GfÖ
GfÖ Ecological Society of Germany, Austria and Switzerland
Basic and Applied Ecology 52 (2021) 82–94
Basic and Applied Ecology
www.elsevier.com/locate/baae

A conceptual framework for urban ecological restoration and rehabilitation

Valentin H. Klaus[a,*], Kathrin Kiehl[b]

[a]ETH Zurich, Institute of Agricultural Sciences, Universitätstr. 2, 8092 Zurich, Switzerland
[b]Osnabrück University of Applied Sciences, Oldenburger Landstr. 24, 49090 Osnabrück, Germany

Received 31 July 2020; accepted 15 February 2021
Available online 16 February 2021

Abstract

Urban greenspace has gained considerable attention during the last decades because of its relevance to wildlife conservation, human welfare, and climate change adaptation. Biodiversity loss and ecosystem degradation worldwide require the formation of new concepts of ecological restoration and rehabilitation aimed at improving ecosystem functions, services, and biodiversity conservation in cities. Although relict sites of natural and semi-natural ecosystems can be found in urban areas, environmental conditions and species composition of most urban ecosystems are highly modified, inducing the development of novel and hybrid ecosystems. A consequence of this ecological novelty is the lack of (semi-) natural reference systems available for defining restoration targets and assessing restoration success in urban areas. This hampers the implementation of ecological restoration in cities. In consideration of these challenges, we present a new conceptual framework that provides guidance and support for urban ecological restoration and rehabilitation by formulating restoration targets for different levels of ecological novelty (i. e., historic, hybrid, and novel ecosystems). To facilitate the restoration and rehabilitation of novel urban ecosystems, we recommend using established species-rich and well-functioning urban ecosystems as reference. Such *urban reference systems* are likely to be present in many cities. Highlighting their value in comparison to degraded ecosystems can stimulate and guide restoration initiatives. As urban restoration approaches must consider local history and site conditions, as well as citizens' needs, it may also be advisable to focus the restoration of strongly altered urban ecosystems on selected ecosystem functions, services and/or biodiversity values. Ecosystem restoration and rehabilitation in cities can be either relatively inexpensive or costly, but even expensive measures can pay off when they effectively improve ecosystem services such as climate change mitigation or recreation. Successful re−shaping and re-thinking of urban greenspace by involving citizens and other stakeholders will help to make our cities more sustainable in the future.

Keywords: Urban ecosystem; Novel ecosystem; Hybrid ecosystem; Restoration target; Reference system; Urban grassland; Urban woodland; Urban greenspace; Native species; Biodiversity

SPECIAL ISSUE: Urban ecosystems: challenges, potentials and solutions
*Corresponding author.
E-mail address: valentin.klaus@usys.ethz.ch (V.H. Klaus).

https://doi.org/10.1016/j.baae.2021.02.010

1. Increasing importance of urban greenspace for biodiversity and multifunctionality

Urban greenspace can provide numerous ecosystem services and promote native biodiversity und rare species (Aronson *et al.*, 2014; Planchuelo, von der Lippe, & Kowarik, 2019 and references therein). Due to the steadily increasing pressure on natural and semi-natural habitats by ongoing urbanisation, in addition to other forms of land-use change, urban areas should be included in the search for opportunities to strengthen biodiversity conservation efforts (Zari, 2018). Moreover, urban ecosystems constitute the only daily contact with nature for billions of people, and urban human-nature interactions are highly important for human well-being and experiential education about the beauty and value of nature (Dearborn & Kark, 2010; van den Bosch & Sang, 2017). Thus, although cities cover only about 3% of the global land area (Liu, He, Zhou, & Wu 2014), well-functioning urban ecosystems, with their services and biodiversity, are an important pillar of the sustainable development of urban societies.

Urban greenspaces, as elements of so-called green infrastructure, are increasingly challenged to be multifunctional, serving a wide range of provisioning (e.g. urban gardening), regulating (e.g. water retention, heat regulation) and cultural functions (e.g. educational, ornamental) (Jerome, Sinnetta, Burgess, Calvert, & Mortlock, 2019; Keeler *et al.*, 2019). Many urban ecosystems, however, are highly modified and ecologically degraded due to i) planting of monocultures or species-poor plant mixtures in technical or ornamental sites, ii) the intended use or unwanted spreading of non-native species or cultivars, iii) mis- or missing management, iv) frequent disturbances (e.g. construction or intensive use by residents), v) adverse abiotic conditions such as drought due to technogenic and compacted soils with low water-holding capacities, vi) constant nutrient input by fertilization and/or traffic and dog waste, vii) pollution by trash, fuel or heavy metals, and viii) very small patch size and fragmentation, in combination with interrupted seed dispersal (especially of native species into urban areas; McCleery, Moorman, & Peterson, 2014). This deficient state considerably limits the actual contribution of urban areas to biodiversity conservation (Klaus, 2013; Bretzel *et al.*, 2016) and strongly reduces important ecosystem functions and services, some of which may directly depend on biodiversity (Bullock, Aronson, Newton, Pywell, & Rey-Benayas, 2011; Lin, Philpott, & Jha, 2015; Lindemann-Matthies & Matthies, 2018). Causal relationships between urban biodiversity and ecosystem services remain, however, strongly understudied (Schwarz *et al.*, 2017). Despite this knowledge gap, several initiatives, such as the *"Decade on Ecosystem Restoration 2021–2030"* launched by the UN, underline the urgent need to improve urban ecosystems in order to better exploit their potential for biodiversity conservation and ecosystem services. This development is supported by the preference of many citizens for diverse urban greenspaces that offer habitats for native species over species-poor lawns or plantings (Sikorski *et al.*, 2018; Fischer *et al.*, 2018, 2020). In addition, the adaptation of cities to climate change requires a re-thinking of urban greenspace design and management (Mathey, Rößler, Lehmann, & Bräuer, 2011; Maimaitiyiming *et al.*, 2014; Liu, Yia, & Niu, 2017). These socio-ecological developments highlight the need to restore degraded urban ecosystems.

Most urban and peri-urban ecosystems are fundamentally different from natural or semi-natural ecosystems, in biotic and abiotic terms, and their shape is subjected to strong societal constraints (Aronson *et al.*, 2014; McCleery, Moorman, & Peterson, 2014). Consequently, many of these ecosystems have been classified as novel ecosystems due to their irreversible abiotic (e.g. technogenic soils, pollution) and biotic (e.g. high abundances of non-native plants) changes (see Box 1 for a note on novel, hybrid and designed urban ecosystems; Hobbs *et al.*, 2006; Kowarik, 2011). As such, novel ecosystems do not have a historic reference system, restoring urban ecosystems requires specific strategies, which can only partly rely on existing approaches for ecological restoration in non-urban environments (Kiehl, 2019). Here, we present a new conceptual framework that highlights opportunities for urban ecological restoration and rehabilitation to stimulate scientific discussions and to provide support for urban restoration initiatives.

Box 1. ***Novel Ecosystems* - the right term for urban ecological restoration?**

The concept of *novel ecosystems*, first formulated by Hobbs *et al.* (2006), has stimulated considerable controversy, but is still used because of its suitability for decision-making processes concerning irreversibly changed ecosystems. While some researchers criticize this concept as being inconsistent or unnecessary, others, especially those that emphasize the cultural dimensions of managed ecosystems, support its use in the context of restoration ecology (Macdonald & King, 2018). Although the majority of publications on novel ecosystems originate from non-urban settings (Teixeira & Fernandes, 2020), the concept is especially promising in an urban context, as it highlights the socio-ecological nature of urban ecosystems and the norms and ideas that determine their existence, design, management, and restoration (Kowarik, 2011; Higgs, 2017; Macdonald & King, 2018). Thus, the term *novel ecosystem* is not only used to classify certain ecosystems that differ in biotic and abiotic conditions from historic ones, but also to underline the challenge in defining specific restoration goals in a pluralistic world. *Hybrid ecosystems* are intermediate between historic and novel ecosystems in that they retain characteristics of the historic system, but their biotic and/or abiotic characteristics lie outside the range of variability in the historic system (Hobbs *et al.*, 2009).

In this context, it is further possible to distinguish between novel (and hybrid) ecosystems, which are in the narrow sense self-assembling ecosystems, and *designed ecosystems*, which have been planned and planted for a specific purpose (Higgs, 2017). However, over time, a designed ecosystem can develop into a novel ecosystem by spontaneous colonisation, and both types experience essentially similar ecological processes. It is thus difficult to define a threshold, i.e. when exactly a designed ecosystem may be said to have developed into a novel ecosystem. Furthermore, the planning of restoration and rehabilitation activities in the urban context often has the earmarks of actively designing ecosystems. Consequently, in this study, we only use the term *novel ecosystems* but explicitly include designed ecosystems.

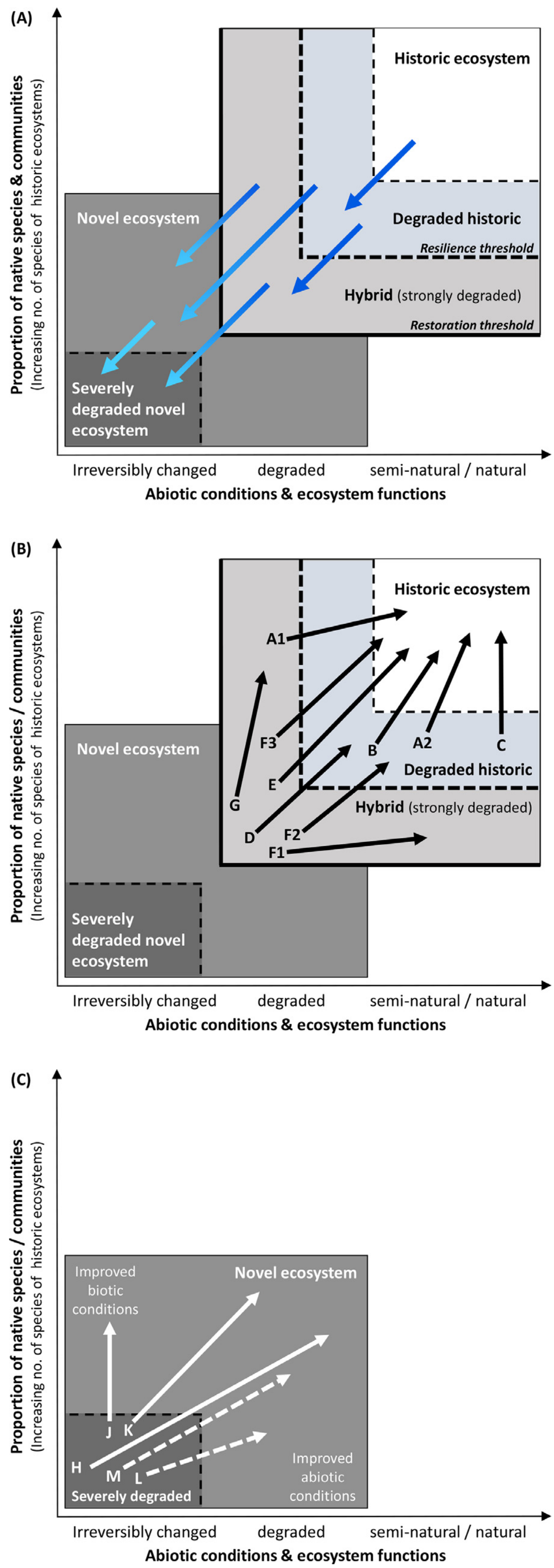

Fig. 1. Conceptual model visualising (A) the degradation of historic natural and semi-natural ecosystems to hybrid or irreversibly changed novel ecosystems (adapted from Kollmann (2019), strongly modified); (B) ecological restoration of degraded historic and hybrid ecosystems in urban areas (black arrows) and (C) ecological rehabilitation of novel urban ecosystems. Dashed arrows represent the conversion of grey into (partially) green surfaces. Note that arrow at G could be a result of either the restoration of an existing green roof or the development of a green roof with native species from a grey roof. Letters and numbers refer to ecosystem types described in Tables 1, 2 and 3.

2. Framing urban ecological restoration

The restoration of natural or semi-natural ecosystems has a long tradition, but a comprehensive framework for the definition of restoration targets for different types of urban ecosystems and different interest groups (e.g. greenspace users, managers, nature conservationists) is still lacking. Standish, Hobbs, and Miller (2013) discuss urban ecological restoration in relation to human-nature interactions, but do not provide specific ecological targets for different types of urban greenspaces. In our literature-based study, we elaborate on a new conceptual framework and describe different restoration targets and levels of intervention for improving the biotic and abiotic conditions of ecosystems in urban areas, depending on the level and reversibility of degradation (Fig. 1). **Ecological restoration** is defined as the process of assisting the recovery of a degraded, damaged, or destroyed ecosystem in the direction of a historic reference state (SER, 2004). For strongly degraded, so-called hybrid ecosystems, biotic and abiotic conditions can be improved by restoration activities in the direction of the reference state, but most often without completely reaching it (Fig. 1B). For novel ecosystems, we propose the term **ecological rehabilitation** to signify improving a habitat with the aim of enhancing ecosystem functions and/or biodiversity but without returning to a historic, pre-disturbance ecosystem state (Fig. 1C; van Andel & Aronson, 2012). This also includes designed ecosystems (Box 1). In addition to restoration and rehabilitation, **remediation**, i.e. the removal of pollutants and garbage, may be involved as the appropriate first step in improving the abiotic conditions of extremely degraded ecosystems.

Novel and hybrid ecosystems are often unable to attain historic reference conditions, due to irreversible changes, lack of space, societal norms, excessive restoration costs, or because it is not advisable in the urban context. Nevertheless, it is necessary to define targets for ecological restoration or rehabilitation of strongly degraded ecosystems. Hence, we recommend using specific *urban reference systems*, which should experience similar conditions and restrictions as the restoration sites but display a desired species composition and/or high levels of desired ecosystem functions and services. Examples of such services are water infiltration, carbon storage, heat reduction, usability by residents, and attractive appearance. We assert that such reference ecosystems can be identified in many regions, as demonstrated for urban grasslands in north-western

Germany (Rudolph, Velbert, Schwenzfeier, Kleinebecker, & Klaus, 2017). To support and facilitate decision-making, urban reference systems should *a priori* be comprehensively mapped, described, and measured, and their ecological value should be compared with that of degraded ecosystems. It is obvious that the restoration of an urban ecosystem should not exactly follow a restricted set of reference sites (especially when allowing for succession, i.e. passive restoration), but urban reference systems may be suitable to choose as realistic restoration targets according to site conditions. Hence, urban reference systems can provide reliable guidance in negotiations of targets with stakeholders. For extremely degraded novel ecosystems, restoration targets should focus on selected goals that may be realistically reached, for example reducing pollution, mitigating negative effects of climate change, supporting higher levels of native plant species, or creating ecological corridors to increase patch connectivity (Hejkal, Buttschardt, & Klaus 2017; Derkzen, van Teeffelen, Nagendra, & Verburg, 2017).

In the following, we will discuss targets and measures of urban ecosystem restoration and rehabilitation along gradients of degradation and ecological novelty (see Tables 1, 2, and 3). This categorisation is meant to logically order potential restoration and rehabilitation measures, while recognising that the actual conditions and level of degradation of an urban greenspace will vary locally (Lososová *et al.*, 2012).

2.1. Ecological restoration and rehabilitation of historic and hybrid ecosystems

Even in large cities, remnants of historic natural (e.g. forests, rivers, wetlands, prairie) and semi-natural ecosystems (e.g. temperate grasslands, hedgerows) that are relevant to nature conservation and recreation can be found (Kowarik, 2011). For these ecosystem types, reference sites and restoration approaches similar to those used in rural areas can be applied to increase, for example, ecosystem services such as water retention and habitat quality to promote native species (Table 1 − types A to C; Fig. 1B).

Remnants of ancient forests can be restored by passive restoration, which allows for natural succession, deadwood accumulation, and increased carbon sequestration by decreasing or abandoning wood extraction (Table 1 − type A1; Fig. 2A). Particularly in young and fast-growing cities, ecological restoration of ancient woodlands focuses on measures to reduce potentially dominant exotic species (Table 1 − type A2).

Nearly every city contains degraded **urban wetlands**, **rivers**, **shorelines**, **or other aquatic ecosystems**. Only in some cases are relatively light restoration measures sufficient; these measures include decreasing management intensity of bank vegetation, re-introducing locally extinct native species, or adding deadwood or rocks to increase structural diversity (Table 1 − type B; Fig. 2B). In many cases, ecological restoration of urban freshwater ecosystems can only tackle a few aspects of degradation, with others such as a fixed riverbed remaining untouched (Baldwin, 2004; Bernhard & Palmer, 2007). The geomorphology and hydrology of these freshwater ecosystems are often so strongly modified that it is debatable to what extent improvement of their environmental conditions may still be considered ecological restoration, rather than ecosystem rehabilitation (Ravit *et al.*, 2017). Opening embankments, widening canalised watercourses, rewetting formerly drained areas, and allowing for natural erosion are complex interventions, and often restricted by available space and high costs (Table 2 − type D). Nevertheless, wetlands and aquatic systems offer unique opportunities to restore attractive urban landscapes for recreation and human interaction with nature (Fig. 2D; EEA, 2016; Zingraff-Hamed, 2018). Despite the technical difficulty of the restoration and rehabilitation of urban aquatic ecosystems, this topic is much more comprehensively researched than other urban ecosystem types (Perini & Sabbion, 2017).

In historic parks, old cemeteries, and vacant lots, relicts of ancient **natural or semi-natural grassland** that have been protected from destruction and agricultural intensification can be found (Fig. 2C; Maurer, Peschel, & Schmitz, 2000; Kenny, 2019). If such highly valuable grasslands are only moderately degraded due to inappropriate management, they can be restored by reducing mowing frequency, abandoning fertilisation, or clear shrubs (Table 1 − type C). If species richness has been reduced in parts of these sites due to former sowing of dominant cultivars, intensive management, or abandonment, native species can be introduced by transfer of seed-containing green hay from species-rich ancient grasslands to preserve local genetic diversity. In addition, seeding with native seeds of regional provenance may also be applicable and is recommended if donor sites for hay transfer are lacking (Durka *et al.*, 2017; Kiehl, Kirmer, Donath, Rasran, & Hölzel, 2010). These restoration measures are also suitable for species introduction into hybrid grassland ecosystems such as **lawns and road verges**, which are often characterised by species-poor, frequently cut vegetation dominated by a few cultivars of grassspecies (Klaus, 2013; Table 2 − type E). A sole reduction of mowing frequency of formerly seeded lawns usually results in species-poor tallgrass vegetation of low conservation value. A state, which is also not very attractive for citizens (Lampinen et al., 2020; Fischer *et al.*, 2020). Therefore, a reduction in maintenance intensity should be accompanied by introducing native herb species with attractive flowering aspects (Fig. 2E) that can also improve habitat conditions for flower-visiting insects. Here, medium to strong interventions are necessary to destroy dense swards and potentially incorporate nutrient-poor soil material before sowing mixtures of regionally adapted native species (Fig. 2E). Old species-rich urban grasslands with long-term

Table 1. Targets for ecological restoration of different types of historic ecosystems in urban areas with potential reference systems and examples for restoration activities at different levels of intervention. Fig. 1B illustrates the potential changes in biotic and abiotic conditions.

Ecosystem type (prior restoration)	Restoration target	Ecological novelty	Reference system	Intervention level	Examples for restoration activities	References
Relicts of historic ecosystems						
(A) Ancient forests in cities	(A1) Promote natural processes and ecosystem functions by reducing or abandoning management intensity	Historic ecosystem: relicts of old forest ecosystems with natural soils and no or few invasive species	Ancient forests	No intervention (passive restoration)	Natural succession by abandonment of forest management, more deadwood and structural diversity	Fähser *et al.* (2013); Marzluff and Ewing (2001)
	(A2) Promote native biodiversity by invasive species management			Light to moderate	Restoration by improved management to reduce exotic species, introduction of native species	Silva Matos *et al.* (2002); Smith and Gehrt (2010); Clarkson and Kirby (2016); Johnson and Handel (2019)
(B) Ancient wetlands, ponds, creeks, rivers, lakeshores, and floodplains in cities	Promote native biodiversity and ecosystem functions by allowing for more natural dynamics and hydrology, reduction of management intensity	Historic ecosystem: Relicts of original wetlands and aquatic ecosystems with natural morphology and no or few invasive species	Natural wetlands and aquatic ecosystems	Light to strong	Rewetting, re-connection of backwaters, reduction of bank management, allowing for regrowth of natural bank vegetation, measures to reduce exotic species, introduction of site-specific native species	Salas (2008); Weigelhofer *et al.* (2011); Clarkson and Kirby (2016)
(C) Ancient grassland (incl. dune grasslands and prairies) in old parks, vacant lots or cemeteries etc.	Promote native biodiversity by optimisation of management	Historic ecosystem: relicts of old (self-assembled) grasslands modified by management with natural soils and no or few invasive species	Ancient natural or semi-natural grasslands	Light to moderate	Improved management, e.g. by extensive mowing or grazing, nutrient reduction by removal of mown plant material instead of mulching, shrub removal, leaving stripes of temporarily uncut vegetation for insects	Maurer *et al.* (2000); Seitz *et al.* (2012); Clarkson and Kirby (2016), Kenny (2019)

Table 2. Targets for the ecological restoration or rehabilitation of different types of hybrid ecosystems in urban areas with urban reference systems, examples for restoration activities at different levels of intervention. Fig. 1C illustrates the suggested changes in biotic and abiotic conditions after ecological restoration or rehabilitation.

Ecosystem type (prior restoration)	Restoration / rehabilitation target	Ecological novelty	Reference system	Intervention level	Examples for restoration or rehabilitation activities	References
Hybrid ecosystems						
(D) Urbanized ponds, wetlands, creeks, rivers, lakeshores, and floodplains in cities	Improve habitat functions for certain species and restore attractive green space for recreation and education by enhancing natural dynamics and vegetation	Hybrid ecosystems: lightly altered soils but fixed embankment and/or managed hydrology and degraded plant communities	Urban reference system (wetland or aquatic ecosystem)	Strong	Rewetting, pond restoration, partial de-embankment, creation of near-natural riverbed within artificial riverbed, reintroduction of rock, gravel and deadwood in rivers, reintroduction of native species	Baldwin (2004); Bernhardt and Palmer (2007); Perini and Sabbion (2017); Ravit *et al.* 2017; Gerner *et al.* (2018); Zingraff-Hamed (2018)
(E) Lawns, roadside vegetation, grass on vacant lots, and other perennial herbaceous vegetation	Promote native biodiversity and create attractive flowering vegetation for recreation and education	Hybrid ecosystem: usually designed on altered soils, dominance of non-native genotypes of plant cultivars	Urban reference system (extensive grassland in an urbanized context)	Moderate to strong	Reduction of management intensity (mowing, fertilisation, and irrigation), removal of existing vegetation, introduction of native species (may need soil preparations or exchange)	Fischer *et al.* (2013); Wastian *et al.* (2016); Rudolph *et al.* (2017); Sehrt *et al.* (2020); Anderson and Minor (2020)
(F) Urban brownfields, wastelands, and abandoned military areas (various soil conditions from slightly to highly altered)	(F1) Develop wild urban woodlands for recreation and other ecosystem services at low costs ("new wilderness")	Hybrid or novel ecosystem, depending on the level of change of abiotic and/or biotic conditions: often with technogenic soils and mixtures of native and non-native species	Urban reference system (extensive grassland or woodland in an urbanized context)	No intervention (passive restoration)	Development of wild urban woodlands with native and non-native species by natural succession after abandonment	Dettmar (2005); Rebele (2009); Kowarik *et al.* (2019); Włodarczyk-Marciniak *et al.* (2020)
	(F2) Promote biodiversity by development of spontaneous pioneer and grassland communities			Light to moderate	Shrub removal, management or soil disturbance to promote pioneer species, introduction of extensive mowing or grazing schemes	Kowarik and Langer (2005); Schadek *et al.* (2009); Latz (2017)
	(F3) Promote native biodiversity by introduction of native species			Moderate to strong	Introduction of native target species after soil preparation, may require regular management of grasslands (see E2)	Kausch and Felinks (2012); Fischer *et al.* (2013); Kövendi-Jakó *et al.* 2019; Anderson and Minor (2020); Schröder and Kiehl (2020a)
(G) Conventional green roof or grey roof suitable for greening with native plants	Promote native biodiversity on green roofs by introduction of regionally typical native grassland species	Hybrid ecosystem: built roof, mostly technogenic substrate, in some cases with natural soil, mostly native species	Urban reference system (dry grassland in an urbanized context)	Strong	Establishment of native plant species from dry grasslands (for 8–15 cm substrate layer depth) or mesophytic grassland (for substrate layers > 15 cm), use of natural soil if roof statics allows, introduction of nesting structures such as sand piles or deadwood	Landolt (2001); Lundholm 2006; SIA (2013); Catalano *et al.* 2018; FLL (2018); Schröder and Kiehl (2020b); Kiehl *et al.* (2021)

Table 3. Targets for the rehabilitation (or remediation) of different types of novel ecosystems or unvegetated surfaces in urban areas with urban reference systems, examples for restoration activities at different levels of intervention. Fig. 1C illustrates the suggested changes in biotic and abiotic conditions after rehabilitation.

Ecosystem type (prior rehabilitation)	Rehabilitation target	Ecological novelty	Reference system	Intervention level	Examples for rehabilitation	References
Novel ecosystems						
(H) Built ponds, basins, artificial wetlands, and creeks including cased streams	Promote ecosystem services (water retention, cooling) and biodiversity, improve aesthetic appearance for recreation	Novel Ecosystem: highly modified fixed banks, (cased) watercourses and high proportions of non-native/invasive species	Urban reference system	Strong	Designing artificial wetlands and ponds with different microhabitats and more native species, opening of cased rivers, introduction of gravel and/or dead wood in channelized rivers to improve habitat conditions	Wild *et al.* (2011); Weber *et al.* (2012); Chou (2016); Perini and Sabbion (2017); Ravit *et al.* (2017)
(J) Planted flower and vegetable beds in gardens, intensively managed parks, cemeteries, and similar horticultural systems	Promote ecosystem services for humans (aesthetics, recreation, provisioning, education), increase proportion of native species and habitat functions for insects, birds, and other taxa	Novel ecosystem: often highly altered soil conditions, mixtures of ornamental non-native plants and/or food plants and native (“weed”) species	Urban reference system or novel design – depends on aims of local stakeholders	Light to moderate	Converting bare soil and former ornamental plantings into e.g. grass-free lawns to provide aesthetic and flower-rich habitats for people and insects, planting of native (fruit) trees and shrubs, create nesting and resting structures for wild bees, birds or bats, introduction of endangered weeds	Standish *et al.* (2013); Smith and Fellowes (2014); Derkzen *et al.* (2017)
(K) Small patches of herbaceous vegetation such as traffic islands, flower decorations or shrubberies	Promote native biodiversity and aesthetic appearance, enhance habitat connectivity to create urban habitat networks for more biodiversity at landscape level	Novel ecosystem: technogenic and often shallow soils, non-native plants, very small and fragmented, often abandoned	Urban reference or newly created designs such as mixtures of native and non-native ornamental plants, adaptation to disturbance	Light to strong	Introduction of native (flowering) plant species, extensive maintenance such as mowing, control of dominant invasive species, protection from disturbance and pollution (e.g. railings)	Smith and Fellowes (2014); Mody *et al.* (2020)
Grey to green						
(L) Grey roof suitable for conventional greening	Promote ecosystem services (water retention, thermoregulation) and biodiversity values on conventional extensive green roof (see G for native biodiversity)	Novel ecosystem: technogenic soils, mostly non-native plants	Designed green roof according to standard roof-greening guidelines	Strong	Convert roofs without greening into conventional extensive green roofs with *Sedum*/*Phedimus* mixtures (cultivars) or intensive green roofs using other ornamental plants, introduction of additional native plant species where possible	Oberndorfer *et al.* (2007); SIA (2013); Catalano *et al.* 2018; FLL (2018)
(M) Sealed ground and buildings, e.g. streets, tram tracks, parking lots, facades, strongly degraded brownfields with high amounts of sealed and polluted soils, and other grey infrastructure	Promote ecosystem services (aesthetics, shade, cooling, dust reduction), create vegetation and habitat functions for some animal species	Novel ecosystem: highly altered soils or technogenic substrates, buildings as artificial cliffs, potentially polluted soils, sealed ground, gravel beds, high proportion of non-native plants	Urban reference system or novel design depending on aims of local stakeholders	Strong	Removal of pollutants, pavement, tarmac, or concrete e.g. at tram ways, former roads and post-industrial sites, revegetation with native and/or non-native plant species, planting of trees and hedgerows along infrastructure lines, greening of facades, installation of large pots/containers with vegetation	Lundholm (2006); Rebele (2009); Francis and Lorimer (2011); Zölch *et al.* (2016); Derkzen *et al.* (2017); Latz (2017); Sikorski *et al.* (2018)

Fig. 2. Examples of different types of urban ecosystems corresponding to potential restoration and rehabilitation measures as described in Tables 1 and 2. (A) Deadwood in an ancient forest relict with reduced management; (B) near-natural lakeshore at Rapperswil, Switzerland; (C) old cemetery transformed into a park with remnants of species-rich ancient dry sandy grassland in Osnabrück, Germany; (D) restoration of the river Isar in Munich, Germany, with a combination of dynamic gravel banks and partly fixed banks; (E) restoration of roadside vegetation (formerly species-poor lawn) by seeding native grassland species, Zurich, Switzerland; (F) combination of passive restoration by woodland succession and managed pioneer and grassland vegetation in the Duisburg Nord landscape park, Germany; (G) extensive green roof with heterogeneous environmental conditions, native wildflowers and a sand pile as nesting site for Hymenoptera in Germany; (H) rehabilitation of an urban creek under restricted spatial conditions, Zurich, Switzerland; (J) native wildflowers for insects in a garden flower bed, compared to neighbouring gravel bed and pavement, Osnabruck, Germany; (K) native grassland species introduced by seeding at a small traffic island in Osnabrück, Germany; (L) conventional extensive green roof with *Sedum* cultivars; (M) street with alley providing shade in a hot summer for humans and fragrant flowers of the native tree species *Tilia cordata* for bees in Germany.

continuous management can serve as urban reference systems here (Rudolph *et al.*, 2017).

Depending on the level of biotic and/or abiotic alterations, **urban brownfields** are either hybrid or novel ecosystems, often with highly disturbed soils (Table 2 − types F1−3; Rebele, 2009; Schadek, Strauss, Biedermann, & Kleyer, 2009). Their development is closely linked to the abandonment of former industrial areas or infrastructure sites and to shrinking cities (Haase, 2008). Urban brownfield restoration and rehabilitation can improve urban climate regulation, carbon sequestration, biodiversity, access to nature, and recreation in areas lacking greenspace (Dettmar, 2005; Bonthoux, Brun, Die Pietro, Greulich, & Bouché-Pillon, 2014; De Valck *et al.*, 2019). For brownfields, several targets, requiring different methods, can be defined. In many post-industrial landscapes (e.g. in the German Ruhr area), "wild urban woodlands" with mixtures of native and exotic species have developed through *passive restoration* (Table 2 − type F1). These have later been turned into attractive recreational areas simply by constructing footpaths to access the areas. Such woodlands can also be established on former military areas and sites of historic fortifications (Pardela, Kowalczyk, Bogacz, & Kasowska, 2020). An alternative target for brownfield rehabilitation is preserving early successional stages that include species-rich pioneer and grassland vegetation, which often contain numerous rare and endangered native plant and animal species. This target requires regular shrub removal or soil disturbance to preserve high species diversity (Table 2; Fig. 2 − type F2). The Duisburg Nord landscape park (Latz, 2017) and the Schöneberger Südgelände in Berlin (Kowarik & Langer, 2005), both located in Germany, are fascinating examples of the planned combination of different ecosystem types, including various successional stages from open managed pioneer grassland with threatened native species to urban woodlands, which resulted in ecologically valuable und attractive semi-designed urban landscapes that are highly appreciated by the public (Fig. 2F). For smaller brownfields and vacant lots, development into semi-natural grasslands and/or forests by introducing native species may be an advisable means of increasing biodiversity values (Anderson & Minor, 2020; Table 2 − type F3).

Although **green roofs**, i.e. all types of roof surfaces with one or more substrate layers overgrown by plants, are even more artificial than brownfields, plant communities on naturally occurring shallow soils can serve as habitat templates for these features (Lundholm, 2006). When their vegetation is dominated by native species, we classify them as hybrid ecosystems (Table 2 − type G), whereas conventional extensive green roofs dominated by non-native species are classified as novel ecosystems (see below). In the city of Zurich, 175 grassland species, including nine native orchid species, have established on a regularly mown 3 ha green roof, which was originally constructed in 1914 with a 30 cm layer of relocated natural soil (Landolt, 2001). For extensive green roofs with shallow substrate layers (8−15 cm), dry grasslands can serve as habitat templates to guide ecological restoration (Lundholm, 2006). Recent studies indicate that several but not all species of regionally typical dry sand grasslands introduced by seeding or the transfer of raked material are suitable for extensive roof greening in northern Germany (Schröder & Kiehl, 2020b). The value of green roofs for insects can be further improved by including nesting structures such as piles of sand or deadwood (Fig. 2G). As for many urban ecosystems, further research is needed to evaluate long-term success of such rehabilitation measures on green roofs.

2.2. Rehabilitation of novel ecosystems

Strongly altered, often formerly designed, urban ecosystems can be classified as novel ecosystems (Kowarik, 2011; Standish *et al.*, 2013; Kollmann, 2019). Despite highly modified soils, permanently altered nutrient and water cycles, and high proportions of non-native species, there are many options to improve habitat quality and ecosystem functioning in these environments. In such cases, specific urban reference systems can guide ecological rehabilitation. Alternatively, it is possible to focus on the improvement of selected ecosystem services and biodiversity values.

Urban brownfields have already been described above because they often comprise both hybrid and novel ecosystems, depending on the degree of degradation and modification of local site conditions or species composition. Below, we concentrate on the rehabilitation potential of even more artificial designed ecosystems and unvegetated grey infrastructure.

For example, even **artificially built ponds or canals with paved banks** can be enriched with different substrates and newly created flood areas to retain stormwater and provide different microhabitats to increase biodiversity (Table 3 − type H). Daylighting of culverted and revitalisation of canalised rivers in inner cities are very complex and costly measures (Wild *et al.*, 2011). Where embankments cannot be removed to allow for more natural dynamics due to lack of space, it is possible to introduce at least gravel, deadwood and some native plant species as rehabilitation measures (Fig. 2H). As a positive side effect, such measures considerably enhance the attractiveness of the urban environment for citizens (Perini & Sabbion, 2017).

In **horticultural ecosystems** such as urban gardens, yards, and parks, the cultivation of ornamental and food plants has a long cultural history resulting in novel species compositions (Sukopp, 2002; Kowarik, 2011). In gardening and park design, the focus is usually on selected ecosystem services such as food production, aesthetic improvement, and recreation. Nevertheless, ecological rehabilitation is possible, for example by using native plant species and providing nesting sites for birds, bats, and insects (Table 3 − type J; Fig. 2J). The reintroduction of highly endangered weed species in urban gardens has, to our knowledge, not yet been tested.

Further examples of rehabilitation measures in novel ecosystems include the conversion of **urban shrub plantings**, **flower beds or traffic islands** with non-native species into meadow-like communities of native plants, or into grass-free lawns (Mody *et al.*, 2020; Smith & Fellowes, 2014; Table 3 − type K; Fig. 2K). Despite the small size of such ecosystems, their rehabilitation can contribute to large-scale measures, enhance habitat connectivity, and provide resources to insects. More elaborate rehabilitation measures change grey into green infrastructure by **greening of buildings**, **streets**, **or tram tracks** (Table 3; Fig. 2L-M). To facilitate the rehabilitation of strongly degraded novel ecosystems and grey infrastructure, more engagement in the ecological “upcycling” of commonly ignored novel ecosystems is needed. Future research and the documentation of successful examples may show how networks of small patches in cities can be turned into an effective green infrastructure that benefits nature and citizens.

3. Urban ecological restoration will pay off

To facilitate urban ecological restoration and rehabilitation, lower costs of extensive compared to conventional greenspace are often the central justification to change to near-natural greenspace management. Reduced maintenance intensity can indeed result in lower running costs when expensive management measures (e.g. spraying, irrigation, intensive mowing, pruning, seasonal planting or sowing) are abandoned or replaced by cheap management schemes, for example when lawns or flowerbeds are converted into wildflower meadows or left to succession (Barnes *et al.*, 2018; Mody *et al.*, 2020; Watson *et al.*, 2020). This argument of reduced running costs is also linked to sustainable city management in terms of reduced resource consumption (e.g. fertilizers, water) and adherence to the budgetary constraints of many cities. However, the argument of lower costs only holds true concerning the extensive management. More intensive interventions needed to establish suitable plant communities (e.g. by the exchange of topsoil and seeding) or the removal of impervious surfaces are costly and often not considered in this calculation. The examples we list in Tables 1−3 cover a wide range from cheap to expensive measures, but a detailed overview of the costs for restoring different types of urban ecosystems is currently lacking, mostly because of the great dependency of such measures on local conditions.

The most important economic justification for urban restoration and rehabilitation is the increase in ecosystem services and quality of life in cities (Elmqvist *et al.*, 2015). Urban ecological restoration activities can pay off, directly as well as indirectly, when the restored greenspaces enhance recreational value (De Valck *et al.*, 2019) and attractiveness to investment and tourism (Jim & Chen, 2010). Additionally, urban restoration measures can help reduce energy costs, for example by tree plantings to increase shading or roof and facade greening to promote thermoregulation of buildings (Oberndorfer *et al.*, 2007; Zölch, Maderspacher, Wamsler, & Pauleit, 2016). Remarkably, the overall benefit of Beijing's public greenspaces was estimated to be 2−4 times their maintenance costs (Biao, Gaodi, Bin, & Canqiang, 2012). As costs of restoration or rehabilitation and subsequent ecosystem service benefits vary among different ecosystem types, the benefit-cost ratios of respective measures span a wide range, but are always positive (Elmqvist *et al.*, 2015).

We recognise that many of these arguments are not restricted to urban vegetation composed of native species. Nevertheless, we argue that non-native vegetation was often introduced for ornamental reasons, and mostly not at particularly lower costs or because of a special functional attribute (apart from some examples such as street trees; Grote *et al.*, 2016). In many cases, benefits can also be achieved with native plant species or communities that provide more habitats for specialised native insect species and can increase citizens' identification with "their" city (Kausch & Felinks, 2012). Benefits of using native plants are even higher when urban greenspaces are used for education and to increase the connectedness of urban residents with nature by observing plants, butterflies, birds and other animals (Standish, Hobbs, & Miller, 2013; Clarkson & Kirby, 2016). For intensively used and ornamental urban greenspaces such as parks, however, a combination of visually appealing designed plantings with attractive non-native and native plants, along with some near-natural structures to increase habitat diversity, may be suitable to fulfil both aesthetic and ecological requirements.

In summary, it must be said that the sustainable development of urban areas will inherently lead to certain costs and extra effort. However, even if comprehensive economic analyses on the multiple benefits (and potential risks) of specific urban restoration measures and the relevance of native versus non-native vegetation are still lacking, urban ecological restoration can pay off.

4. Conclusions and the way ahead

Improving the quality of urban green infrastructure by restoring a broad variety of different ecosystem types is needed to facilitate urban biodiversity conservation, ecosystem services, and climate change adaptation. Urban ecological restoration and rehabilitation span multiple dimensions, from light to strong interventions, on large to small patches, and in historic to novel ecosystems. Even small-scaled ecosystems such as road verges, hedgerows, green roofs, or traffic islands can become attractive and valuable greenspaces, and act as steppingstones to improve habitat connectivity (Marzluff & Ewing, 2001). City planning, for its part, needs to protect and even enlarge urban greenbelts and "green fingers", thus ensuring corridors for the production and flow of fresh air to mitigate negative effects of climate change (Pierer & Creutzig, 2019) and multifunctional greenspace networks for biodiversity and recreation activities (Casperson & Olafsson, 2010).

As societal expectations and popular concepts of nature strongly co-determine the appearance of urban greenspaces (Faeth, Bang, & Saari, 2011; Standish, Hobbs, & Miller, 2013), it is crucial to involve citizens and other stakeholders when re−thinking, restoring, and re−shaping these areas (Aronson *et al.*, 2017). The fact that citizens value both neat ornamental features and ecological habitat functions (Fischer *et al.*, 2020) clearly shows the need to overcome the idea of "one−size-fits−all" approaches for greenspace design and management. This calls for the development of novel concepts for multifunctional and biodiverse urban greenspaces by strengthening research efforts and the practical implementation of flagship projects by interdisciplinary teams of ecologists, landscapers, and city planners.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Anderson, E. C., & Minor, E. S. (2020). Assessing four methods for establishing native plants on urban vacant land. *Ambio*, 1–11.

Aronson, M. F., La Sorte, F. A., Nilon, C. H., Katti, M., Goddard, M. A., Lepczyk, C. A., & Winter, M. (2014). A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. *Proceedings of the Royal Society B: Biological Sciences*, *281*,(1780) 20133330.

Aronson, M. F., Lepczyk, C. A., Evans, K. L., Goddard, M. A., Lerman, S. B., ..., & Vargo, T. (2017). Biodiversity in the city: key challenges for urban green space management. *Frontiers in Ecology and the Environment*, *15*, 189–196.

Baldwin, A. H. (2004). Restoring complex vegetation in urban settings: The case of tidal freshwater marshes. *Urban Ecosystems*, *7*, 125–137.

Barnes, M. R., Nelson, K. C., Meyer, A. J., Watkins, E., Bonos, S. A., Horgan, B. P., & Yue, C. (2018). Public land managers and sustainable urban vegetation: The case of low-input turfgrasses. *Urban Forestry & Urban Greening*, *29*, 284–292.

Bernhardt, E. S., & Palmer, M. A. (2007). Restoring streams in an urbanizing world. *Freshwater Biology*, *52*, 738–751.

Biao, Z., Gaodi, X., Bin, X., & Canqiang, Z. (2012). The effects of public green spaces on residential property value in Beijing. *Journal of Resources and Ecology*, *3*, 243–252.

Bonthoux, S., Brun, M., Di Pietro, F., Greulich, S., & Bouché-Pillon, S. (2014). How can wastelands promote biodiversity in cities? *A review*. Landscape and Urban Planning, *132*, 79–88.

Bretzel, F., Vannucchi, F., Romano, D., Malorgio, F., Benvenuti, S., & Pezzarossa, B. (2016). Wildflowers: From conserving biodiversity to urban greening—A review. *Urban forestry & urban greening*, *20*, 428–436.

Bullock, J. M., Aronson, J., Newton, A. C., Pywell, R. F., & Rey-Benayas, J. M. (2011). Restoration of ecosystem services and biodiversity: conflicts and opportunities. *Trends in Ecology & Evolution*, *26*, 541–549.

Caspersen, O. H., & Olafsson, A. S. (2010). Recreational mapping and planning for enlargement of the green structure in greater Copenhagen. *Urban Forestry & Urban Greening*, *9*, 101–112.

Catalano, C., Laudicina, V. A., Badalucco, L., & Guarino, R. (2018). Some European green roof norms and guidelines through the lens of biodiversity: Do ecoregions and plant traits also matter? *Ecological Engineering*, *115*, 15–26.

Chou, R. J. (2016). Achieving successful river restoration in dense urban areas: Lessons from Taiwan. *Sustainability*, *8*, 1159.

Clarkson, B. D., & Kirby, C. L. (2016). Ecological restoration in urban environments in New Zealand. *Ecological Management & Restoration*, *17*, 180–190.

De Valck, J., Beames, A., Liekens, I., Bettens, M., Seuntjens, P., & Broekx, S. (2019). Valuing urban ecosystem services in sustainable brownfield redevelopment. *Ecosystem Services*, *35*, 139–149.

Dearborn, D. C., & Kark, S. (2010). Motivations for conserving urban biodiversity. *Conservation Biology*, *24*, 432–440.

Derkzen, M. L., van Teeffelen, A. J., Nagendra, H., & Verburg, P. H. (2017). Shifting roles of urban green space in the context of urban development and global change. *Current Opinion in Environmental Sustainability*, *29*, 32–39.

Dettmar, J. (2005). The project "Industrial Forests of the Ruhr. I. Kowarik, & S. Körner, *Wild urban woodlands: New perspectives for urban forestry* I. Kowarik, & S. Körner. (pp. 263−276). Springer.

Durka, W., Michalski, S. G., Berendzen, K. W., Bossdorf, O., Bucharova, A., Hermann, J. M., & Kollmann, J. (2017). Genetic differentiation within multiple common grassland plants supports seed transfer zones for ecological restoration. *Journal of Applied Ecology*, *54*, 116–126.

EEA − European Environment Agency. (2016). Rivers and lakes in European cities - past and future challenges. *EEA Report* 26/2016.

Elmqvist, T., Setälä, H., Handel, S. N., Van Der Ploeg, S., Aronson, J., Blignaut, J. N., & De Groot, R. (2015). Benefits of restoring ecosystem services in urban areas. *Current Opinion in Environmental Sustainability*, *14*, 101–108.

Faeth, S. H., Bang, C., & Saari, S. (2011). Urban biodiversity: patterns and mechanisms. *Annals of the New York Academy of Science*, *1223*, 69–81.

Fähser, L. (2013). Ökosystemleistungen bei „Naturnaher Waldnutzung" im Stadtwald Lübeck - Erfahrungsbericht von 20 Jahren. *BfN-Skripten*, *334*, 87–93.

Fischer, L. K., Honold, J., Cvejić, R., Delshammar, T., Hilbert, S., Lafortezza, R., ..., & Kowarik, I. (2018). Beyond green: Broad support for biodiversity in multicultural European cities. *Global Environmental Change*, *49*, 35–45.

Fischer, L. K., Neuenkamp, L., Lampinen, J., Tuomi, M., Alday, J. G., Bucharova, A., & Klaus, V. H. (2020). Public attitudes toward biodiversity-friendly greenspace management in Europe. *Conservation Letters*, e12718.

Fischer, L. K., von der Lippe, M., Rillig, M. C., & Kowarik, I. (2013). Creating novel urban grasslands by reintroducing native species in wasteland vegetation. *Biological Conservation*, *159*, 119–126.

FLL − Landscape Development and Landscaping Research Society e.V. (2018). *Green Roof Guidelines - Guidelines for the planning, construction and maintenance of green roofs* (6th ed.). in German: FLL.

Francis, R. A., & Lorimer, J. (2011). Urban reconciliation ecology: The potential of living roofs and walls. *Journal of Environmental Management*, *92*, 1429–1437.

Gerner, N. V., Nafo, I., Winking, C., Wencki, K., Strehl, C., Wortberg, T., & Birk, S. (2018). Large-scale river restoration pays off: A case study of ecosystem service valuation for the Emscher restoration generation project. *Ecosystem Services*, *30*, 327–338.

Grote, R., Samson, R., Alonso, R., Amorim, J. H., Cariñanos, P., Churkina, G., ..., & Calfapietra, C. (2016). Functional traits of urban trees: air pollution mitigation potential. *Frontiers in Ecology and the Environment*, *14*, 543–550.

Haase, D. (2008). Urban ecology of shrinking cities: an unrecognized opportunity? *Nature and Culture*, *3*, 1–8.

Hejkal, J., Buttschardt, T. K., & Klaus, V. H. (2017). Connectivity of public urban grasslands: implications for grassland conservation and restoration in cities. *Urban Ecosystems*, *20*, 511–519.

Higgs, E. (2017). Novel and designed ecosystems. *Restoration Ecology*, *25*, 8–13.

Hobbs, R. J., Arico, S., Aronson, J., Baron, J. S., Bridgewater, P., Cramer, V. A., ..., & Zobel, M. (2006). Novel ecosystems: theoretical and management aspects of the new ecological world order. *Global Ecology and Biogeography*, *15*, 1–7.

Hobbs, R. J., Higgs, E., & Harris, J. A. (2009). Novel ecosystems: implications for conservation and restoration. *Trends in Ecology & Evolution*, *24*, 599–605.

Jerome, G., Sinnetta, D., Burgess, S., Calvert, T., & Mortlock, R. (2019). A framework for assessing the quality of green infrastructure in the built environment in the UK. *Urban Forestry & Urban Greening*, *40*, 174–182.

Jim, C. Y., & Chen, W. Y. (2010). External effects of neighbourhood parks and landscape elements on high-rise residential value. *Land Use Policy*, *27*, 662–670.

Johnson, L. R., & Handel, S. N. (2019). Management intensity steers the long-term fate of ecological restoration in urban woodlands. *Urban Forestry & Urban Greening*, *41*, 85–92.

Kausch, E., & Felinks, B. (2012). Dünen, Heiden, Trockenrasen − Neue Vegetationsbilder für städtische Freiflächen. European Journal *of* Turfgrass Science, *3*, 43–49.

Keeler, B. L., Hamel, P., McPhearson, T., Hamann, M. H., Donahue, M. L., Prado, K. A. M., ..., & Wood, S. A (2019). Social-ecological and technological factors moderate the value of urban nature. *Nature Sustainability*, *2*, 29–38.

Kenny, J. (2019). *Pristine prairie at Calvary Cemetery thrives amid urban landscape*. St. Louis Review. 25 July 2019 www.archstl.org/pristine-prairie-at-calvary-cemetery-thrives-amid-urban-landscape-4227.

Kiehl, K. (2019). Urban-industrielle Ökosysteme. J. Kollmann, A. Kirmer, A. Tischew, N. Hölzel, & K. Kiehl, *Renaturierungsökologie* J. Kollmann, A. Kirmer, A. Tischew, N. Hölzel, & K. Kiehl. (pp. 389−410). Springer.

Kiehl, K., Jeschke, D., & Schröder, R. (2021). Using native plant species of dry sandy grasslands for roof greening in north-western Germany - opportunities and challenges. In C. Catalano, M. Leone, M. B. Andreucci, F. Bretzel, P. Menegoni, R. Guarino (Eds.), *Urban Services to Ecosystems: Green Infrastructure Benefits from the Landscape to the Urban Scale*. Springer.

Kiehl, K., Kirmer, A., Donath, T., Rasran, L., & Hölzel, N. (2010). Species introduction in restoration projects - evaluation of different techniques for the establishment of semi-natural grasslands in Central and Northwestern Europe. *Basic and Applied Ecology*, *11*, 285–299.

Klaus, V. H. (2013). Urban grassland restoration: a neglected opportunity for biodiversity conservation. *Restoration Ecology*, *21*, 665–669.

Kollmann, J. (2019). Neuartige Ökosysteme und invasive Neobiota. J. Kollmann, A. Kirmer, A. Tischew, N. Hölzel, & K. Kiehl, *Renaturierungsökologie* J. Kollmann, A. Kirmer, A. Tischew, N. Hölzel, & K. Kiehl. (pp. 435−447). Springer.

Kövendi-Jakó, A., Halassy, M., Csecserits, A., Hülber, K., Szitár, K., Wrbka, T., & Török, K. (2019). Three years of vegetation development worth 30 years of secondary succession in urban-industrial grassland restoration. *Applied Vegetation Science*, *22*, 138–149.

Kowarik, I. (2011). Novel urban ecosystems, biodiversity, and conservation. *Environmental Pollution*, *159*, 1974–1983.

Kowarik, I., Hiller, A., Planchuelo, G., Seitz, B., von der Lippe, M., & Buchholz, S. (2019). Emerging Urban Forests: Opportunities for Promoting the Wild Side of the Urban Green Infrastructure. *Sustainability*, *11*, 6318. https://doi:10.3390/su11226318.

Kowarik, I., & Langer, A (2005). Natur-Park Südgelände: Linking conservation and recreation in an abandoned railyard in Berlin. I. Kowarik, & S. Körner, *Wild urban woodlands: New perspectives for urban forestry* I. Kowarik, & S. Körner. (pp. 287−299). Springer.

Lampinen, J., Tuomi, M., Fischer, L. K., Neuenkamp, L., Alday, J. G., Bucharova, A., & Klaus, V. H. (2020). Acceptance of near-natural greenspace management relates to ecological and socio-cultural assigned values among European urbanites. *Basic and Applied Ecology*, *50*, 119–131.

Landolt, E. (2001). Orchideen-Wiesen in Wollishofen (Zürich) - ein erstaunliches Relikt aus dem Anfang des 20. *Jahrhunderts. Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich*, *146*, 41–51.

Latz, P. (2017). *Rust Red: The Landscape Park Duisburg Nord*. Hirmer, Munich.

Lin, B. B., Philpott, S. M., & Jha, S. (2015). The future of urban agriculture and biodiversity-ecosystem services: Challenges and next steps. *Basic and Applied Ecology*, *16*, 189–201.

Lindemann-Matthies, P., & Matthies, D. (2018). The influence of plant species richness on stress recovery of humans. *Web Ecology*, *18*, 121–128.

Liu, H., Jia, Y., & Niu, C. (2017). ''Sponge city'' concept helps solve China's urban water problems. *Environmental Earth Sciences*, *76*, 473. doi:10.1007/s12665-017-6652-3.

Liu, Z., He, C., Zhou, Y., & Wu, J. (2014). How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. *Landscape Ecology*, *29*, 763–771.

Lososová, Z., Chytrý, M., Tichý, L., Danihelka, J., Fajmon, K., Hájek, O., ..., & Řehořek, V. (2012). Native and alien floras in urban habitats: a comparison across 32 cities of central Europe. *Global Ecology and Biogeography*, *21*, 545–555.

Lundholm, J. (2006). *Green roofs and facades: A habitat template approach: 4* (pp. 87−101). Urban Habitats.

Macdonald, E., & King, E. G. (2018). Novel ecosystems: A bridging concept for the consilience of cultural landscape conservation and ecological restoration. *Landscape and Urban Planning*, *177*, 148–159.

Maimaitiyiming, M., Ghulam, A., Tiyip, T., Pla, F., Latorre-Carmona, P., Halik, Ü., ..., & Caetano, M. (2014). Effects of green space spatial pattern on land surface temperature: Implications for sustainable urban planning and climate change adaptation. *ISPRS Journal of Photogrammetry and Remote Sensing*, *89*, 59–66.

Marzluff, J. M., & Ewing, K. (2001). Restoration of fragmented landscapes for the conservation of birds: A general framework and specific recommendations for urbanizing landscapes. *Restoration Ecology*, *9*, 280–292.

Mathey, J., Rößler, S., Lehmann, I., & Bräuer, A. (2011). Urban green spaces: potentials and constraints for urban adaptation to climate change. K. Otto-Zimmermann, *Resilient Cities* K. Otto-Zimmermann. (pp. 479−485). Springer.

Maurer, U., Peschel, T., & Schmitz, S. (2000). The flora of selected urban land-use types in Berlin and Potsdam with regard to nature conservation in cities. *Landscape and Urban Planning*, *46*, 209–215.

McCleery, R. A., Moorman, C. E., & Peterson, M. N (2014). *Urban wildlife conservation: theory and practice*. Springer.

Mody, K., Lerch, D., Müller, A. K., Simons, N. K., Blüthgen, N., & Harnisch, M. (2020). Flower power in the city: Replacing roadside shrubs by wildflower meadows increases insect numbers and reduces maintenance costs. *Plos one*, *15*, e0234327.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K. K, Y., & Rowe, B (2007). Green roofs as urban ecosystems: ecological structures, functions, and services. *BioScience*, *57*, 823–833.

Pardela, Ł., Kowalczyk, T., Bogacz, A., & Kasowska, D. (2020). Sustainable green roof ecosystems: 100 years of functioning on fortifications—A case study. *Sustainability*, *12*, 4721.

Perini, K., & Sabbion, P. (2017). *Urban Sustainability and River Restoration*. Wiley Blackwell.

Pierer, C., & Creutzig, F. (2019). Star-shaped cities alleviate trade-off between climate change mitigation and adaptation. *Environmental Research Letters*, *14*, 085011.

Planchuelo, G., von der Lippe, M., & Kowarik, I. (2019). Untangling the role of urban ecosystems as habitats for endangered plant species. *Landscape and urban planning*, *189*, 320–334.

Ravit, B., Gallagher, F., Doolittle, J., Shaw, R., Muñiz, E., Alomar, R., Hoefer, W., Berg, J., & Doss, T. (2017). Urban wetlands: restoration or designed rehabilitation? *AIMS Environmental Science*, *4*, 458–483.

Rebele, F. (2009). Renaturierung von Ökosystemen in urban-industriellen Landschaften. S. Zerbe, & G. Wiegleb (Eds.), *Renaturierung von Ökosystemen* (pp. 389−422) S. Zerbe, & G. Wiegleb (Eds.). Spektrum.

Rudolph, M., Velbert, F., Schwenzfeier, S., Kleinebecker, T., & Klaus, V. H. (2017). Patterns and potentials of plant species richness in high-and low-maintenance urban grasslands. *Applied Vegetation Science*, *20*, 18–27.

Salas, D. J. (2008). Developing an ecological restoration management plan: John Heinz National Wildlife Refuge, Philadelphia. *Ecological Restoration*, *26*, 246–253.

Schadek, U., Strauss, B., Biedermann, R., & Kleyer, M. (2009). Plant species richness, vegetation structure and soil resources of urban brownfield sites linked to successional age. *Urban Ecosystems*, *12*, 115–126.

Schröder, R., & Kiehl, K. (2020a). Ecological restoration of an urban demolition site through introduction of native forb species. *Urban Forestry & Urban Greening*, *47*, 126509.

Schröder, R., & Kiehl, K. (2020b). Extensive roof greening with native sandy dry grassland species: Effects of different greening methods on vegetation development over four years. *Ecological Engineering*, *145*, 105728.

Schwarz, N., Moretti, M., Bugalho, M. N., Davies, Z. G., Haase, D., Hack, J., ..., & Knapp, S. (2017). Understanding biodiversity-ecosystem service relationships in urban areas: A comprehensive literature review. *Ecosystem Services*, *27*, 161–171.

Sehrt, M., Bossdorf, O., Freitag, M., & Bucharova, A. (2020). Less is more! Rapid increase in plant species richness after reduced mowing in urban grasslands. *Basic and Applied Ecology*, *42*, 47–53.

Seitz, R., Lang, A., Hanak, A., & Urban, R. (2012). Der Schlosspark Nymphenburg als Teil eines Natura 2000-Gebietes. *LWF Wissen*, *68*, 46–54.

SER (Society for Ecological Restoration International Science & Policy Working Group). (2004). *The SER international primer on ecological restoration*. Tucson, Arizona https://www.ser.org/page/SERDocuments.

SIA 312. (2013). *Begrünung von Dächern. Schweizerischer Ingenieur- und Architekten-Verein*. Zurich.

Sikorski, P., Wińska-Krysiak, M., Chormański, J., Krauze, K., Kubacka, K., & Sikorska, D. (2018). Low-maintenance green tram tracks as a socially acceptable solution to greening a city. *Urban Forestry & Urban Greening*, *35*, 148–164.

Silva Matos, D. M., Junius, C., Santos, F., & de R. Chevalier, D. (2002). Fire and restoration of the largest urban forest of the world in Rio de Janeiro City. *Brazil.* Urban Ecosystems, *6*, 151–161.

Smith, D. A., & Gehrt, D. D. (2010). Bat response to woodland restoration within urban forest fragments. *Restoration Ecology*, *18*, 914–923.

Smith, L. S., & Fellowes, M. D. E (2014). The grass-free lawn: management and species choice for optimum ground cover and plant diversity. *Urban For.* Urban Green, *13*, 433–442.

Standish, R. J., Hobbs., R. J., & Miller, J. R (2013). Improving city life: options for ecological restoration in urban landscapes and how these might influence interactions between people and nature. *Landscape Ecology*, *28*, 1213–1221.

Sukopp, H. (2002). On the early history of urban ecology in Europe. *Preslia*, *74*, 373–393.

Teixeira, C. P., & Fernandes, C. O. (2020). Novel ecosystems: a review of the concept in non-urban and urban contexts. *Landscape Ecology*, *35*, 23–39.

van Andel, J., & Aronson, J. (2012). *Restoration ecology − the new frontier*. Wiley Blackwell.

van den Bosch, M., & Sang, A. O. (2017). Urban natural environments as nature-based solutions for improved public health—A systematic review of reviews. *Environmental Research*, *158*, 373–384.

Wastian, L., Unterweger, P. A., & Betz, O. (2016). Influence of the reduction of urban lawn mowing on wild bee diversity (Hymenoptera, Apoidea). Journal *of* Hymenoptera, *49*, 51–63.

Watson, C. J., Carignan-Guillemette, L., Turcotte, C., Maire, V., & Proulx, R. (2020). Ecological and economic benefits of low-intensity urban lawn management. *Journal of Applied Ecology*, *57*, 436–446.

Weber, A., Lautenbach, S., & Wolter, C. (2012). Improvement of aquatic vegetation in urban waterways using protected artificial shallows. *Ecological Engineering*, *42*, 160–167.

Weigelhofer, G., Hein, T., Kucera-Hirzinger, V., Zornig, H., & Schiemer, F. (2011). Hydrological improvement of a former floodplain in an urban area: Potential and limits. *Ecological Engineering*, *37*, 1507–1514.

Wild, T. C., Bernet, J. F., Westling, E. L., & Lerner, D. N. (2011). Deculverting: reviewing the evidence on the 'daylighting' and restoration of culverted rivers. *Water and Environment Journal*, *25*, 412–421.

Włodarczyk-Marciniak, R., Sikorska, D., & Krauze, K. (2020). Residents' awareness of the role of informal green spaces in a post-industrial city, with a focus on regulating services and urban adaptation potential. *Sustainable Cities and Society 102236.*

Zari, M. P. (2018). The importance of urban biodiversity−an ecosystem services approach. *Biodiversity International Journal*, *2*, 357–360.

Zingraff-Hamed, A. (2018). *Urban river restoration - a socio-ecological approach*. PhD thesis, TU München & Université de Tours.

Zölch, T., Maderspacher, J., Wamsler, C., & Pauleit, S. (2016). Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. *Urban Forestry & Urban Greening*, *20*, 305–316.