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REVIEW ARTICLE

Novel ecosystems: a review of the concept in non-urban and urban contexts

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Abstract
Context Anthropogenic changes (e.g., climate change, land-use change, species introductions, etc.) are reshaping ecosystems processes and patterns and causing an intense reorganization of the Earth's biotic systems. As a result, unprecedented combinations of species are emerging, forming "novel ecosystems".
Objectives The goals of this work are: (1) to examine the history and relevance of the novel ecosystems concept in non-urban and urban contexts, and (2) to evaluate what has been the focus of the research about the novel ecosystems concept in non-urban and urban contexts.
Methods Through an extensive systematic review, we collected 548 records published between 1997 and 2018. After applying inclusion/exclusion criteria the final database comprised 255 relevant records that were further examined and classified according to the scope of this review.
Results Our results demonstrated that research referring to the novel ecosystems concept has been mainly focused on non-urban areas. Still, there is a growing interest in exploring this concept in the urban domain. The definition and criteria used to describe novel ecosystems have been transforming over the years. Research has been mainly targeted on multiple taxonomic groups and plants, on terrestrial ecosystems, and conducted in North America. Overall, restoration ecology, conservation, biodiversity, ecosystem services, and climate change have been the most discussed topics in the novel ecosystems' literature.
Conclusions Our review confirms that the application of the novel ecosystems concept to urban areas is pertinent and auspicious. Future research should seek to understand the limits and differences of novel ecosystems in non-urban and urban contexts.

Keywords Anthropocene · Novel ecosystems · Urban context · Conceptual framework · Systematic review

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Introduction

Over the past years, human actions and movement, technological advances, and global trade have emerged as drivers of change, allowing the spread and introduction of species into regions that would probably never have been reached in different circumstances (Harris et al. 2006; Hobbs et al. 2006). These rapid transformations have contributed to a biotic globalization and, consequently, to the reconfiguration of ecosystem processes and patterns (Ellis 2015). As a result, new species combinations are emerging throughout the globe, forming what is being designated as "novel ecosystems" (sensu Hobbs et al. 2006).

Due to anthropogenic factors and by the addition and/or loss of species (species migrations, introductions, and extinctions), these systems are unprecedented and composed by an assemblage of native and non-native organisms that may have never coexisted before (Seastedt et al. 2008; Higgs 2017). Nevertheless, the movement and introduction of species is not a recent phenomenon and has occurred for many millennia (Hobbs et al. 2006). Many non-native species were intentionally introduced (legally or illegally) to increase or restore specific ecosystem services, to produce goods and food, and even for ornamental purposes (Wilsey et al. 2011; Potgieter et al. 2019). Whereas other introduced species were accidentally transported to new regions through shipping products such as timber or fruit, ballast water, by hitchhiking on people traveling, etc. (Simberloff et al. 2005). Some introduced species adapted to the new conditions in which they were placed and acquired the ability to overcome barriers that were limiting their reproduction and dispersion (Richardson et al. 2000; Kowarik 2011).

Also, ecosystems have been experiencing periodic changes over the past millennia in response to disturbances (Williams and Jackson 2007; Hobbs et al. 2009). Thus, novel ecosystems are *novel* in the sense that recent and increasing human pressure has been responsible for complex and accelerated rates of change (Hobbs et al. 2006; Lindenmayer et al. 2008). Since the effects caused by the human agency on the planet are becoming more and more pervasive (Hobbs et al. 2009; Ellis 2013; Kueffer and Kaiser-Bunbury 2014), many scientists are accepting that the planet has entered a new geological epoch labeled as "Anthropocene" (sensu Crutzen 2006).

Given important issues and concerns raised by the emergence of novel ecosystems and the effects of the anthropocene, this concept has been mostly discussed within the restoration ecology and conservation biology disciplines (e.g., Lindenmayer et al. 2008; Hobbs et al. 2009; Hobbs 2013; Perring et al. 2013b; Guan et al. 2018). The challenges posed by novel ecosystems are transforming the foundations of these disciplines. Traditionally, ecosystems are managed and preserved according to historical references (Seastedt et al. 2008). Nevertheless, the idea that it is possible, realistic and desirable to return to a historical state (i.e., prior to human-induced disturbances) is being widely questioned (e.g., Seastedt et al. 2008; Hobbs et al. 2009, 2011; Perring et al. 2013b). Recovering historical conditions (abiotic and/or biotic) in a particular area may even have several undesirable consequences. Besides entailing an enormous amount of resources and effort, it may lead to the creation of ill-adapted populations that are more susceptible to future changes, including climate change and local extinction of species (Millar et al. 2007; Perring et al. 2013b).

This way, new paradigms are arising due to the emergence of novel ecosystems. According to Dooling (2015), rather than restoring previous conditions, the challenge of the moment is to realign the systems for present and future conditions so that organisms respond adaptively to change. Develop a unique and efficient method to manage novel ecosystems will, therefore, be an extremely difficult and possibly ineffective task (Seastedt et al. 2008). Not only will a combination of approaches be required to achieve multiple objectives (Hobbs et al. 2014), but actions will have to be adapted to each context (Kueffer et al. 2010). A more integrated, dynamic and flexible approach will allow managers to consider several options in different scenarios and will enable them to make more efficient decisions that are anchored in the current reality of rapid ecosystem change (Hobbs et al. 2014).

However, it is important to safeguard that more flexible methods do not imply the abandonment of all previously established values and guidelines, but rather consider several possibilities to deal with an uncertain future (Hobbs et al. 2009; Standish et al. 2013b). Hobbs et al. (2006) argue that currently less affected areas must be conserved first and resources should not be spent to recover systems that are less likely to recover. In this respect, the identification of novel ecosystems can be extremely useful to avoid the misuse of scarce resources on attempts to return these systems to historical conditions (Perring et al. 2013b).

In the urban context, the effects of human agency and the anthropocene can be even more pronounced (Schmidt et al. 2014), since cities are artificial and deeply constructed systems where human population is more concentrated (MEA 2005; Perring et al. 2013a). Urban areas result from diverse and complex interactions between socioeconomic factors and biophysical processes (Schaefer 2011) and are constantly exposed to a variety of disturbances (Schmidt et al. 2014). Due to transport networks and human activities and preferences, cities are often the entry points of many introduced species (Perring et al. 2013a; Gaertner et al. 2017). Additionally, urban ecosystems have different physical and chemical properties in contrast with non-urban areas, which highly influences species distribution and ecosystems functioning (Kowarik 2011; Perring et al. 2013a). This way, as a whole, urban areas have been usually considered *novel* in relation with their non-urban counterparts (Kowarik 2011), because novelty tends to manifest and be widespread in these populated regions (Hobbs et al. 2014). However, when analyzing cities in a more detailed scale, urban areas are comprised by a variety of fragmented habitats with different degrees of novelty, land-use legacy, and pace of transformation (Kowarik 2011; Perring et al. 2013a).

Over recent years the novel ecosystems concept has been largely discussed (Chapin III and Starfield 1997; Hobbs et al. 2006, 2013a; Lugo 2009; Davis et al. 2011; Higgs 2017). The definition and value of novel ecosystems have been questioned (e.g., Aronson et al. 2014; Murcia et al. 2014; Simberloff 2015; Kattan et al. 2016), generating divergent opinions within the scientific community and triggering an intense debate around the concept. This debate often generates more misunderstanding instead of providing elucidation about the concept, so a review of the literature about novel ecosystems is fundamental. Previous studies have already reviewed the concept regarding different aspects (e.g., Perring et al. 2013b; Collier and Devitt 2016), but systematic reviews usually provide a more inclusive overview of topics.

In this sense, a systematic review about novel ecosystems and novel urban ecosystems may be useful to provide a much-needed clarification about the concept definition, history, and value, as well as to reflect on future research opportunities and challenges. This way, the specific goals of this systematic review are (1) to examine the history and relevance of the novel ecosystems concept in non-urban and urban contexts and (2) to evaluate what has been the focus of the research about the novel ecosystems concept in non-urban and urban contexts.

Methods

Literature search

This systematic review was conducted following the guidelines provided by the CEE (2018). The literature search was performed in ISI Web of Science Core Collection, Scopus, and ScienceDirect using the search terms "novel ecosystems" OR "novel urban ecosystems". The time span of the search corresponded to "all years" to 2018 and the searches were conducted in April 2019. Records retrieved from each search database were combined and stored in the referencing software EndNote X8 where duplicate records were removed, resulting in a total of 548 unique records.

Inclusion/exclusion criteria were applied by screening individually each record at two distinct stages. First, the title and abstract were examined to identify potentially relevant records, and then the full text was reviewed. For a record to be considered as relevant it had to discuss and explore the concept (and not just mention it), contribute to a better understanding of novel ecosystems and/or provide case studies or examples of novelty around the globe. This process resulted in a database with 232 relevant records.

To ensure a comprehensive review of the literature about the subject, additional searches were performed in Google Scholar using the same search terms. The full text of the first 50 hits was assessed and relevant records that were absent from the database were added. The reference lists of the records of the database were also examined—snowballing method (see CEE 2018 for details). Relevant records that were absent from the database were included, resulting in a final database with 255 records (Fig. 1; see Supplementary Material Appendix A for details on the literature search process and on the inclusion/exclusion criteria used). Although there was an effort to collect all the relevant literature about this concept, we note that this may not have been completely possible for two main reasons: (1) in an earlier phase the concept had other designations such as "synthetic

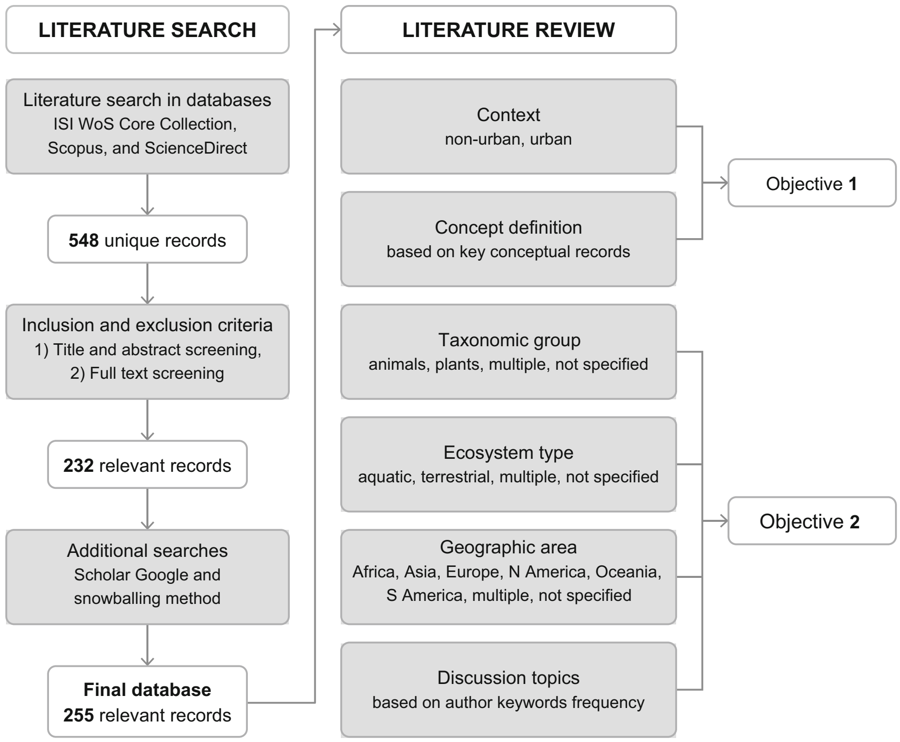


Fig. 1 Literature search and literature review process. We first searched for records in ISI Web of Science Core Collection, Scopus, and ScienceDirect. To select relevant records, inclusion and exclusion criteria were applied at two distinct stages. Additional searches were conducted using Scholar Google and the snowballing method. The final database was reviewed and classified according to the context and concept definition (to address objective 1), taxonomic groups, ecosystem types, geographic areas, and discussion topics (to address objective 2)

ecosystems" (Odum 1962) and "emerging ecosystems" (Milton 2003), and (2) since the term "novel ecosystem" has been disapproved by some researchers it may exist other publications about the concept that are simply using other terminology.

Literature review and data analysis

The full text of each record from the final database (n = 255) was reviewed to address the objectives of this work (Fig. 1). To examine the history and relevance of the novel ecosystems concept in non-urban and urban contexts (objective 1) we started by analyzing individually each record. Then we were able to classify each record according to the context: records focused on non-urban contexts (which we associated with the broader concept, i.e., novel ecosystems), and records focused on the urban context (which we associated with novel urban ecosystems) (see Supplementary Material Appendix B). Even records that were not retrieved using the keyword "novel urban ecosystems" on the literature search could have been classified as records focused on the urban context. We created a line graph with the number of published records per year, distinguishing the context of the records (non-urban and urban) with colors. We also represented differently 42 records that constitute the book chapters of a seminal book about the concept (Hobbs et al. 2013a) using column bars. Otherwise, the total number of records in the year 2013 would be biased and anomalous (note that the book and the 42 chapters were retrieved individually from the search databases, comprising a total of 43 records within the overall 255 records of the final database). To examine more closely how the concept has been altering through time, we identified key records that provided a conceptual framework and a definition of novel ecosystems in non-urban and urban contexts. These definitions were organized in a table and examined against a set of criteria proposed by Morse et al. (2014).

To evaluate what has been the focus of the research about the novel ecosystems concept in non-urban and urban contexts (objective 2), first, each record was classified according to three categories: taxonomic groups, ecosystem types, and geographic areas (see Table 1 for details and Supplementary Material Appendix B). We created stacked bar graphs with the number of published records per year for each category. Records focused on non-urban contexts

Table 1 Categories (taxonomic groups, ecosystem types, and geographic areas) and the corresponding classes used to classify the records of the final database (n = 255)

Categories	Classes
Taxonomic groups	
What is the taxonomic group of focus?	Plants, Animals, Other taxa, Multiple (i.e., more than one taxonomic group), Not specified (i.e., no taxonomic groups are specified or referred)
Ecosystem types	
What is the ecosystem type of focus?	Aquatic, Terrestrial, Multiple (i.e., more than one ecosystem type and/or ecotones), Not specified (i.e., no ecosystem types are specified or referred)
Geographic areas	
What is the geographic area of focus?	Africa, Antarctica, Asia, Europe, North America, South America, Oceania, Multiple (i.e., more than one geographic area, regions within more than one continent and/or when the focus is the entire globe), Not specified (i.e., no geographic areas are specified or referred)

were placed on the top and records focused on the urban context were placed in the bottom. The 42 book chapters from the comprehensive book (Hobbs et al. 2013a) were represented separately by column bars. Additionally, to analyze with more detail the geographic areas of the records, we created a map with the geographic distribution of the studies. We have only included in the map the studies that provided details on the specific location (n = 136), therefore the remaining studies conducted on multiple geographic areas and without specified location (n = 119) were not included. Finally, we identified which have been the most discussed topics in the literature regarding the concept in non-urban and urban contexts, by analyzing the frequency of author keywords of the records. We used the software VOSviewer 1.6.11 (van Eck and Waltman 2010) to generate maps in which author keywords frequency were represented (see Supplementary Material Appendix C).

Results and discussion

History and relevance of the concept in non-urban and urban contexts

The final database included 255 records distributed through 22 years of publications, from 1997 to 2018 (Fig. 2). The high number of publications in a short period of time highlights how recent, yet trendy, the novel ecosystem concept is. The majority of the records (87.1%) were focused on non-urban contexts and the remaining 12.9% were targeted on the urban context.

The "novel ecosystems" term was first used about two decades ago (Chapin III and Starfield 1997), but only later the first definition of the concept emerged in a seminal paper by Hobbs et al. (2006), placing novel ecosystems in the spotlight. In the origin and formulation of the concept, other terms were used to designate the concept even though they have not persisted in the literature. From Hobbs et al. (2006) paper it is possible to verify that the concept was based on what Howard T. Odum (1962) had described as "synthetic ecosystems" and it was initially discussed at a workshop held in Granada in 2002 in which the term "emerging ecosystems" (Milton 2003) was the one predominantly agreed. After 2006, as the concept inspired interest among researchers, the number of records increased noticeably every year. In 2013, a comprehensive book emerged "Novel ecosystems: Intervening in the new ecological world order" (Hobbs et al. 2013a) as a result of a workshop held in Pender Island (Canada), in 2011, in which 50 researchers from several parts of the world and from different research backgrounds were gathered to discuss the concept. Even though the 42 chapters that comprise this book were displayed separately in Fig. 2, 2013 still was the year with the higher number of records so far. Nonetheless, the interest in the concept persisted in the following years to date.

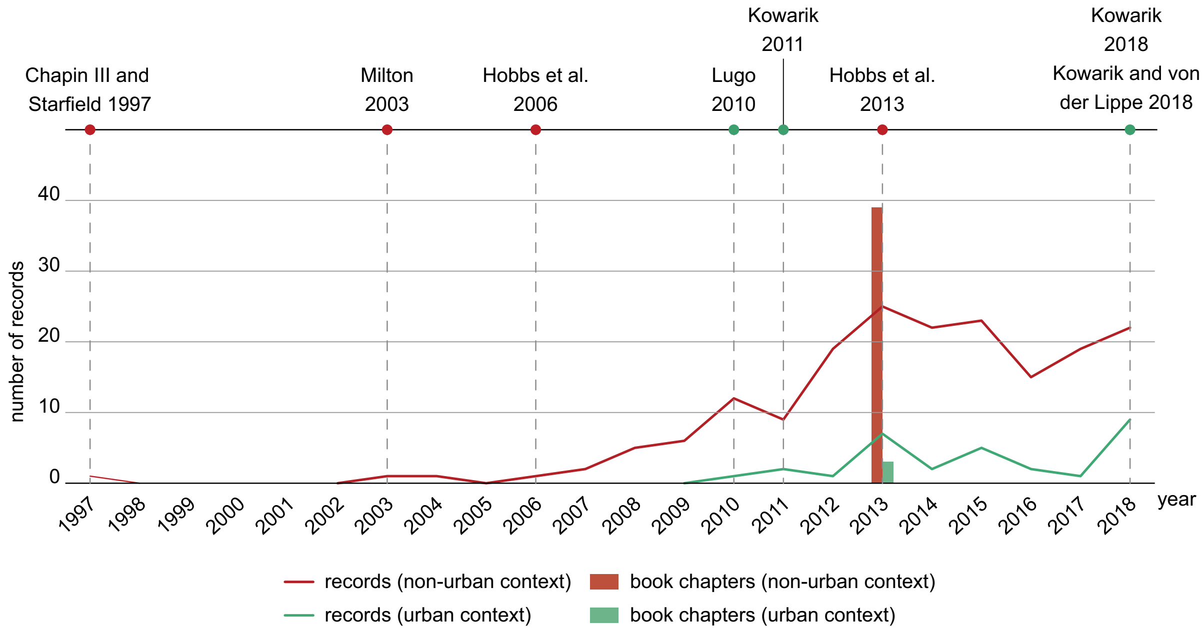


Fig. 2 The number of published records per year (from 1997 to 2018). Records focused on non-urban contexts are represented in red and records focused on the urban context are represented in blue. The number of records per year is represented by lines and the 42 book chapters from the comprehensive book (Hobbs et al. 2013a) are represented by column bars. Key moments in the evolution of the concept are highlighted and discussed with more detail in the text

Although Hobbs et al. (2006) make reference to the urban context, the concept was only objectively applied to the urban domain in 2010 (Lugo 2010). The term "novel urban ecosystems" was first employed by Kowarik (2011), highlighting the pertinence and urgency of discussing the concept in cities. Afterward, the number of publications increased and in Hobbs et al. (2013a) book a total of 3 book chapters were already focused on urban areas (Seastedt 2013; Seastedt et al. 2013; Perring et al. 2013a). From 2014 to 2017, the number of records remained constant. In 2018 it increased again, which demonstrates a recent growing interest in studying novel ecosystems in urban areas. This concept might have started to be applied to the urban context because novelty tends to manifest in cities (Hobbs et al. 2014) and also because cities contain highly altered ecosystems. Moreover, growing concerns about the future effects of climate change and other anthropogenic effects (e.g., introduction of species, land-use change, urbanization, etc.) demand the discussion of this subject on the urban context.

Over the years, many researchers urged to provide a concise and thorough definition of novel ecosystems. 12 key records that provided a conceptual framework and a definition of novel ecosystems in non-urban and urban contexts were identified and organized in Table 2. For each record the definition of the concept was extracted and examined against a set of criteria proposed by Morse et al. (2014):

- *Human-induced*: novel ecosystems result from human-induced changes;
- *Species assemblages*: novel ecosystems have new species assemblages and abiotic conditions (i.e., new ecosystem composition, structure, and function);
- *Self-sustaining*: novel ecosystems are persistent and self-sustaining (i.e., do not depend on continued human intervention for their maintenance);
- *Thresholds*: novel ecosystems have crossed ecological thresholds that are practically irreversible.

Regarding the "human-induced" criterion, the majority of the definitions referred that novel ecosystems result from human-induced changes ("anthropogenic drivers", "human agency", "by virtue of human influence", etc.). However, Morse et al. (2014) considered that human-induced change must be direct

Table 2 Evolution of the concept definition through time in non-urban and urban contexts

Reference	Context	Criteria			
		Human-induced	Species assemblages	Self-sustaining	Thresholds
Milton (2003)	Non-urban	X	X		
Hobbs et al. (2006)	Non-urban	X	X	X	
Hobbs et al. (2009)	Non-urban	X	X		X
Kowarik (2011)	Urban	X	X		
Hobbs et al. (2013a)	Non-urban	X	X	X	X
Morse et al. (2014)	Non-urban	X[a]	X	X	X
Radeloff et al. (2015)	Non-urban		X		
Truitt et al. (2015)	Non-urban	X	X		
Ahern (2016)	Urban	X	X		
Higgs (2017)	Non-urban	X	X	X	X
Kowarik (2018)	Urban	X	X		
Kowarik and von der Lippe (2018)	Urban	X	X		X

The information is organized chronologically from 2003 to 2018. See Supplementary Material Appendix D for the complete version of this table

[a]Only direct human-induced change

(whether intentional or unintentional), and indirect human agency (e.g., climate change, ocean acidification, and nitrogen deposition) should not be considered a driver of novelty. On the other hand, Radeloff et al. (2015) did not consider human agency as a criterion to identify novel ecosystems, since the influence of mankind on ecosystems is now so pervasive.

"Species assemblages" was the only criterion referred in all the definitions. Novel ecosystems present new abiotic conditions and unprecedented species compositions that consequently change ecosystem functions, processes, patterns, interactions, etc. These novel assemblages of species comprise native and non-native organisms (Higgs 2017) and resulted from human-induced changes such as species introductions, extinctions, colonization, land-use change, and climate change (Hobbs et al. 2006, 2009, 2013a; Ahern 2016).

The "self-sustaining" criterion was only referred in some definitions (Hobbs et al. 2006, 2013a; Morse et al. 2014; Higgs 2017). This criterion states the idea that, even though novel ecosystems result from anthropogenic drivers, they are self-organizing and do not need or depend on continued human intervention to manifest novel qualities. This is subjective and hard to identify (Morse et al. 2014; Radeloff et al. 2015) especially because even managed or human-engineered ecosystems can reveal spontaneous dynamics such as the emergence of new species and their interactions (Backstrom et al. 2018).

The "thresholds" criterion has only emerged in 2009 (Hobbs et al. 2009), but persisted in some of the following definitions (Hobbs et al. 2013a; Morse et al. 2014; Higgs 2017), particularly for non-urban contexts. This criterion reflects the idea that novel ecosystems have crossed ecological thresholds that are practically irreversible, constraining the system from returning to a previous state (i.e., the historical state). Although this idea has been considered useful for management frameworks, the ability to identify and measure ecological thresholds is still very limited (Hobbs et al. 2013b). Moreover, the capacity to restore a system will mostly depend on the available resources rather than on intrinsic properties of an ecosystem (Radeloff et al. 2015). Hobbs et al. (2013b) also argue that with enough effort, even systems that have experienced massive changes can be reversed at some extent, so the change will only be irreversible in a practical sense when resources, institutional will and social barriers prevent the reversal.

While some researchers defended that novelty occurs along a continuum or a gradient of ecological novelty (Corlett 2014; Radeloff et al. 2015), others suggested that a more categorical classification of systems is helpful to identify if a system is novel or not (Hobbs et al. 2013c; Kowarik and von der Lippe 2018). The definition provided by Radeloff et al. (2015) defends the idea that novelty exists along a continuum and that some ecosystems are more novel than others, i.e., novelty is everywhere with varying degrees. Other definitions also place novel ecosystems along a gradient of ecological novelty, still providing a categorization of systems sometimes with clear break-points, other times with more gradual distinctions between the systems.

For instance, Hobbs et al. (2006) placed novel ecosystems in the middle of a gradient between wild and intensively managed systems, since the authors considered that novel ecosystems result either from the degradation of wild ecosystems or from the abandonment of intensively managed systems. This idea was preceded by Milton (2003) but has not persisted in the following definitions.

The "historical-hybrid-novel" gradient emerged in 2009 (Hobbs et al. 2009) and prevailed in the succeeding definitions from the same group of authors (Hobbs et al. 2013a; Higgs 2017). In this case, the authors considered that novel ecosystems should be always compared to a historical reference in which novelty represents a clear departure from a historical condition (Hobbs et al. 2013b). In this gradient, historical ecosystems represent systems that remain within their historical range of variability, hybrid ecosystems are biotically and/or abiotically different from the historical state but still able to return to a historical condition, and, finally, novel ecosystems are biotically and/or abiotically different from the historical state and have crossed a threshold that practically prevents it to return to a historical state (Hobbs et al. 2009; Hallett et al. 2013). When using this gradient, historical states should be accurately defined with a clear reference to a time and space, which not always is the case (Hobbs et al. 2013b).

Regarding the urban context, a different gradient was proposed by Kowarik (2011, 2018): the Four Natures Approach (Kowarik 2005). This author defends that urban ecosystems are submitted to different degrees of human-induced alteration resulting in a gradual transformation of remnants of pristine landscapes ("nature of the first kind"), into patches of agrarian landscapes ("nature of the second kind"), into designed urban green spaces ("nature of the third kind"), and, finally, into novel urban ecosystems ("nature of the fourth kind"). Later Kowarik (2018) established a clear relationship between the "Four Natures Approach" and the "historical-hybrid-novel" gradient that evolved to the gradient: "natural-hybrid-novel" (Kowarik and von der Lippe 2018). See Fig. 3 for an illustrative synthesis.

The definition of novel ecosystems has been highly transforming over the years and a clear distinction between the definition on non-urban and urban contexts is still in need. The constant transformation of the concept definition is usually considered one of the sources of controversy about the concept (Aronson et al. 2014; Murcia et al. 2014; Simberloff 2015; Kattan et al. 2016). Critics also suggest that even the terminology used ("novel") may confer a character of innovation and improvement regarding previous ecosystems (historical ecosystems) and, therefore, influencing how society and decision makers perceive these systems (Aronson et al. 2014; Kattan et al. 2016). Researchers that criticize the concept are also concerned that the acceptance of novel ecosystems will lead to irreversible biodiversity losses through uncontrolled species invasions (Light et al. 2013). Simultaneously, they worry that decision makers will eventually reduce investments in conservation and that land managers will renounce restoration even when it is feasible (Murcia et al. 2014).

However, the various authors that recognize the concept share many of these concerns (Standish et al. 2013b). Acknowledging the existence of novel ecosystems does not imply that managers cease to control invasive species or that traditional conservation and restoration practices are completely replaced from now on (Hobbs et al. 2013d; Light et al. 2013). The widespread adoption of novel ecosystems should be cautious, nonetheless, the discussion of this subject is urgent to clarify misunderstandings and concerns (Standish et al. 2013b) (see Supplementary Material Appendix E for more detailed information about the controversial aspects of novel ecosystems).

The novel ecosystems concept allows the valuation of species or communities of species that are usually considered to eradication (Starzomski 2013). It provides opportunities for experimentation that may inform management practices in the future and

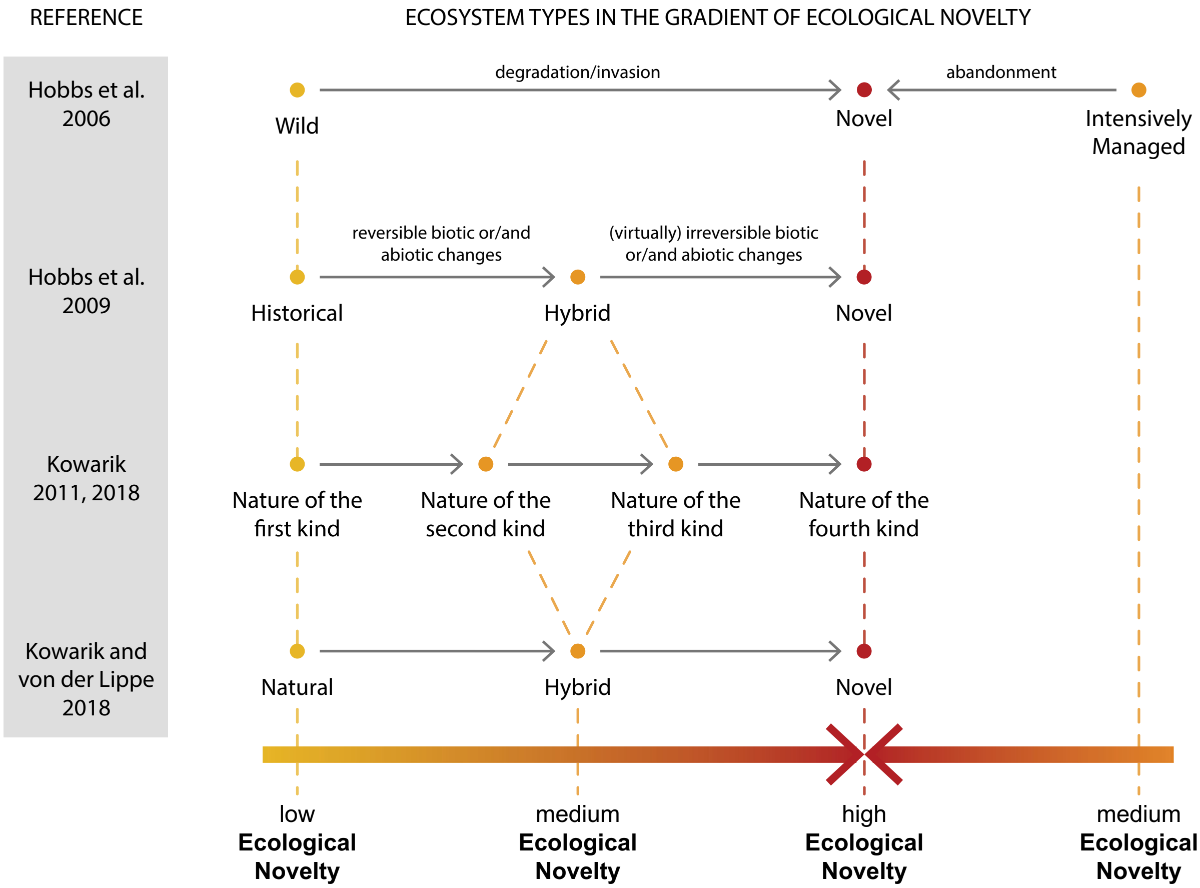


Fig. 3 Gradients of ecological novelty based on the following publications: Hobbs et al. (2006, 2009) Kowarik (2011, 2018,), Kowarik and von der Lippe (2018). Grey arrows represent the transition between types of ecosystems. Dashed lines connect types of ecosystems from different publications that are parallel. The gradient of ecological novelty is represented at the bottom of the figure, varying between low to high ecological novelty

develop important tools to face uncertain scenarios of change (Light et al. 2013; Standish et al. 2013b; Radeloff et al. 2015). According to Light et al. (2013), novel ecosystems may have more species richness, contribute to increase resilience and even assist conservation efforts. Moreover, novel ecosystems can provide services such as degraded land reclamation, watershed protection, carbon sequestration and storage, habitat for rare and native species, resources, recreational opportunities, and even new ecosystem services that we still do not know (Mascaro et al. 2012; Light et al. 2013; Collier 2014; Hobbs et al. 2014; Ahern 2016).

In the urban context, the concept can get even more relevance. The majority of the world's population lives now in urban settlements and people are increasingly experiencing nature in cities (MEA 2005; Kowarik 2011). Novel assemblages of species are already living and thriving in the extreme conditions of cities (Kowarik 2011) which suggests that they may be pre-adapted to current urban climates, therefore, offering models to support climate change adaptation. This way, novel urban ecosystems can be deliberately integrated into urban planning and designed to play a key role in creating more resilient cities and in adapting to future climate changes (Light et al. 2013; Ahern 2016). Moreover, given ongoing ecosystem transformations experienced in cities, it may not be practical or desirable to restore urban areas according to historical references (Sack 2013; Standish et al. 2013a). This way, interventions on urban ecosystems may depend on the degree of novelty: spaces with lower levels of novelty can be restored to enhance native communities for instance, whereas spaces with higher levels of novelty can be manipulated to provide more ecological, cultural, and aesthetic services (Perring et al. 2013a; Sack 2013).

Research focus of the concept in non-urban and urban contexts

The results of the classification of the records according to taxonomic groups, ecosystem types, and geographic areas for non-urban and urban contexts were represented in Fig. 4.

Taxonomic groups

On non-urban contexts, the majority of the records are focused on multiple taxonomic groups (41.9%), followed by plants (37.8%) and animals (9.0%), with the remaining 11.3% representing records that had no specified taxonomic group of focus. In urban contexts, the majority of the records are focused on plants (45.5%), followed by multiple taxonomic groups (42.4%) and animals (3.0%), with the remaining 9.1% representing records that had no specified taxonomic group of focus (Fig. 4a). Records focused on multiple taxonomic groups emerged almost every year. Records focused on plants were also observed almost every year, occasionally targeting specific plant species (e.g., Kueffer et al. 2010), but often discussing plant communities. Records focused on animals were less frequent (especially on the urban context), encompassing a variety of animal classes such as birds (e.g., Pias et al. 2016), mammals (e.g., Müller et al. 2017), and fish (e.g., Harborne and Mumby 2011).

Ecosystem types

On non-urban contexts, the majority of the records are focused on terrestrial ecosystems (58.6%), followed by multiple (21.2%) and aquatic ecosystems (10.4%), with the remaining 9.8% representing records that had no specified ecosystem type of focus. In urban contexts, the majority of the records are also focused on terrestrial ecosystems (81.9%), followed by multiple (12.1%) and aquatic ecosystems (6.0%) (Fig. 4b). Records focused on terrestrial ecosystems emerged almost every year, targeting for instance forests (e.g., Lugo and Helmer 2004), grasslands (e.g., Tognetti 2013), and former mine sites (e.g., Doley and Audet 2013). Records focused on multiple ecosystem types were also observed almost every year and included both terrestrial and aquatic ecosystems (e.g., Evers et al. 2018) or ecotones such as riparian ecosystems (e.g., Catford et al. 2013). Records focused on aquatic ecosystems were less frequent (especially on the urban context), focusing for instance on wetlands (e.g., Prospere et al. 2016), rivers and streams (e.g., Ibáñez et al. 2012), and coral reefs (e.g., Graham et al. 2014).

Geographic areas

On non-urban contexts, the majority of the studies were conducted on multiple geographic areas (33.8%), followed by North America (25.2%), Europe (9.0%), Oceania (7.7%), South America (5.4%), Africa (5.4%), and Asia (1.4%), with the remaining 12.1% representing studies that had no specified geographic area of focus. In urban contexts the majority of the studies were conducted in North America (42.4%), followed by Europe (24.3%), multiple geographic areas (15.2%), Oceania (9.1%), South America (3.0%), and Asia (3.0%), with the remaining 3.0% representing studies that had no specified geographic area of focus (Figs. 4c, 5). Studies involving multiple geographic areas or with global focus emerged every year since 2006. Studies conducted on North America emerged almost every year, including in the earliest record (Chapin III and Starfield 1997). Studies conducted in Europe and South America emerged almost every year since 2010 (Quine and Humphrey 2010; Tognetti et al. 2010). Studies conducted in Asia were scarce (e.g., Pethiyagoda 2012). Note that our geographic results could be biased since we exclusively collected records written in English.

A predisposition for studying certain types of novel ecosystems in specific parts of the globe was verified. For instance, novel forests have been largely studied in Puerto Rico (e.g., Lugo and Helmer 2004; Lugo 2010), Hawaii (e.g., Mascaro et al. 2012) and Seychelles (e.g., Kueffer et al. 2010). Novel grasslands have been investigated in several parts of the USA such as the Blackland Prairie region of Texas (e.g., Wilsey et al. 2011) and also in Inland Pampa, Argentina (e.g., Tognetti 2013). In Australia, several studies concerning industrial landscapes have been conducted (e.g., Erskine and Fletcher 2013). Studies in the urban context referring to ecosystems as "novel" have been mostly conducted in Germany (e.g., Kowarik and von der Lippe 2018) and in the USA (e.g., Beals et al. 2014).

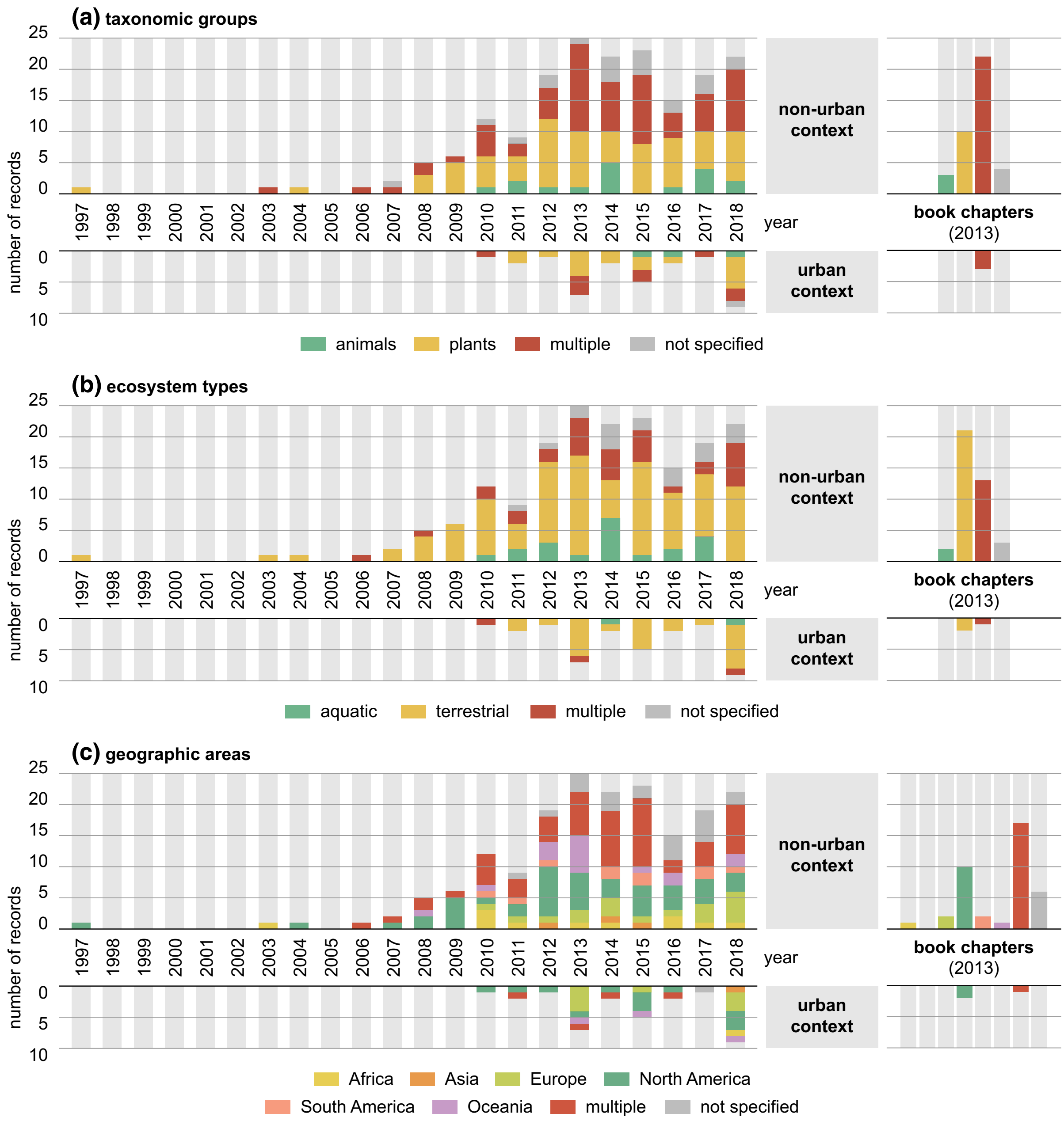


Fig. 4 The number of published records per year (from 1997 to 2018) by category: **a** taxonomic groups, **b** ecosystem types, and **c** geographic areas. Records are represented in stacked bar graphs (records focused on non-urban contexts are on the top and records focused on the urban context are in the bottom). The 42 book chapters from the comprehensive book (Hobbs et al. 2013a) are represented separately by column bars

Discussion topics

Based on author keywords, the main discussion topics regarding novel ecosystems in non-urban and urban contexts were identified. 18 records of the final database (n = 255) did not provide author keyword information, so this analysis was made based on 237 records (93%). On the whole, there were a total of 1705 author keywords (1478 author keywords belonging to records focused on non-urban contexts and 305 author keywords belonging to records focused on the urban context). Two maps with author keywords frequency information (Fig. 6) were generated using the open-source software VOSviewer 1.6.11 (van Eck and Waltman 2010) (see Supplementary Material Appendix C for more details).

Regarding the records focused in non-urban contexts, we verified that, apart from the keyword "novel ecosystems", "restoration ecology", "conservation", and "biodiversity" were the most frequent keywords, representing the three clusters formed in Fig. 6a. Thereby, these were the most discussed topics in the examined literature. The keyword "restoration ecology" (blue cluster) appears closely linked to the species assemblages and invasions subject ("invasive species", "biological invasions", "native species", and "exotic species"). The keyword "biodiversity" (yellow cluster) is more associated with keywords such as "ecosystem services" and "ecosystem function". And the keyword "conservation" (red cluster) is more connected to keywords that reflect human-induced changes such as "climate change", "introduced species", "anthropogenic effect", "human activity", and "Anthropocene". On the other hand, this group of keywords is also highly linked to keywords that reflect human management and action towards the negative anthropogenic effects ("ecosystem management", "adaptive management", "decision making", and "policy").

Fig. 6 Co-occurrence network of author keyword map generated using the software VOSviewer 1.6.11 (van Eck and Waltman 2010): **a** for records focused on non-urban contexts and **b** for records focused on the urban context. Each circle represents a keyword and the size of the circle varies according to the frequency of the keyword (i.e., the larger the circle the higher the frequency). The distance between circles and the established networking represented by lines characterizes the relation between keywords (i.e., keywords that are closer and have stronger links are more relatable). Colors are determined by the cluster to which the keyword belongs, which was automatically determined by the software based on the previous information ▶

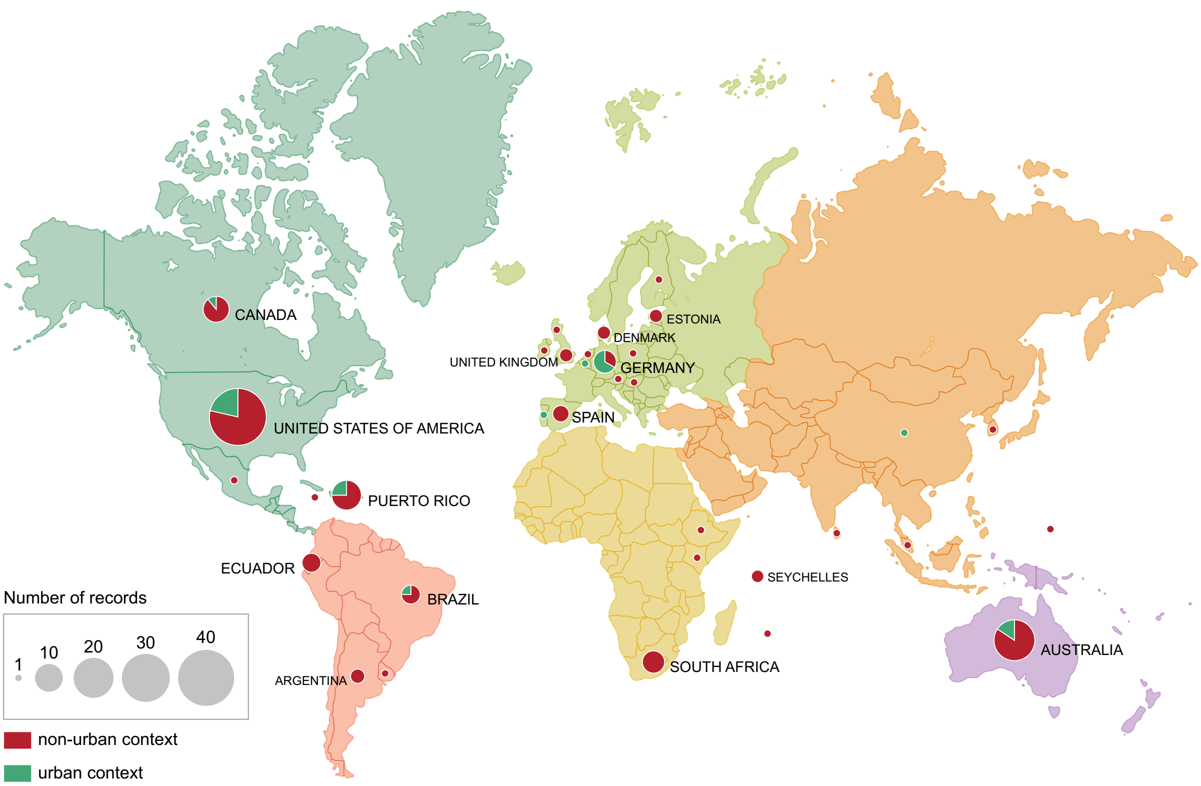
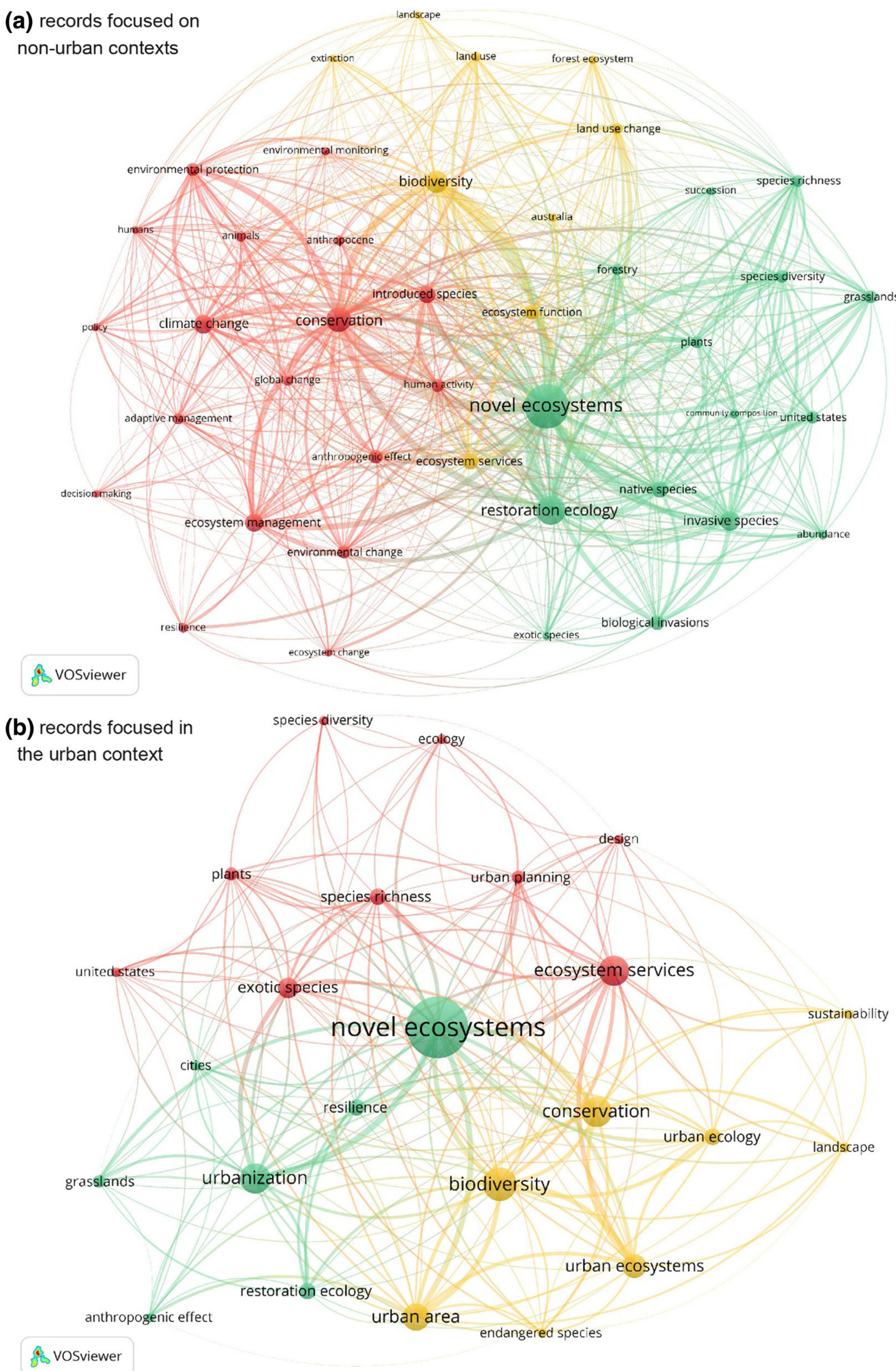


Fig. 5 Geographic distribution of the studies that provided details on the location (n = 136). The remaining studies conducted on multiple geographic areas and without specified location (n = 119) were not included in the map. The size of the circles is proportional to the number of records and colors in the pie charts represent the distribution of the records in non-urban contexts and urban contexts. Countries with a higher number of studies are captioned


(a) records focused on non-urban contexts
landscape
extinction
land use
forest ecosystem
land use change
environmental monitoring
environmental protection
biodiversity
succession
species richness
humans
animals
anthropocene
australia
forestry
species diversity
grasslands
introduced species
ecosystem function
policy
climate change
conservation
plants
global change
human activity
novel ecosystems
community composition
united states
adaptive management
anthropogenic effect
ecosystem services
decision making
native species
restoration ecology
invasive species
ecosystem management
abundance
environmental change
resilience
biological invasions
exotic species
ecosystem change
VOSviewer
(b) records focused in the urban context
species diversity
ecology
design
plants
urban planning
species richness
united states
ecosystem services
exotic species
sustainability
novel ecosystems
cities
resilience
conservation
urban ecology
landscape
grasslands
urbanization
biodiversity
urban ecosystems
restoration ecology
anthropogenic effect
urban area
endangered species
VOSviewer

Regarding the records focused in urban contexts, we verified that apart from the keyword "novel ecosystems", "biodiversity", "urbanization", and "ecosystem services" were the most frequent keywords, representing the three clusters formed in Fig. 6b. Thereby, these were the most discussed topics in the novel urban ecosystems' literature. The keyword "biodiversity" (yellow cluster) appears closely linked to the keyword "conservation". The keyword "urbanization" (blue cluster) is mostly associated with keywords such as "resilience", and "restoration ecology". Finally, the keyword "ecosystem services" (red cluster) appears closely related to keywords such as "design", "urban planning", and "exotic species".

The examined literature has been mostly discussed within the restoration ecology and conservation biology disciplines. These disciplines often focus on the topic of biological invasions which is considered one of the major drivers of novelty (Hobbs et al. 2006; Richardson and Gaertner 2013). Likewise, species origins and colonization are central discussion topics regarding the concept since novel species assemblages are the product of an intense reorganization of the Earth's biotic systems (Vitousek et al. 1997). Climate change is also frequently discussed, once it influences drastically evolutionary and ecological processes such as the distribution, interaction, and behavior of species (Starzomski 2013). Biodiversity is a recurrent discussion topic in both non-urban and urban contexts, but we verified that the discussion about ecosystem services, non-native species, urbanization, resilience, design, and urban planning gets a greater emphasis on the urban context. Cities generally have greater plant species richness compared to rural environments due to the high heterogeneity of habitats and the presence of a high number of non-native species (Kowarik 2011), which in turn influences the delivery of services and enhances cities' resilience. Additionally, design and urban planning have been considered important tools to promote cultural, aesthetic and regulating services (Sack 2013; Perring et al. 2013a; Chen et al. 2018).

Conclusion

This extensive systematic review intended to evaluate the existing literature that uses the terms "novel ecosystems" and/or "novel urban ecosystems". A considerable, yet recent, amount of literature was examined. This work excludes publications that only mention the term "novel ecosystems" without discussing it or contributing to the understanding of the concept. Nevertheless, relevant literature about the concept might as well have been excluded since the concept had different designations and also because it may exist research about this subject that uses other terminology.

Based on the examined literature, a thorough description of the history and relevance of the concept in non-urban and urban contexts was provided, as well as an evaluation of what has been the focus of the research on this subject. The definition and criteria used to describe novel ecosystems have been transforming over the years. Research on this subject has been mainly targeted on multiple taxonomic groups and plants, on terrestrial ecosystems, and has been mainly conducted in North America. Overall, the most discussed topics in the examined literature were restoration ecology, conservation, biodiversity, ecosystem services, and climate change. Although novelty occurring in the urban domain was not profoundly explored in the original elaboration of the concept (Perring et al. 2013a), this review confirms that the application of the concept to urban areas is not only pertinent but also necessary and opportune. There has been less research investment in the urban context, but we believe that this is where the concept can get more clarification and future research opportunities.

Although over the last 22 years research has produced relevant findings, there are still many unanswered questions. For instance, is everything novel in cities or urban ecosystems are comprised of different degrees of ecological novelty? Do we need a different definition and criteria to identify novel urban ecosystems? More information is needed to fully understand if the concept gets different limits in the city since urban ecosystems are constantly changing and have the constant presence of human-agency. Future research should continue this dialogue and address the clarification of the concept by creating and testing methodologies to classify and measure novelty in non-urban and urban contexts. Challenges posed by novelty should not overshadow the opportunities of researching these ecosystems, especially in urban areas. Novel ecosystems might become the new normal and novel urban ecosystems an unavoidable component of contemporary cities where most of the world's population now lives.

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