay paradigm	DP	100
Green roofs	GR	100
Habitat diversity	HD	100
Habitat isolation	HI	100
Matrix species	MS	100
Population pressure hypothesis	PPH	100
Species-area relationship	SAR	100
Street barrier effect	SBE	100
Street corridor effect	SCE	100
Suburban peak	SP	100
Urbanization tolerance	UT	100
Urban fragmentation	UF	50
Biodiversity-wealth	BW	33
Intermediate disturbance	ID	33
Urban biodiversity hotspots	UHS	33
Ecological trap	ET	25
Home-range reduction	HRR	33

Urban ecosystems		%
Resilience of urban hybrid systems	RUH	100
Urban ecosystem convergence	UEC	100
Urban ecosystem functioning	UEF	100
Biodiverse cities	BC	33
Urban biodiversity hotpots	UHS	33
Microbiota Exposure	ME	20

Urban
Urbanized
Related field

Figure 2.2 62 Hypotheses in urban ecology are here grouped into clusters, that were identified by a link clustering algorithm. The best separated and meaningful clusters are shown here and were subsequently named *urban species traits & evolution*, *urban communities*, *urban habitats* and *urban ecosystems*. Cluster membership of all hypotheses attributed to a cluster are listed below. Cluster membership values indicates the proportion of links leading to a hypothesis that belong to that cluster. Color circles indicate whether a hypothesis has been formulated within urban ecology (blue), adapted to urban ecology ("urbanized", orange-blue), or is a general hypothesis from a related field (orange). Links that belong to a cluster are black, other links are grey.

fruitful to consider how the paramount of work in urban ecosystems, which may not be hypotheses-oriented, could be covered within a community-built knowledge base as proposed here.

Critical reflections

The network presented here was built by combining expert knowledge with a network algorithm. While there are many possibilities to build networks, we chose to create a bipartite network with the advantage that the information about the assessed hypotheses are directly translated into a network structure, instead of relying on one of numerous possible measures of (dis)similarity. This approach is also flexible and easier to adjust, should the underlying dataset grow, which we hope will happen in the near future (see below). The resulting network represents a first step towards a knowledge map for urban ecolgy. It has to be noted, however, that by building on explicity formulated hypotheses only, certain topics addressed in urban ecology might be underrepresented or even missing. Grogan (2005) found that less than half of a selection of articles from ecological journals explicitly used hypotheses. In Nilsen *et al.* (2020) this proportion was only 19% in a random selection of articles from practitioners-orientated journals in conservation biology, applied ecology and wildlife management. We expect that proportion to be equally low in urban ecology, but also to vary profoundly among its sub-disciplines, due to its inherent multidisciplinarity. For example, we expect the urban ecosystem cluster to grow profoundly once more implicit hypotheses are included, because urban ecosystem models and analyses of material flow and processes in cities implicitly contain hypotheses. Whether it makes sense to formulate these hypotheses, and add them to our network, or whether it might be more constructive to adapt the network to include models, concepts or research questions need to be further discussed.

Additional hypotheses will probably alter the structure of our network. For example, the evolution and traits cluster is currently well separated from all other clusters, and only few hypotheses are shared with the community cluster (e.g. *Plant host switching*) and the habitat cluster (e.g. *Ecological trap*, *Urban fragmentation*). We expect that increasing the network resolution (i.e. including additional sub-hypotheses and adding new hypotheses) will probably strengthen the overlap between these clusters, as habitat fragmentation, community composition and novel organisms are also studied as important evolutionary factors (Shochat *et al.*, 2006; Diamond & Martin, 2021; Winchell, Battles & Moore, 2020; Borden & Flory, 2021).

The collection and network of hypotheses are a result of the joint contributions and expertise within our group. Our scientific work is currently predominantly carried out in Berlin (Germany), and even though many of us have close connections or backgrounds with other research schools and scientists around the world, we expect that other researchers would have selected different hypotheses and added their very own perspective to the creation of a hypothesis map in urban ecology. In the next and final section, we therefore discuss how the present selection and map of hypotheses can be expanded to incorporate a more diverse and less biogeographically and culturally biased view on hypotheses in urban ecology.

Co-creating a knowledge base of urban hypotheses

The hypotheses we mapped so far are far from being exhaustive, but can serve as a basis to think of other known hypotheses and expand the map with additional (sub-)hypotheses from urban ecology, and link it to other disciplines from within and outside urban ecology. We hope that the network can act as a starting point around which other disciplines from urban ecology in the broader sense can culminate and expand on, and rearrange, where appropriate, by urban ecologists from other research schools. Knowledge gaps are known to be especially pronounced in the Global South and areas with the highest urbanization pressure, as well as on a comparative global level with most research still carried out locally (Young & Wolf, 2006; Shackleton *et al.*, 2021). To synthesize existing theory and constantly update new findings, as well as to identify research gaps, it is necessary to compare and communicate between different research disciplines and stakeholders. As a first step, all hypotheses are also provided in an openly expandable Wikidata file, that we envision to grow in the future by including scientists worldwide. As part of the Wikidata project, well studied hypotheses can, if available, also be linked to already performed meta-analyses and other literature reviews on specific hypotheses, or to the body of relevant data and literature. Hypotheses can thus be assessed directly, as well as analyzed from a meta-perspective, i.e. by generating bibliometric networks, and charts, as well as evidence maps, with the aim to identify open gaps and biases in research.

Meanwhile, we advocate for a more frequent use of (explicit) hypotheses in urban ecology and would like to present our list and network of hypotheses as an invitation to expand on it both laterally (adding more hypotheses, or adding alternative hypotheses) and in layers (adding explanatory to overarching and descriptive hypotheses).

Filling all the above-mentioned gaps will be a task best done with joint efforts of researchers from different backgrounds, geographical regions and fields of expertise. This is why we created an openly accessible and interactive Wikidata project at wikidata.org/wiki/Wikidata:WikiProject_Ecology/Task_Force_Urban_Ecology. At this site, we included the set of 62 hypotheses introduced in Table 1 as a starting point; it can now be extended by researchers, practitioners and other researchers interested in urban ecology. We chose Wikidata as a platform, as it is entirely free, open-access, community-run, user-friendly, well established and adheres to the FAIR-principles (Wilkinson *et al.* 2016, Waagmeester *et al.* 2020). All entries can be easily linked to entries from other Wiki-platforms like Wikipedia or Wiki-Commons, and existing knowledge (in our case: hypotheses) can be linked to existing literature and datasets (Erxleben *et al.*, 2014; Vrandečić & Krötzsch, 2014). Eventually, such a collection and map of hypotheses would greatly benefit from adding information about the validity or generality of the collected hypotheses. A step that was already put forward in invasion ecology is linking the hypotheses with empirical data (hi-knowledge.org). We think building an online knowledge base that connects hypotheses with evidence will also be very useful for urban ecology. For the future, we envision a more extensive knowledge base covering related fields like urban ecology, restoration ecology (Heger *et al.*, in revision) or invasion biology.

Conclusions

1. Urban ecology is a growing research field that can benefit from applying new syntheses tools.
2. A map of 62 hypotheses from urban ecology broadly clusters into four main themes: Urban traits & evolution; Urban communities; Urban habitats and Urban ecosystems.
3. We propose using this network as a basis for a community-built knowledge base of hypotheses in urban ecology, and introduce a Wikidata project for this purpose.
4. Creating a map of hypotheses in urban ecology can foster knowledge exchange, help identify research gaps, and provide orientation and guidance for researchers and practitioners.

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Chapter 3 | Urban biotic homogenization: approaches and knowledge gaps

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Chapter 4 | Impact of mowing frequency on arthropod abundance and diversity in urban habitats: a meta-analysis

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General Discussion

This thesis includes four interlaced chapters that are embedded within the wider framework of knowledge and metascience. Chapter 2-4 present examples from urban ecology (see Figure D.1). In the beginning of this thesis, I introduced different facets of knowledge, emphasizing that knowledge (and science) has been found by several disciplines to be socially constructed, and that our established knowledge system has shown significant flaws in light of the recent reproducibility crisis. I also mentioned that solutions are being developed by a new discipline called metascience, which looks at the scientific enterprise with the methods of science itself. I pointed to the role of knowledge in our 'knowledge society', especially in the context of global uncertainty and crises, and introduced some peculiarities of urban ecology – a highly inter-, and even transdisciplinary, scientific discipline. In the following sections, I will discuss how all chapters align to the overarching themes of knowledge gaps and research synthesis, summarize and reflect on their results, and raise a couple of critical reflections and suggestions. Each of the four individual chapters raises different perspectives, although the answers to some of the questions remain rather speculative.

Starting with a discussion of how biases and dark knowledge are present in chapters 2-4, and how they are connected to urban ecology in general, I continue through the main points raised in the individual chapters: How can such biases be identified, what are possible approaches to knowledge syntheses (chapters 3 & 4), and could a map of urban ecology contribute to research synthesis and knowledge transfer (chapter 2)?

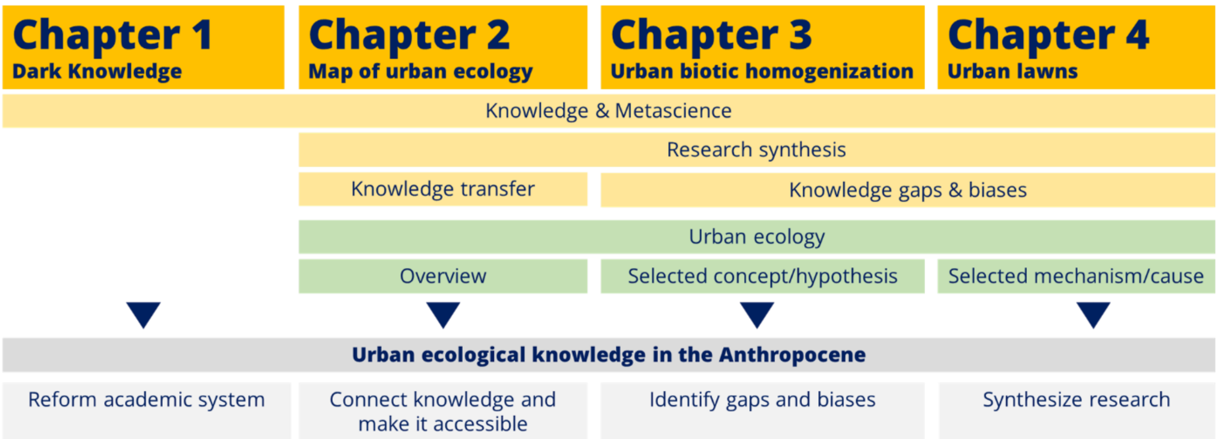

Figure D.1 Overarching themes of the four chapters. Each chapter contributes certain aspects to the overarching topics knowledge and metascience. Chapters 2-4 are situated within urban ecology, while chapter 1 takes a very general stance at science - or more concretely, the limits and flaws of knowledge production and research synthesis in academia. The second chapter presents a map of concepts and hypotheses within urban ecology, with the aim to capture research trends and help both researchers from within the field, and outsiders, to navigate among them. The third chapter focuses on one of the identified hypotheses, and analyses knowledge gaps, trends, and conflicting terminology by combining literature review and bibliometrics for assessing research on urban biotic homogenization. The fourth and final chapter adds to the broader perspective of scientific knowledge and research synthesis with a very practical example: widespread, tidy mowed lawns as selected cause of biotic homogenization in cities. All chapters raise points for discussing urban ecological knowledge in the Anthropocene.

Weaving these lines of thought together, I will conclude the discussion by raising several points that arise in each of the chapters in the light of the global environmental emergency. Could dark knowledge be relevant to urban ecology in this context? How can urban researchers combine their knowledge and facilitate interdisciplinary knowledge exchange? And what role do other forms of knowledge play for sustainable urban development? To answer these questions, I will briefly draw a comparison to the IPBES framework, which focuses on the question of making knowledge synthesis in biodiversity research not only sound and accessible, but also fair and practicable.

Biases and knowledge in the dark

Knowledge in the dark, or short: dark knowledge, describes that hypothetical aspect of knowledge that is not available or simply *not known*, but potentially could be. Dark knowledge, thus, can (potentially) be brought to light. We outline this concept in chapter 1. It does not, in contrast to most other concepts related to counterparts of knowledge, include the inherently unknowable (see Proctor 2008). Navigating in the context of academia, we identify several underlying mechanisms for dark knowledge in chapter 1 and conclude with several possible ways forward in order to improve the generation and transfer of scientific knowledge. As main reasons for dark knowledge in academia, we identify: (1) loss of academic freedom, (2) academic research biases, (3) lack of reproducibility, and (4) the Scientific Tower of Babel. All these topics directly connect to the general introduction in the beginning of the thesis, and although written by ecologists, the issues we raise are general for the academic system. So how can dark knowledge be applied to urban ecology?

In urban ecology, (1) loss of academic freedom and (2) academic research biases are highly intertwined: First, the biases that we see in urban ecology reflect a general pattern in the northern vs southern hemisphere found in science in general, and mirror biases in biodiversity research in particular (Tydecks et al. 2018). Similarly pronounced is a bias towards certain taxonomic groups (chapter 3, Rega-Brodsky et al. 2022). Second, although the need for high-quality long-term data in biodiversity research and ecology has been reiterated, such long-term studies continue to be rare und underfunded (Willis et al. 2007, Hughes et al. 2017). Indeed, long-term research in ecology can take a lifetime or longer, but even mid-term research projects stretching longer than a few years are difficult to implement in an academic funding system based on short-term research grants with a large proportion of scientists working on fixed-term contracts (Petersen et al. 2012, Burns 2017). This lack of long-term data is especially immanent in chapter 3, with over 80% of the assessed studies substituting space for time, and only a minority of studies using temporal data for urban biotic homogenization, a process that can best be studied over time (see chapter 3 and Damgaard 2019).

Chapter 4 assesses one causal mechanism of urban biotic homogenization: the global phenomenon of lawns. Lawns are a symbol of wealth and control over nature. They have been popular in France and England since the 18th century. Tidy green lawns became an emblem of upper-class America, and a common feature of public parks and representative buildings all around the globe. For a nature-loving ecologist[15], though, manicured lawns are also an alarming symptom of anthropogenically driven biotic homogenization. Even though urban lawns are a global

[15] Science is, as outlined in the introduction, rarely value-free, and this has also been shown in ecology (Steel et al. 2018).

phenomenon, all of the 28 studies included in our meta-analysis in chapter 4 were conducted in the western hemisphere – either Europe or Northern America. This obvious gap in our dataset in chapter 4 mirrors again the general problem in global biodiversity research, with a huge geographical bias towards research being performed in, or administered by, researchers from the western hemisphere (Martin et al. 2012, Trimble & van Aarde 2012, Di Marco et al. 2017, Tydecks et al. 2018). These geographical biases are of particular concern for urban ecology, as the urbanization rate is higher in areas that are poorly monitored for changes in biodiversity (Elmqvist et al. 2013). The pronounced knowledge gap in cities in the global south persists in urban ecology, and can also be found in chapter 3, where research on beta diversity and biotic homogenization is predominantly concentrated in the northern hemisphere (see also Shackleton et al. 2021). Language barriers are potentially strengthening the geographical bias. The number of publications in biodiversity research in other languages than English is rising steadily and might be underestimated by many reviews and synthesis studies (Hickisch et al. 2019, Chowdhury et al. 2022). Language, as well as cultural barriers to knowledge, must be taken into account when setting the framework for knowledge synthesis in the Anthropocene (see last section).

A very important cause of knowledge in the dark that I introduced also in the general introduction is the problem of reproducibility in academic research. To this date, the rate of reproducibility in urban ecology is unassessed. A phenomenon that should be discussed in this context because it has been shown to be relevant in ecological research and allows to draw some conclusions about the replicability of research findings, is the decline effect[16]. There is, to my knowledge, no systematic report on decline effects in an urban context, but Costello & Fox (2022) showed very recently that decline effects seem to be the exception in ecological research. The reforming impact of the reproducibility crisis has certainly reached ecology and evolution (Parker et al. 2016): Leading journals now require open data and transparent reporting, and in 2019, the Society for Open, Reliable, and Transparent Ecology and Evolutionary biology" was founded (O'Dea et al. 2021). At the intersection to psychology and quantitative social sciences, the need to improve research quality has been recognized also within urban ecology (e.g. MacDonald 2019), and in 2015 the Journal of Urban Ecology was founded as an Open Access journal. A large fraction of urban ecology research however does not consist of randomized controlled trials or (quasi-)natural experiments. But even in disciplines that are doing empirical research, comparing results (and replicating studies, consequently) can be difficult: In chapter 3, for example, we realized during the data compilation that approaches to studying the seemingly straight-forward concept of urban biotic homogenization vary to such a high degree that it was impossible to perform a formal meta-analysis. If the underlying hypotheses are too variable, the concept of reproducibility, and that of testable hypotheses, cannot be easily applied.

[16] The decline effect describes the observation that some research findings or hypotheses are initially well supported, but then get less and less support over time. It has been mainly explained with temporal trends in publication bias, which typically leads to positive results being favoured in the publication process. Only after some time does it become 'interesting' to publish contradictory findings to an established hypothesis (Schooler 2011, Jeschke et al. 2012, Clements et al. 2022).

Looking at how biases can be detected in quantitative urban ecology studies, ecologists are used to the prevailing circumstance that there is just very little data on some taxonomic groups, or that some habitat types are highly understudied. It is a common pattern in biodiversity research, that knowledge about aquatic systems is scarce compared to terrestrial systems (e.g. Tydecks et al. 2018), and this bias is also present in chapter 3. Chapter 3 additionally shows that biotic homogenization is mainly studied in plants and birds, but much less so in other taxa, while chapter 4, looking at arthropods, finds biases towards data on "charismatic" arthropod groups like butterflies or wild bees in contrast to such enigmatic or less appreciated groups as millipeds or arachnids[17]. The biases found in chapters 3 and 4 are comparable to the findings of a recent review on the state of urban biodiversity research (Rega-Brodsky, 2022).

Assuming that there is enough data on a given research question, it is possible to use meta-analytic techniques in order to identify additional biases that arise from the research and publication process (Sterne et al. 2001, Peters et al. 2006, Lin & Chu 2018). In Chapter 4, we used so-called 'funnel plots'. These are scatter plots that map the effect sizes of all studies included in the analysis against a measure of their precision, e.g. their standard error. In theory, an asymmetrical funnel plot indicates a publication bias. A way to counterbalance possible publication biases is to use 'trim-and-fill' plots which visualize which effect sizes are potentially missing. These potentially missing values are then computed with the original data, and the result are compared to the originally computed effect sizes, giving an estimate of how big the bias in the original data may have been (Duval & Tweedie 2000, Egger et al. 1997). Our dataset on the effect of mowing in urban areas showed some peculiarities in this regard: Usually, publication biases are strongly skewed towards positive effect sizes, because positive results are more incentivized by the publication system to get published (Mlinarić et al. 2017). But at least in the case of taxon richness, the opposite was the case. The reasons are discussed in chapter 4, but it shows how important it is to watch out for patterns and causes of potential biases when analyzing data from different sources.

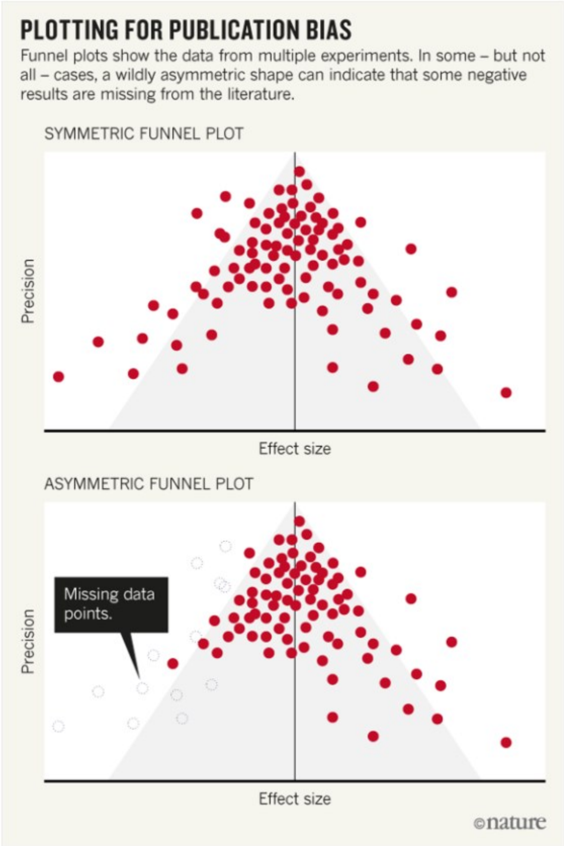

Figure D.2 Meta-analytic tools like funnel plots can help to identify biases like publication bias in the underlying data set. Figure from Cressey (2017)

[17]Ecologists might be familiar with the concept of dark diversity. Dark diversity is the diversity that ecologists predict to potentially occur in a given area – but are notably absent. It is thus the gap between potential, and actual diversity – a vivid analogue to what we propose as dark knowledge in chapter 1 (see Pärtel et al. 2011).

An important aspect that we raise in the chapter on dark knowledge are systematic biases due to financial interest. Urban ecology research might be prone to this bias when it comes to highly invested new technologies and "promising" planning tools. For example, just this year (2022), the European Commission has launched several calls on Research and Innovation for climate neutral and smart cities spanning over 150 million euros as one of five large investment plans (called EU Mission)[18]. Smart cities are a beacon of science and technology investment (Kourtit & Nijkamp 2012), with the market value of smart cities being forecasted to rise from 1.2 trillion to over 7 trillion US dollars by 2030[19]. Yet, the actual benefits of smart cities in terms of carbon emission reduction and sustainability may be overstated (Cugurullo 2018, Karvonen et al. 2018, Yigitcanlar et al. 2019) and – forestalling a bias that is also present in chapters 3 and 4 – focused on high-income countries and the global north (Tabane et al. 2019).

The last aspect of dark knowledge, which we have termed "the Scientific Tower of Babel" (4) refers to the prevailing problem that science is detached not only from general society, but that scientific (sub-)disciplines are often incomprehensible even to members of academia in other disciplines. This is particularly relevant to an inter- and transdisciplinary field like urban ecology. Thus, a clear communication among the different disciplines as well as with stakeholders, the political sphere and general public is crucial. I will address this issue in the next section.

Research and knowledge synthesis

> *"[…] the spread, both in width and depth, of the multifarious branches of knowledge during the last hundred odd years has confronted us with a queer dilemma […]. It has become next to impossible for a single mind fully to command more than a small specialized portion of it".* – Schrödinger (1944)

> "*Researchers develop studies differently in different cities, with results that are not easily comparable. For example, although urban ecological research has developed general indicators for services produced in urban ecosystems, both the indicators and their calculations are derived from a wide variety of methods […]. The barriers to comparing ecosystem services across different urban contexts are shared with other cross-system efforts, such as sustainability indicators and mileposts, responses to climate extremes, and effects of design interventions."* – McPhearson et al. (2016)

Science, now possibly more than ever, heavily relies on synthesis. With the number of scientific articles skyrocketing, many researchers, policymakers and others interested in gaining access to scientific knowledge depend on reliable research synthesis of a given research field or research question. According to Jeschke et al. (2021), "this [rapid expansion in literature] makes research relatively ineffective and inefficient, as existing evidence is often not found, collaboration opportunities are missed, and research is too often conducted in pursuit of dead ends". Research synthesis not only summarizes existing knowledge. It allows for the creative formation of new connections, that enable theory development and the formulation of new hypotheses and ideas. Research synthesis also enables the identification of gaps and biases, as we have seen in the previous

[18]https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en Accessed: 07.10.2022.

[19]https://www.precedenceresearch.com/smart-cities-market

section. To generate knowledge from a number of smaller, case-specific studies, ecologists rely on meta-analyses to combine the vast amount of different small-scale, short- to mid-term research projects. However, meta-analysis is not always possible, as we saw in chapter 3. Meta-analyses are limited by the underlying singular studies they are based on, and depending on the inclusion criteria and how the data are statistically combined, can lead to opposing results – even if the research question and the underlying data are the same (de Vrieze 2018). Meta-analyses focus on the data that is available, and often reframe the initial research questions depending on what data turns out to be available during data retrieval and analysis. Therefore, they tend not to put as much emphasis on the unknown as traditional reviews (Guzzo et al. 1987) or studies using other synthesis methods like the HoH approach or research weaving.

To make research synthesis sound and reliable, standardized methods have been developed in the second half of the past century (Chalmers et al. 2001). Different types of systematic reviews and meta-analyses are standardized, often adapted to the specificities of the disciplines they have been developed in, focusing on either quantitative or qualitative data, or a combination of both (Boaz et al. 2006, Tricco et al. 2011, Pluye & Hong 2014). Best known are meta-analyses that statistically combine quantitative effect sizes from several studies. But critical reviews, scoping reviews, mixed-studies reviews, umbrella reviews, as well as systematic maps and research weaving are examples of other synthesis methods with standardized protocols (Grant & Booth 2009, Paré et al. 2015, Peters et al. 2015, Munn et al. 2018, Snyder 2019, Page et al. 2021). Recently, automated text recognition techniques including artificial intelligence have been added to the list (e.g. Tsafnat et al. 2014, Marshall & Wallace 2019, Porciello 2020, Ryo et al. 2020, Kokol et al. 2022)[20].

Within this plethora of synthesis methods, the HoH approach was developed to enable literature synthesis of research fields with heterogeneous research methods, non-comparable statistics, and ambiguously formulated questions (Jeschke et al. 2012, Heger & Jeschke 2014, Braga et al. 2017, Heger and Jeschke 2018). These limitations are of particular relevance to the literature published on the topic of biotic homogenization (Olden 2018), as shown in Chapter 3: While biotic homogenization has been studied in different places and was repeatedly confirmed, the single studies rarely assessed the same system, and even if they seemingly did so, the results could not necessarily be reproduced. For example, biotic homogenization has been confirmed for birds and plants in McKinney (2004) and Ibáñez-Álamo et al. (2017), while Aronson et al. (2014) did not find evidence for it. For invertebrates, Niemelä et al. (2002) even demonstrated an increase in β-diversity in urban areas. The evidence map presented in chapter 3 can be regarded in this context: Each facet shows the amount of studies that can count to some degree as replication of each other, because they study the same aspect of the hypothesis in question (here: biotic homogenization in and of cities).

[20] They had already been added to that list in 1993, but are only now becoming relevant (see Bratko 1993).

Research synthesis often focuses on specific research questions and hypotheses. But how can researchers (and others) navigate between them, and find relevant ones? One answer is by creating maps.

Maps as synthesis tools

> "*I sense that humans have an urge to map – and that this mapping instinct, like our opposable thumbs, is what makes us human" – Katharine Harmon, cited from* Börner (2010)

Communication between researchers within the same discipline can be challenging, with terminology being used with different connotations (as illustrated in chapter 3). It gets only harder when navigating between different disciplines, but in urban ecology, very different disciplines, with very different methods, questions, and understandings of knowledge, all study the same system (cities)[21]. Meanwhile, urban ecology shows an increase in publications around the turn of the millennium comparable to other active research fields (Zhang et al. 2015). So how can researchers, both from within one discipline and across disciplines, and those that use the knowledge generated from urban ecology, keep track of all the information, and find the knowledge they are looking for?

One answer are maps. Maps of science (or specific research fields) visually guide us through the complex social and topical structure of research disciplines. They can help guide scientists from both within and outside the discipline, as well as policy makers or others interested in the field. Maps and networks are being more and more applied in literature syntheses and as a tool to structure growing research fields. Numerous maps of science have been published (see Klavans & Boyack 2009, Leydesdorff et al. 2013). Most commonly, such maps are based on bibliographic data (Petrovich 2021), although networks of scientific research can also be applied to organize other entities in a scientific research field (researchers, journals, research institutes, topics, theories). In chapter 2, my co-authors and I chose hypotheses as central units to structure the network.

[21] To illustrate this, I selected two excerpts from very different parts of urban ecology, the first from environmental geography (1), the second from climatology (2):

(1) *"We can think of the wild as the commons, the everyday affective site of human-nonhuman entanglement. Politics in the wild involves democratizing science, relinquishing the authority that comes with speaking for a singular Nature. Multispecies, often urban, wilds are where political life takes place now that laboratories of modern science have taken over the world and we have all become caught up in the global experiment that is the Anthropocene."* (Lorimer 2015, p. 11)

(2) *"The system functions easily and inexpensively in any city or region. We therefore anticipate that it can meet a basic requirement in urban climate studies through standardized description of surface structure and cover; meaningful definition and intercity comparison of UHI magnitude ($\Delta_{TLCZ\,X-Y}$); guided exploration of heat island causes and controls; clear communication of site metadata; and inter-disciplinary transfer of urban climate knowledge" (*Stewart & Oke 2012, p. 1894)

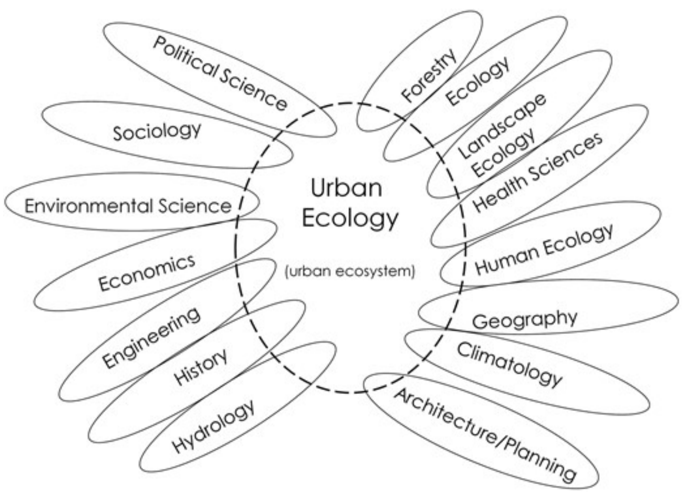

Figure D.3 Multiple disciplines all intersect with the field of urban ecology. Most of my co-authors (and I) are situated within ecology. Figure from McDonnell (2015)

A map of hypotheses grouped by focal topics and ecological drivers can help to identify related research hypotheses and visualize the theoretical structure of a field. The seminal advantage of using hypotheses is that they can in a second step get connected with related empirical evidence and linked to research syntheses. In invasion ecology, a list of 29 leading hypotheses was introduced by Catford et al. in 2009 and subsequently structured in a network (Enders et al. 2018, 2020). An interactive platform is currently under development for hypotheses in invasion ecology [https://hi-knowledge.org], in which available evidence for the selected hypotheses can be accessed directly from within the network. The map laid out in chapter 2 is intended as a template for an interactive map of urban ecology, in order to expand this knowledge portal in the future. Chapter 2 is the first attempt to draft a map of urban ecology as a reference point for researchers from all disciplines, clustering hypotheses and concepts into themes. Its aim is to frame a "common knowledge base" for urban ecology, and based on a collection of hypotheses from urban ecology that I assembled together with urban ecology researchers, mainly based in Berlin. The selection of hypotheses is not exhaustive, which is why we invite other researchers to contribute additional hypotheses to an open Wikidata-Project[22]. Ideally, the network will be interactive and kept alive, i.e. extended and reshaped, from within the urban ecology community. In the future, a near exhaustive map, that becomes only possible with community efforts would be a quick tool to spot gaps in research, and to navigate among research questions.

Taking the high trans-disciplinarity of urban ecology seriously, the map, if it were to grow towards disciplines like qualitative geography, ethnography and the like, hypotheses may not be an ideal unit for the interconnected links. Alternatively, it could include concepts, or just structure scientific publications by topics, methodology, or focal entity. The obvious advantage of hypotheses, as mentioned above, is that they can in a second step be linked with empirical evidence and structured into narrower sub-hypotheses. This allows to identify gaps and empirical support, and identify particularly fruitful and well established as well as unsupported hypotheses. It is difficult to imagine

[22] Wikidata is a community-curated project that adheres to the standards of open and reproducible science (Wilkinson et al. 2016, Waagmeester et al. 2020).

that something similar would be possible in less hypotheses-centred research disciplines, where it may be much more important to navigate among concepts and discourses. In any case, an expansion of the network to become fully interdisciplinary will require in-depth exchange with other disciplines, and creating joint maps may be a promising first step to strengthen transdisciplinary collaboration (Brown et al. 2015, Marrone et al. 2020, Hundsdörfer 2022).

Urban ecological knowledge in the Anthropocene

According to Marina Alberti, urban planning must consider a high level of uncertainty, and has to account for the unknown. The unknown that she describes is a consequence of the nature of urban complexity, and our inability to predict the future when it comes to environmental and social threats. Looking at all the biases and problems that have been found in other disciplines (see introduction and chapter 1), and that at least to some degrees are present also in urban ecology as shown in chapters 2-4, it becomes clear that 'accounting for the unknown' could, and I argue should, be extended to 'accounting for biases, knowledge gaps and the unknown'.[23]

While the concept of dark knowledge is certainly relevant for urban ecology in the Anthropocene, I suggest that two extensions should be made: The concept of knowledge in the dark originally refers to individual knowledge. In urban ecology, and for decision making in an urban policy environment, individual knowledge is less relevant than collective knowledge (even if collective knowledge can be seen as the culmination of individual knowledge). In fact, the underlying causes for knowledge in the dark that we identified in chapter 1, like financial interests or language barriers to knowledge transfer, are at least as relevant, if not more, for collective scientific knowledge. Second, our concept of knowledge in the dark currently underestimates the importance of local and indigenous (i.e. to a large degree practical and acquaintance knowledge), as it is focused on scientific knowledge generated in academia. However, other forms of knowledge do play a very important role for sustainable urban development, both in decision making, and as a basis for scientific discourse.

In my thesis, I asked how urban researchers can combine their knowledge and facilitate interdisciplinary knowledge exchange. In discourses and research on ecology and nature conservation, the terms indigenous knowledge, local knowledge and traditional knowledge are now widely present. The IPBES framework explicitly aims to cover types of knowledge other than scientific. Knowledge synthesized and represented by IPBES aims to be unambiguous, but at the same time also "adaptable, sharable and reusable" (Dunkley et al. 2018). Interestingly, knowledge synthesis in IPBES is defined as "a concise summary in words or pictures" (Diaz et al. 2015a), which should of course be expanded to maps. In an urban context, indigenous and local knowledge are not less relevant (e.g., Wisner 1995, Corburn 2007), as planning must account for the cultural setting of a city, town, or urban community (Corburn 2003, Nelson et al. 2007). Urban ecology and urban planning in the Anthropocene, which is confronted with all the environmental and social uncertainties and

[23] Studying at research on smart cities could be a very insightful case-study to combine both aspects, i.e. Alberti's uncertainty-argument, and our concept of dark knowledge. It would be interesting to understand biases in how and what possible effects are selected and studied, and if smart city plans are taking uncertainty and risk sufficiently into account.

risks stressed by Marina Alberti, should actively embrace co-creation, community expertise and traditional local knowledge (Sharifi & Yamagata 2018).

Building and transforming environmentally sustainable cities is a crucial leverage point to tackle the sustainability crisis (Mills 2007). Urbanization is responsible for environmental degradation and pollution at the local and global scale, with urban areas estimated to directly or indirectly cause over 70% of global CO_2-emissions[24]. Urbanization is also expected to (directly) cause at least a quarter of projected habitat loss in the next 30 years (Simkin et al. 2022). There is no way to act on climate change and the biodiversity crisis without profoundly lowering the environmental impacts of human cities and settlements that reache far beyond the boundaries of urban areas (McDonald et al. 2019). In October 2017, a couple of months after the US under Donald Trump withdrew from the Paris Agreement, mayors of over a hundred cities in the US pledged to the C40 climate action plan, bringing the US climate policy back on track, and in 2020, The Guardian quoted Boston's mayor Marty Walsh: "I think that Donald Trump's inaction in the long run hopefully will be good for the climate, because it's energised and activated more mayors to do more." Global networks like 'Cities with Nature' and ICLEI (local governments for sustainability) aim to foster biodiversity and green infrastructures that promise multiple ecological and social benefits for the urban population. Reiterating that urban areas are also disproportionally higher threatened from climate change and environmental degradation (Grimm 2008, Boyd & Juhola 2015, Kumar 2021), city administrations are increasingly recognizing their role at the forefront of the sustainability crisis.

Cities may be the most important, but also the most promising places for sustainable change to happen (Mi et al. 2019). Urban ecologists, in turn, are no longer (and possibly never have been) part of the impartial scientific endeavour that seeks knowledge out of a pure desire to know, but are constantly reminded of the explicit purpose to produce knowledge that is useful in the Anthropocene. City administrations, to turn back again, rely on sound, reliable knowledge as a basis for urban planning and decision making. Reliable and accessible synthesis tools are the basis for the necessary knowledge exchange, and structuring them as maps will be a promising way forward.

Conclusions and outlook

There are three core implications that can be carved out from the four chapters of this thesis. The first implication is a reform of the academic system, comprising the "paths forward" discussed in chapter one (e.g., open science, a diverse evaluation system and a scientific court of arbitration). Since the onset of the replication crisis, some major improvements have been proposed, and some very successfully implemented. Many journals and funding agencies now have strict Open Access and Open Data policies. Publishing null and negative results is encouraged, and issues surrounding biases and data quality are increasingly taught in undergraduate classes. In urban ecology, the Journal of Urban Ecology was founded as an Open Access journal in 2015, but as stressed further above, the reproducibility crisis has not echoed much into the field of urban ecology, and the decision to make the Journal of Urban Ecology Open Access was motivated in providing "much needed access to this information by readers from developing countries where the need for this

[24] http://www.globalcarbonatlas.org/en/content/global-cities-emissions

information is the most pressing, as well as increasing access within the ranks of non-academic urban ecology practitioners" (McDonnell 2015, p 1) – which is an important goal, but clearly not a response to the replication crisis. However, it leads me to the second implication, that knowledge, and especially 'urban ecological knowledge in the Anthropocene', has to be made accessible and findable. One of the ways forward may be, as outlined in chapter 2, a map of urban ecology, especially if it is designed as an open, interactive tool that gets adopted by the transdisciplinary community, and if it will be, in a second step, integrated with other forms of knowledge, especially local and practical knowledge.

The third and final implication is that gaps and biases must be detected, and scientists (and others) be made aware of them. This leads us back to the topic of research and knowledge synthesis, the major theme of this thesis. As stated above, modern research synthesis has to account for big data, digital interconnectedness and the (seemingly) endless availability of knowledge. Scientists can instantaneously access millions of articles from bibliometric databases like the Web of Science or Google Scholar. Yet, a disquieting number of articles that floats in the digital realm of accessible knowledge will never get cited and are doomed to quietly disappear from the scientific hive mind. There are synthesis tools that help to overcome the natural limitations of our brain capacity, by focusing on visualization and structure, and thus tackle the problem of information overflow, like research mapping and research weaving, evidence gap maps, and the HoH approach used in chapter 3. Several online tools[25] have been developed to make it easier to find relevant data and results, and on the level of practicioners of urban ecology, networks like iclei or C40 enable knowledge exchange, and share best practice experiences. Considering the problems of the scientific publication system, including the limitations of peer-review, it might be time for science to take a whole new direction in producing meaningful and sound knowledge, and gather data openly and in relation to specific questions and hypotheses, without the immanent pressure to produce publications. Pangeo (Perez et al. 2020) and BRAIN (Pan-Neuro) are initiatives from the geo-sciences and neurobiology that are following such a path. Also, knowledge synthesis would benefit profoundly from making it community-based, as suggested in chapter 2 (see also Nakagawa 2020). In theory, a network-based website like hi-knowledge.org could, for example in concert with Wikidata, provide an infrastructure to collect hypotheses and research question-based raw data for ecology, including urban ecology. Such a tool would certainly contribute to tackle knowledge in the dark.

It is important to note that the concept of knowledge in the dark is not restricted to a particular form of knowledge, like academic knowledge. According to Renn (2020), knowledge production in the Anthropocene must overcome the fragmentation of single disciplines and join forces with others, including artists and non-governmental organizations (NGOs) among others. Knowledge in the Anthropocene, consequentially, also includes non-scientific knowledge. With architects and ecologists working together, artists joining geographers and the like, maybe more than most scientific disciplines, urban ecology is already on that path. And as Paul Crutzen argues: "get[ing] our minds around such massive issue as climate change", and I freely add here to his quote the enormeous challange to make cities sustainable, "[…] may require taking a serious step back, and

[25]Examples are projects like Open Knowledge Maps, WikiData, CoCite and Scholia

becoming more reflective about how our own thoughts work. If we can learn to do this, then not only will we be able to forecast a safe Anthropocene, but perhaps even more importantly: a beautiful Anthropocene." (Crutzen 2021, p. 277)

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Appendix

Supplementary Material to: Chapter 1 - Knowledge in the Dark: Scientific Challenges and Ways Forward

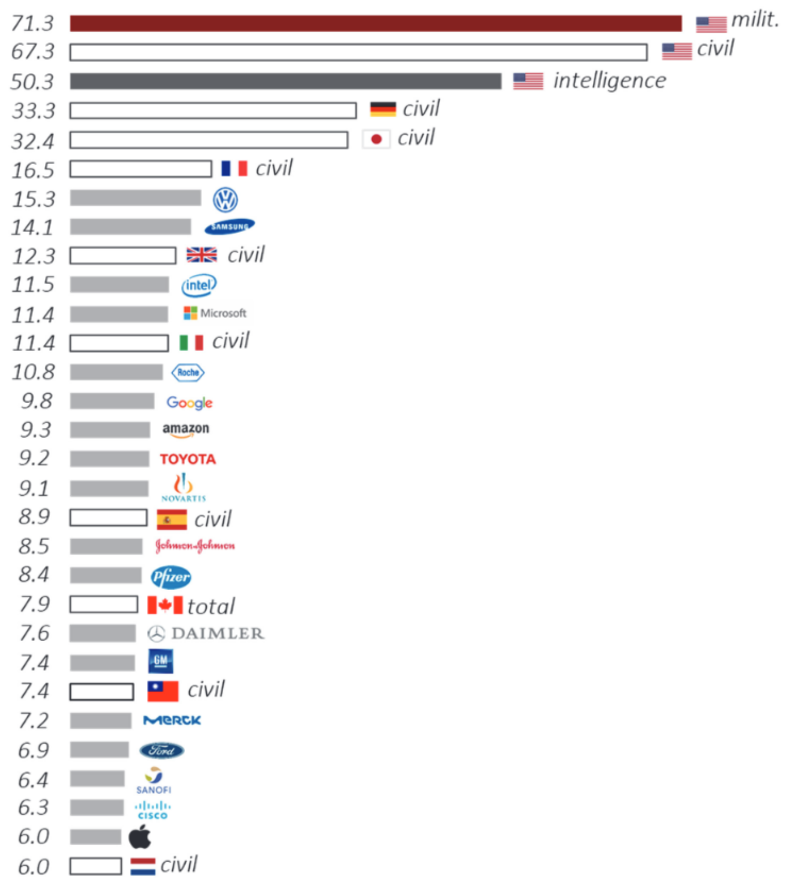

Figure S1.1 Selection of global top investors into research, development or intelligence in 2015: countries and companies with R&D or intelligence expenditures of 6 billion US$ or more in 2015 where data were available to us. Expenditures of countries are divided into military, intelligence and civil (incl. universities) due to the different interests and publication strategies of these sectors (data from: ODNI 2017, OECD 2017, PWC 2017; expenditures from countries such as China or India were not available to us).

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Supplementary Material to: Chapter 2 – Hypotheses in Urban Ecology

Network Analysis: Methods

We performed two steps to cluster hypotheses in the bipartite network. First, they were clustered by applying four frequently used algorithms implemented in the R-package igraph: edge-betweeness or GN algorithm (Newman & Girvan, 2004), Fastgreedy (Clauset et al., 2004), Walktrap (Pons & Latapy, 2006), and the leading-eigenvector algorithm (Newman, 2006). All four algorithms evaluate network partition into disjoint node communities or clusters by calculating modularity (see Newman & Girvan, 2004).

Second, we applied PsiMinL, an algorithm that clusters links instead of nodes. The clusters calculated in step 1 were used as seed clusters, which are then optimized by PsiMinL. PsiMinL evaluates each cluster separately with a function Ψ (normalised node-cut, Havemann, Gläser & Heinz, 2017; Havemann, 2021). Clustering links has the advantage that a node can be a member of more than one cluster according to the clusters its links belong to, or in other words, we obtain overlapping clusters of nodes. This corresponds to our assumption that a hypothesis can have similarities with two other hypotheses that are themselves not very similar with each other and are therefore not in the same cluster.

Link clustering was introduced by Evans & Lambiotte (2009) and by Ahn, Bagrow & Lehmann (2010). In their approaches, graph partitions of disjoint clusters of links are constructed, which result in overlapping clusters of nodes. In contrast to these methods that evaluate the partition of the entire network, PsiMinL evaluates each link cluster independently from other clusters. It can therefore produce clusters that overlap with each other not only in their boundary nodes, but also in inner links and nodes.

PsiMinL calculates Ψ, with minimal values characterizing a maximally separated link cluster. Thus, clusters can be ranked by their Ψ-value, with the best cluster having the smallest value. PsiMinL operates in a model landscape, the Ψ-landscape. Each place in this cost landscape represents a link set L, with neighboring places differing in one link. A resolution parameter r controls the distance of a local minimum that corresponds to a valid cluster to the next deeper place in the landscape: If a local minimum has no deeper place inside a circle of radius $r|L|$, the corresponding cluster is considered to be valid. We set $r = 1/3$, but started with $r = 1/20$ and used the results as seeds for new evolutionary searches in the Ψ-landscape, but now with $r = 1/10$. This was repeated for a sequence of values of resolution parameter r (1/20, 1/10, 1/5, 1/4, 1/3).

PsiMinL was implemented as a (yet unpublished) R-package. It belongs to the class of so-called evolutionary algorithms, which apply operators constructed in analogy to biological evolution. Thus, random "genetic" operators (mutation, crossover) are followed by a selection of the fittest individuals in a model population, which in the case of PsiMinL is formed by some link sets corresponding to places in the Ψ-landscape. Moreover, PsiMinL combines random operators with deterministic local searches in the Ψ-landscape, i.e. it can be called a memetic algorithm (Neri, Cotta & Moscato, 2012). After each random step, a deterministic greedy algorithm is applied, which finds the steepest way down in the Ψ-landscape by excluding and including links. Depending on the resolution parameter r, a local search can tunnel through barriers in the landscape if the end of the tunnel is not too far from its entry (Havemann, 2021, p. 207). A local search starts from the seed subgraph. Then the evolving population is established by mutating the obtained subgraph. The technical parameters of PsiMinL (like population size, mutation rate, maximum number of generations, etc.) do not affect the results, but only the time needed to find them. We here chose the same parameters as Havemann (2021).

Results & Discussion

The four cluster algorithms implemented in the R-package igraph (GN, Fastgreedy, Walktrap and the leading-eigenvector algorithm) led to different clusters, but similar values of modularity: Fastgreedy clustering (6 clusters) had the highest (i.e. best) modularity (0.4), followed by Walktrap (5 clusters) and leading-eigenvector algorithm (4 clusters) with 0.38 and the GN-algorithm (9 clusters) with a modularity value of 0.33.

The 24 clusters obtained from all four algorithms were then used as seed subgraphs for evolutionary minimization of normalized node-cut Ψ. Disjoint clusters forming a network partition are not very well suited as seed subgraphs for an algorithm that evaluates clusters independently from each other. Therefore, we also inspected the dendrogram (see Figure S1) delivered by igraph for the Walktrap algorithm and searched for long branches corresponding to well separated and cohesive clusters (cf. Havemann, 2021, p. 210). Indeed, we found one additional link cluster by using seven of those visually identified Walktrap clusters as seeds and confirmed others (Figure S1).

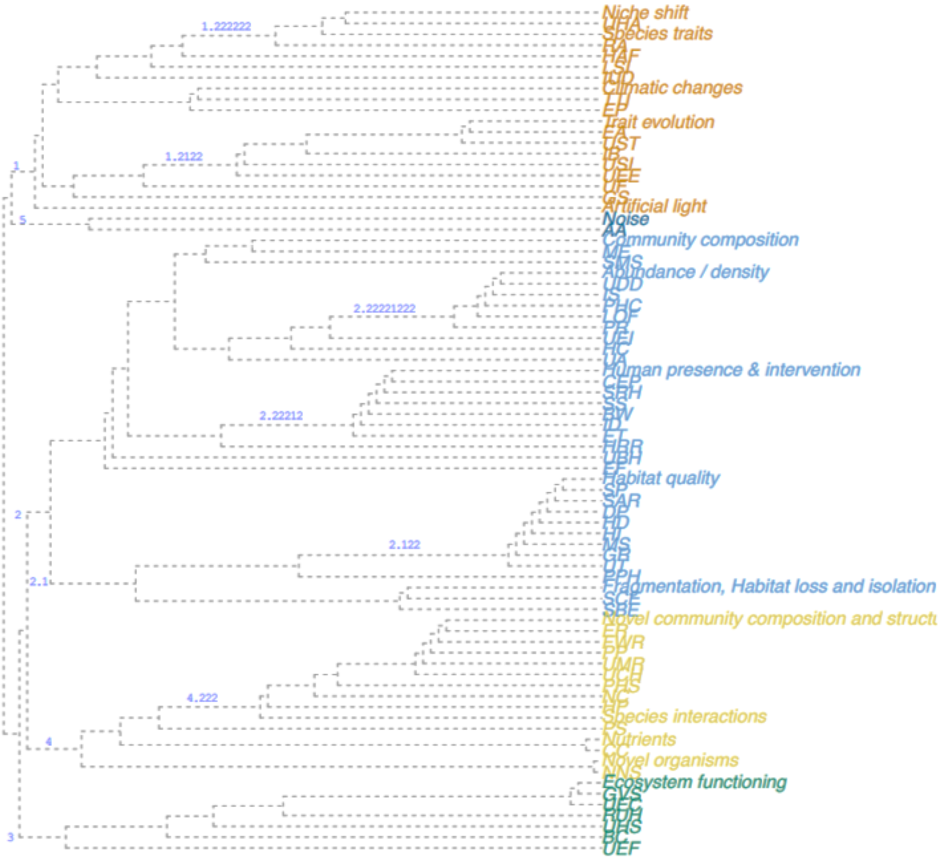

Figure S2.4 Dendrogram of clusters calculated by igraph's Walktrap algorithm.

The paths through the Ψ-landscape starting from the seeds ended in eight local minima for a resolution of r = 1/3. In Table S2.2 you find their sizes and Ψ-values together with the seed numbers corresponding to clusters obtained by edge-betweeness algorithm (eb), Fastgreedy (fg), leading-eigenvector algorithm (le), and Walktrap (wt). Some seeds led to the complement of L1 which has the same Ψ-value as L1 by definition (Havemann, 2021). L3 was found from a subset of the Walktrap cluster wt2. Using the results of the walktrap algorithm resulted in all relevant clusters, which were in part also identified by the memetic searches using the other three igraph algorithms. Figure S2 shows the cost-size diagrams of the search paths through the Ψ-landscape when applying PsiMinL to the walktrap seeds.

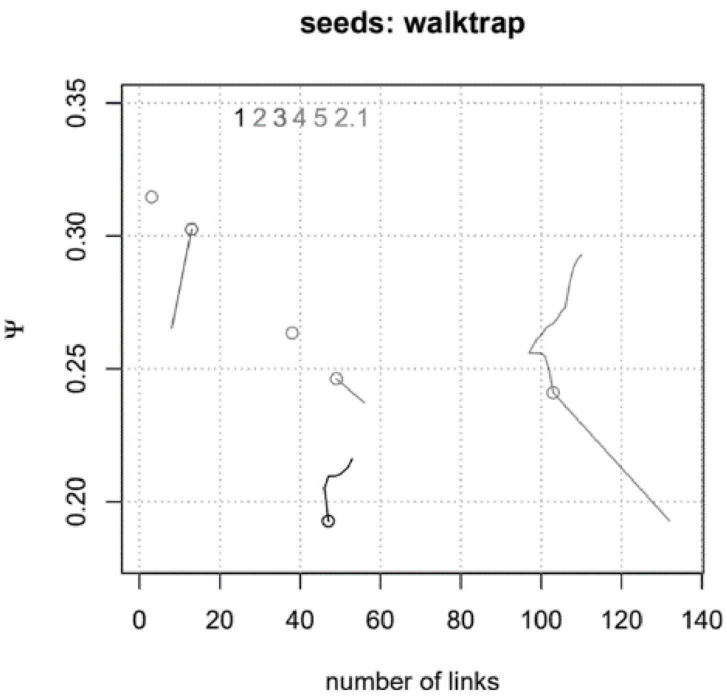

Figure S2.3 Paths through the Ψ-landscape for six seed subgraphs obtained from Walktrap. It shows a projection of paths through the Ψ-landscape onto the height-size plane. For seed wt1, the initial local search (black curve) ends in a subgraph (L1, black circle) that was not improved by memetic search. Seed wt2 was improved by a local search (red curve) and also by a memetic one (straight red line), reaching finally the complement of L1. For seeds wt3 and wt4, Ψ could only be minimised by memetic searches (green and blue lines), resulting in L4 and L2, respectively. Seeds wt5 and wt2.1 were not improved by any search: wt5 = L5 (turquoise) and wt2.1 = L3 (purple).

Table S2.1 Seven link communities (resolution r = 1/3) ordered by Ψ; size is given as number of links and as sum of membership grades of nodes (µtotal).

name	links	μ_{total}	Ψ	seeds
Cluster I – L1	47	22.827	0.1928	eb4, fg1, fg2, le3, wt1
L0 – L1	132	55.173	0.1928	eb1, le1, le4, wt2
Cluster II – L2	56	21.712	0.2372	eb3, fg3, fg5, le2, wt4
Cluster III – L3	38	15.872	0.2635	wt2.1
Cluster IV – L4	8	4.945	0.2653	eb6, fg4, wt3
L5	3	2.144	0.3147	eb2, wt5
L6	9	3.631	0.3725	fg6
L7	7	2.546	0.4054	eb8

All three links of L5 are also part of L1. L4 is a link subgraph of L2. L2 and L3 are subgraphs of L0 – L1 and have one link in common. When we neglect this link and the two small and least well separated clusters L6 and L7, we obtain a hierarchical order of link clusters (Figure S3). L6 and L7 are both partly in L1 and in its complement L0 – L1.

```
          L0
 _______|_______
|               |
L1            L0-L1
|            ____|____
|           |         |
L5          L2        L3
            |
            L4
```

Figure S2.4 Approximative hierarchy of the main clusters we identified.

The modularity values of the four rather different disjoint node clusterings did not differ substantially, a well-known phenomenon (Fortunato, 2010, p. 114), which reflects that often objects (in this case: links and nodes in a network) can be partitioned in different ways that are equally well justified (Gläser et al., 2017). We did not expect that all 24 seed-node clusters would overlap with the five hierarchically ordered link clusters. But exact matches in two cases (L3 = wt2.1, L5 = wt5) and good ones for others (e.g. L1 and wt1) indicate a consensus, which validates the identified clusters. Based on normalised node-cut Ψ, the best separation of the graph into two link sets is found on the highest hierarchical level between L1 and its complement. Three small valid link clusters are not so well separated from the rest of the graph when separation is measured by Ψ (L5, L6, L7).

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