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Article

Initiating Research into Adapting Rural Hedging Techniques, Hedge Types, and Hedgerow Networks as Novel Urban Green Systems

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Abstract: This article seeks to initiate research into traditional rural hedging techniques, hedge types, and hedgerow networks for the purpose of their potential adaptation as urban green systems (UGS). The research involves three scales: (1) the plant scale and related manipulation techniques; (2) hedgerows and their context-specific types, ecosystem function, and ecosystem services; and (3) hedgerow networks as continuous green systems that characterize and support specific landscapes. This research required an interdisciplinary approach. The analysis was conducted by applying different modes of research including: (a) an extensive literature review, (b) analysis and systematization of hedge types and manipulation methods, (c) field experiments, (d) design experiments, and (e) examination of real-life projects that use hedges or hedging techniques as distinct design features. The initial research indicates that traditional hedges can be adapted to vitally contribute to UGS by providing a broad range of urban ecosystem services. Furthermore, the research includes initial proposals on future applications of adapted rural hedge types and techniques. On the larger scale, anticipated difficulties regarding implementation, such as land allocation in cities and resource-intensive planting, management, and maintenance, are discussed and further research questions are outlined.

Keywords: hedges; hedging techniques; hedgerows; hedgerow networks; urban hedges; urban green systems; ecosystem functions and services; biodiversity; design research

1. Introduction

Rapid urbanization is a primary cause of land cover change, land use change, and intensification, and thereby of environmental degradation worldwide [1]. Moreover, urbanization frequently leads to a loss of existing landscape elements and green infrastructure. At the same time, urban green systems (UGS) are increasingly researched and implemented to meet environmental sustainability goals.

However, established approaches are commonly based on generic systems leading to conventional green infrastructure that falls short in meeting the challenges of environmental degradation, climate change, and reduction of ecosystem services and biodiversity. Overcoming the genericness of current UGS is therefore of vital importance for sustainable development of cities and communities. For this reason, there exists a research gap concerning the diversification of condition- and location-specific UGS through the addition of new systems. With this article we therefore seek to initiate research into adapting rural hedge types, hedgerows, and hedgerow networks as a vital addition to existing UGS.

Historically, hedges were a dominant feature of the agricultural landscapes in which they occurred and offered a multitude of ecosystem functions and services. These include the provision of field boundaries, food, material, shelter from wind, organic carbon storage, infiltration promotion, soil health, and increased invertebrate and insect pollinator diversity that are beneficial for humans, biodiversity, and ecosystems. For this reason, traditional hedgerows and related hedging practices are a relevant example for a synergistic human–environment relationship in which ecosystem services—the benefits nature provides to humans—are shaped and managed by humans. The loss of hedgerows and related knowledge accelerates wherever hedges are not part of land conservation and restoration efforts. Therefore, capturing the underlying knowledge needs to proceed immediately. Studies on the role of hedgerows in their typical rural context [2–4] and studies on their ecosystem [5] and biodiversity functions [6,7] exist. However, studies that examine how the services that such green systems provide can be adapted to new or altered settings and uses are sparse. Evidently, our research does not focus on ornamental mono-species hedges that already exist in cities. Instead, this article surveys the role that hedgerows have played in rural and agricultural contexts, and elaborates on the role adapted hedgerows and hedging techniques may play as UGS. In general, this concerns landscape and urban landscape planning, green architecture, conservation and management, and a wide range of functions including ecosystem services. We postulate that the implementation of hedges and hedging techniques in various settings and contexts can fundamentally support sustainable development and deliver a key aspect for regenerative design in established and novel ways [8–10].

The intention of this article is to initiate research into the potential adaptation of rural hedging techniques, hedge types, and hedgerow networks as UGS. This requires a long-term perspective that addresses associated problems and develops design approaches, methods, and strategies for implementation and maintenance on three scales: (1) the plant scale and related manipulation techniques; (2) hedgerows and their context-specific types, ecosystem function, and ecosystem services; and (3) hedgerow networks as continuous green systems that characterize and support specific landscapes.

2. Materials and Methods

For the purpose of initiating research into this topic, focus was placed on reviewing traditional rural hedge types, hedging methods, and functions of hedgerows and hedgerow networks from an overarching and qualitative perspective. We employed a range of methods that included: (a) an extensive literature review, (b) analysis and systematization of hedge types and manipulation methods, (c) field experiments, (d) initial design experiments, and (e) examination of real-life projects that use hedges as design features. The use of the different research methods varied in relation to the three scales described above: (1) On the plant scale, research was based on a literature review and subsequent systematization of hedging techniques, complemented by the description of field experiments. (2) On the scale of hedgerows, research was based on a literature review as well as the systematization of hedge types, complemented by design experiments on adapting hedge types for urban settings. These design experiments were conducted in the context of a seminar at the Professorship for Green Technologies in Landscape Architecture (GTLA) at the Technical University of Munich (TUM, Germany) within a framework of research into and through design in landscape architecture [11]. Additionally, existing projects by various architects and landscape architects that employ hedges or hedging techniques as a key design feature were described to gain insights into the scope of innovative use of hedges and related practices in architecture to chart current approaches and state of the art. (3) The research on the scale of hedgerow networks was solely based on a literature review. Here, the focus was on the role of hedgerow networks in rural settings in order to understand the related services for subsequent adaptation to locally specific key performance indicators for urban hedgerow networks in follow-up research.

The initial literature list for all the addressed scales and topics included circa 100 articles, book chapters, and specialized publications. A keyword search was used to reduce the list of literature for the purpose of this article. The selected keywords included hedges, hedgerows, and hedgerow networks, frequently in combination with additional keywords including biodiversity, ecosystem functions, ecosystem services, etc. Focus was placed on available literature regarding historical use and production of hedges.

3. Results

This section examines the functions that hedges have served in past and present times, and initiates thoughts on the role that hedges and hedging techniques could play when adapted as vital UGS. As mentioned above, this involves three scales: the plant scale and related techniques of creating and managing hedges; the scale of hedgerows and their context-specific composition and ecosystem services; and the large scale of hedgerow networks as continuous green systems. We also reviewed several built and projected works that are relevant to this research. These reveal current state-of-the-art practices, as well as gaps that need to be addressed in future research and works.

3.1. Hedges and Hedging Techniques: From Traditional Practices to Novel Approaches

Understanding hedges on the plant scale requires detailed comprehension of the methods and techniques needed to establish and maintain hedges, such as the manipulation, growth, and regenerative potential of woody plants and related benefits.

Existing categorization of traditional hedges and hedging techniques such as those presented, for instance, in Georg Müller's two volume encyclopedia *Europe's Field Boundaries* [12], frequently use hedge typologies or forms such as "Diagonal Hedge", "Étagère Hedge", or "Coppiced Hedge" to describe different methods, styles, or planting patterns. While this approach is useful to provide an overview of hedge types and forms, it falls short in revealing the full potential of the underlying techniques. Instead of describing the form of the hedge, the analysis and systematization presented in this subsection uses a three-level classification system (Figure 1).

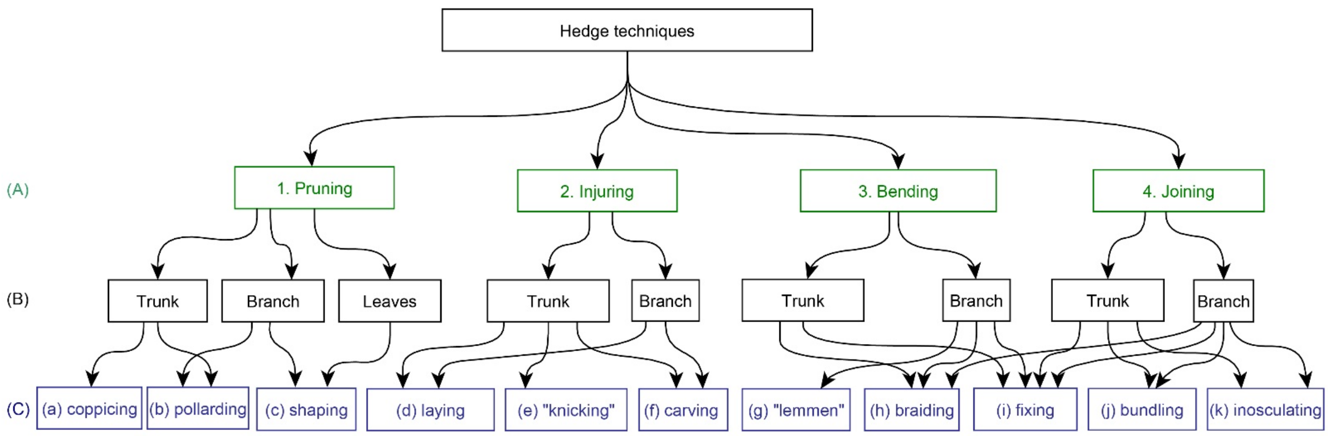

Figure 1. Classification of hedging techniques (L. Höpfl).

First, we differentiate between four main hedge methods to initiate a systematic approach to the plant scale (A). These include:

1. Pruning: cutting through a specific part of the plant and thereby disconnecting it from the plants' supply system;
2. Injuring: harming a specific part of the plant without disconnecting it from the plants' supply system;
3. Bending: pulling a specific part of the plant away from its original growth pattern without harming it;
4. Joining: connecting two (or more) specific parts of one plant or two (or more) plants with another.

Secondly, we differentiate between the part of the plant (trunk/branch/leaves) where the technique is applied (B).

Thirdly, we distinguish between specific techniques (C):

(a) Coppicing: repetitive pruning of trunk(s) or branches at or close to the ground level;
(b) Pollarding: repetitive pruning of the trunk or branches at a certain height;
(c) Shaping: repetitive pruning of the fine branches and leaves or needles;
(d) Laying: cutting a trunk or branch up to 4/5 of its diameter, leaving a thin supporting tongue, and laying it in an angle of 35–45°;
(e) Knicking: breaking a trunk or branch until it tears and splinters, without disconnecting both parts, and assembling it towards the horizontal;
(f) Carving: cutting small wedges into the trunk or branch and bending it towards the horizontal;
(g) Lemmen: bending the branch of a tree towards the ground without harming it, fixing it at the ground;
(h) Braiding: interweaving trunks or branches around each other;
(i) Fixing: connecting a trunk or branch either to a supporting structure (non-living element) or to another trunk or branch (living element) using fixing elements;
(j) Bundling: assembling two or more trunks or branches parallel and very close to each other;
(k) Inosculation: joining two or more trunks or branches together with pressure, using fixing elements with the aim of joining both elements into one unit.

This approach enables the understanding of underlying principles of tree manipulation and gives hints for new implementation possibilities. In the following part, several practices are described in detail.

3.1.1. Pollarding and Coppicing

Coppicing and pollarding entail the cutting of shoots from a woody plant at regular intervals. Pollarding can take place along the main trunk, at the top of the main trunk (head), and at the end of the side branches (Figure 2). The harvesting of the shoots causes the pollarded tree to develop a relatively large root mass compared to the remaining crown. Additionally, dormant buds sprout out and often adventitious buds are formed on the remaining wood, leading to vigorous regrowth [13] (regarding tree species that show these reaction patterns and are therefore particularly suitable for pollarding and coppicing, see [11]). Due to callus formation, the cut surfaces develop thickenings that cause the typical gnarled appearance. The new shoots are more numerous and longer, while the leaves are larger [14], resulting in an increase in biomass. If planted or maintained, hedges are mostly pollarded at the base, which is generally referred to as coppicing. The remaining stump then resprouts from already existing buds, directly from the roots [15], or at the side branches, thus densifying the hedge and keeping it in a desired form. Pollarding is a process that is carried out over a long period of time. If it is interrupted or stopped after prolonged use, plants lose their ability to rejuvenate, and trees change their structural behavior due to the increase in leaf mass in the crown; branches bend and the whole tree can eventually break apart [16].

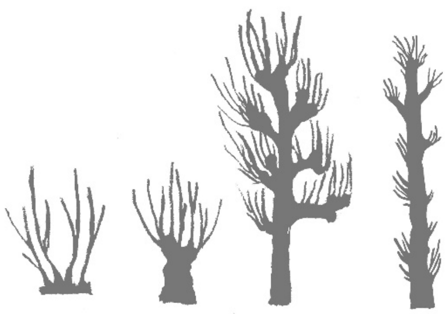

Figure 2. Forms of coppicing and pollarding (L. Höpfl).

Pollarding is a common and frequently applied practice in horticulture and in nurseries to produce candelabra trees, which can often be seen in urban streets, parks, and private gardens. After pruning, leaves grow significantly larger and display more intense coloring. Recently, the technique of coppicing found its way into planting design to foster desired foliage characteristics in woody plants [17].

3.1.2. Shaping

The shaping of trees is still present today and has found its way into garden architecture. At regular intervals, branches, fine branches, and leaves or needles are cut along a defined sharp cutting line. Pruning results in thousands of injuries, and the tree reacts with the same number of bifurcations close to the cut areas. Pruning causes the hedge to densify if the process is repeated while moving the cutting line further away from the old line (Figure 3). This practice was historically common in rural areas to obtain the additional fodder from the densified tree, as well as a living fence and shelter against wind and weather.

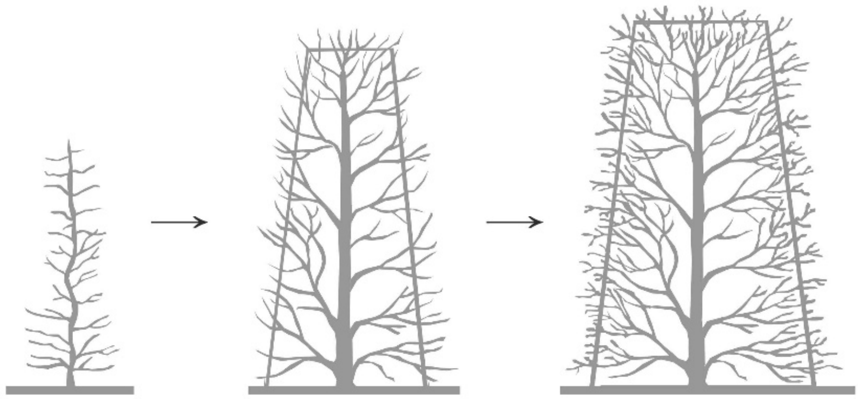

Figure 3. Timeline of shaping: from the planting stage, over the first pruning step during growth, to a densified and pruned hedge (L. Höpfl).

In the Middle Ages, pleasure gardens featured hedges and arcades created from trees [18]. In these gardens, elaborately shaped hedges were no longer planted primarily as a field boundary, but rather to impress with their exact symmetry. Some of the high narrowly cut hedge gardens that reached their peak in the Renaissance and later in the Baroque required extensive horticultural knowledge and craftsmanship, which only the upper class could afford. In contrast to the agricultural tradition, such hedges primarily served the purpose of staffage and thus the demonstration of power and wealth. To this day, hedges and trees pruned into such shapes are still part of the established design repertoire of garden and landscape architecture. As garden hedges, they fulfil a demarcation function, yet have nevertheless primarily become an element of style in which the regenerative potential and multifunctionality of earlier forms of use plays little to no role. In contrast, a special type of hedge grown for a variety of benefits is, for example, found in the region of Monschau, in Germany. Exposure to strong and cold winter winds encouraged the use of domestic hedges planted close to buildings for wind protection (Figure 4). After initial laying and interweaving processes, the domestic beech hedge (*Fagus sylvatica*) has to be pruned and kept in form at regular intervals. Sizes up to 10 m in height and 1 m in width are common. As beeches keep their withered leaves, they can provide protection in winter and shade and cooling in the summer [19].

Figure 4. A huge and well-maintained domestic hedge in Höfen, along the property boundary, protecting the building from wind. (photography: Caronna, CC BY-SA 3.0. [20])

3.1.3. Hedge Laying

Hedge laying is an ancient technique that existed throughout human history and served numerous purposes, such as protection against wild animals or humans, fences for cattle, and protection of crops. In many places, there existed a shortage of resources such as wood until the age of industrialization, thereby necessitating other means to create fences. Until the second half of the 19th century, one way was to plant woody plants and to densify these into living fences through hedge laying. The latter is a practice which turns upright-growing, densely planted trees and shrubs into a horizontal living fence from which new shoots grow. First, the lower branches of the trunk are removed and then shoots are either bent horizontally in such a way that they tear (“knicking”), or larger and thicker trunks are cut 80% through just above the ground with an axe and then “laid” up to 45–35°. In both cases, a thin connection of bark and sapwood assures a constant supply of water and nutrients from the roots to the part above the injured area. The flap formed during the cutting process is removed after the trunk is laid, so that a smooth cut surface can be created to completely heal over time [21,22].

Fast-regenerating woody plants, such as hawthorn, hornbeam, field maple, mountain maple, Norway maple, willow, ash, and hazel [23], were mostly used. These sprout again over the entire length of the trunk after laying. Over time, the new sprouts become thicker and are either removed for material production or are laid another time. This needed to be performed at regular intervals, as the trees would otherwise mature in the laid form, resulting in so-called “Gebück“ [11] (Figure 5). Today, this labor-intensive technique has largely disappeared in Europe except for extensive traditional hedge laying in England.

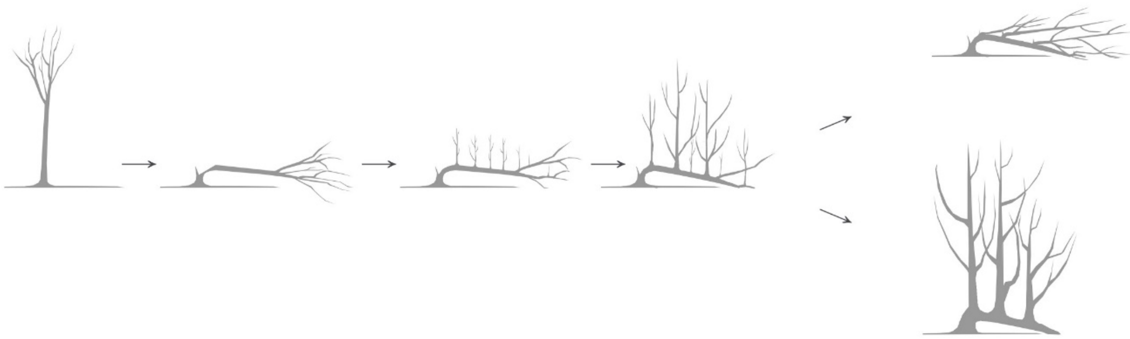

Figure 5. Timeline of laying, shown on a single tree: a chosen tree is partly cut and laid towards the ground, where it resprouts and thickens vertically. From there two steps are possible: another laying process (above) or a maturing process (below) (L. Höpfl).

3.1.4. Inosculation

A further hedging technique concerns the diagonal planting of inosculated shoots to form a dense and stable living fence. Mainly species that inosculate easily are used. Generally, species with thin, low-fiber bark tend to inosculate more often and faster than those with thick, long-fiber bark [24]. Saplings are mostly planted as a pair and guided in an angle of 40–60° [11], subsequently fixed at the crossing points and occasionally also to vertical shoots. Over time, inosculation processes unite the different parts into an inseparable living construction. When left unmaintained, the living fence grows vertically with a remaining cross shaped base at the ground (Figure 6).

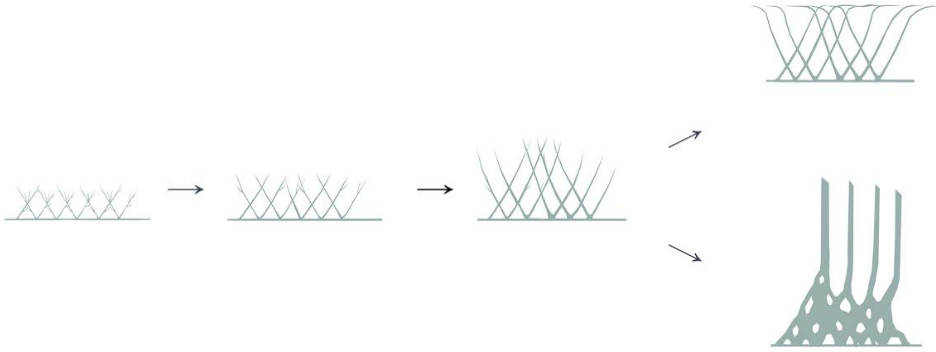

Figure 6. Timeline of inosculation of a diagonal hedge: from planting as a diagonal pair, shoots are fixed at the crossing points to inosculate through thickening processes. Over time the diagonal hedge is either maintained to keep its height (above) or grows out vertically (below) (L. Höpfl).

This old hedging technique is currently explored in the field of *Baubotanik*, a construction method that combines living plants and technical joints, thereby using living plants for structural elements in architecture [25,26]. Ongoing tests located at different test fields in Germany (Figure 7) explore the potential of inosculation on a plant level. These experiments are continually surveyed to document general behavior and species-relevant differences [24].

Figure 7. Test field of the Research Group Baubotanik (TUM) in Bad Zwischenahn, Germany, where inosculation methods and connection stability is investigated by joining pairs of young trees. (photography: Ferdinand Ludwig).

3.2. Studies En Route to Adapting Traditional Hedgerows to Novel Types of Urban Hedges

Hedgerows in traditional agricultural land use practices constitute an important type of green infrastructure, one which could potentially deliver solutions to some of today's environmental challenges in cities (i.e., food production, climate change, pollution).

Throughout human history, a great diversity of hedgerow types has evolved in many rural areas of the world together with their specific species selection, planting schemes, plant manipulation techniques, and management and maintenance practices. In contrast, the implementation of hedges in gardens and cities has led to a homogenization of hedge types associated with standardization of form and a limited range of hedge plants. This realization makes it necessary to study traditional hedges again, as learning from time-tested solutions can provide essential insights into how to better adapt hedgerows to and improve urban environments. The aim of the study presented in this subsection is to address the performance gap linked with the loss of multifunctionality, which becomes apparent when urban hedges are compared with the traditional hedgerows of rural settings. The question of what can be learned from historical hedge systems to improve the design and implementation of hedges in cities was addressed in the seminar "Urban Hedges" (GTLA at TUM, winter semester 2019). A broad range of rural hedge types were analyzed and systematized based on the information derived from an extensive literature review. This entailed exploring the potentials of transferring and adapting this historical knowledge for innovative uses in urban contexts through design exercises. The studies focused on sites in Munich, where hedges are abundant.

3.2.1. Systematization of Hedge Types

The work on systematization started with extensive literature research with the aim to gather data on traditional hedge types from reliable historical and contemporary records and internet sources. A selection of 53 traditional rural hedgerows and hedging practices from different geographic locations and climate zones formed the initial dataset for configuring a hedge database where data derived from historical case study analysis could be stored, managed, and structured (Figure 8). Such a database can complement existing electronic resources, such as the National Hedgerow Database by Woodlands of Ireland [27], which contains samples exclusively from Ireland. Our database is intended to be an extensive source of information and thereby can include border types. It includes information about hedge types, their geographic location, climate, time of origin, plants, plant manipulation techniques, tools, management and maintenance requirements, features, main purpose, functions, and ecosystem contributions and benefits. Unlike common directories, the intention behind building the database was not to simply store data for heritage documentation and conservation purposes, but to provide a tool that can facilitate research and design of novel urban hedge systems.

Table 1. List of historical hedge types presented in Figure 8 [28–33].

Traditional Hedges: Types listed in Figure 8					
Code	**Name**	**Location**	**Main and Beneficial ES**	**Main Plant Species**	**Main Plant Manipulation Technique**
31	Irish Dark Hedge	North Ireland	Aesthetics	European Beech	
38	Grafted Tree Hedge	Germany-Ohrdruf	Field boundary	Swedish whitebeam and dogwood	Planting at an angle of alternating ±45 degrees for natural inosculation over time
42	Willow Cross Hedge (Krushaeg)	Belgium	Field boundary	Willow trees	Bent at an angle of 35-60 degrees and interwoven diagonally

Table 1. *Cont.*

Traditional Hedges: Types listed in Figure 8					
Code	**Name**	**Location**	**Main and Beneficial ES**	**Main Plant Species**	**Main Plant Manipulation Technique**
27	Osage Orange Hedge	USA	Field boundary, separate production zones, provide privacy, confine and protect livestock, protect crops, habitat provision, promote soil health and ecosystem balance	Osage orange	Plants are bent in a low-lying arched form and planted at the tip of their stem back into the ground in an overlapping manner, thereby forming an arched array. Shooters are interwoven once they grow
21	Agave Hedge	Peru	Protective and separative fence, paste for paper production, juice for beverages, leaves used in thatch, fibres used for making strong chords, pins and needles, roots used in cooking	Agave	
23	Cactus Hedge	Caribbean Island	Protect and demarcate boundary, fence in goats to protect farmland, gardens and nature	Cactus	Planted in a triangular manner and as they grow, bent at 30 degrees angle and fixed with metal wire and frame
17	Gabion Hedge	Senegal, Kidira	Curtail run-off water for preventing soil erosion and rehabilitation of downstream ravines in watershed systems by capturing sediments	Grass	
6	Vetiver Grass Hedge	Thailand	Slow down water movement for soil conservation	Vetiver	Planted at regular intervals along the downward edge of a terrace, which forms as a result of soil building up over time in the process of erosion
2	Fire Retardant Hedge	Australia	Fire proof (under moderate fire conditions) property demarcation	e.g., Tree aloe, Oldman saltbush	

Figure 8 gives an overview of the geographic distribution of the rural hedge types that were studied. These hedgerows were typically established first for property demarcation, then for control of animal movement, and then for protection against (usually cold) winds. Our studies show that alongside these prevalent functions, among the selected 53 locally specific hedge types, the use of the hedgerow for 'material production for making hand tools' (a provisioning service) occurs 20 times, followed by 'protection from wind' (a regulating service), shared by 9, while 'stock-proof barrier for horses' (a cultural service), 'protection from wildfires' (a regulating service), 'phytoremediation for polluted land' (a supporting service), and 'production of food for human consumption' (a provisioning service), occurs only 1 time among the surveyed cases. Therefore, from a historical point of view, the latter, for instance, is a more specialized need. The nine examples shown in the photographs (Figure 8) are presented in Table 1. The numbers correspond to the numbering convention used in the illustration.

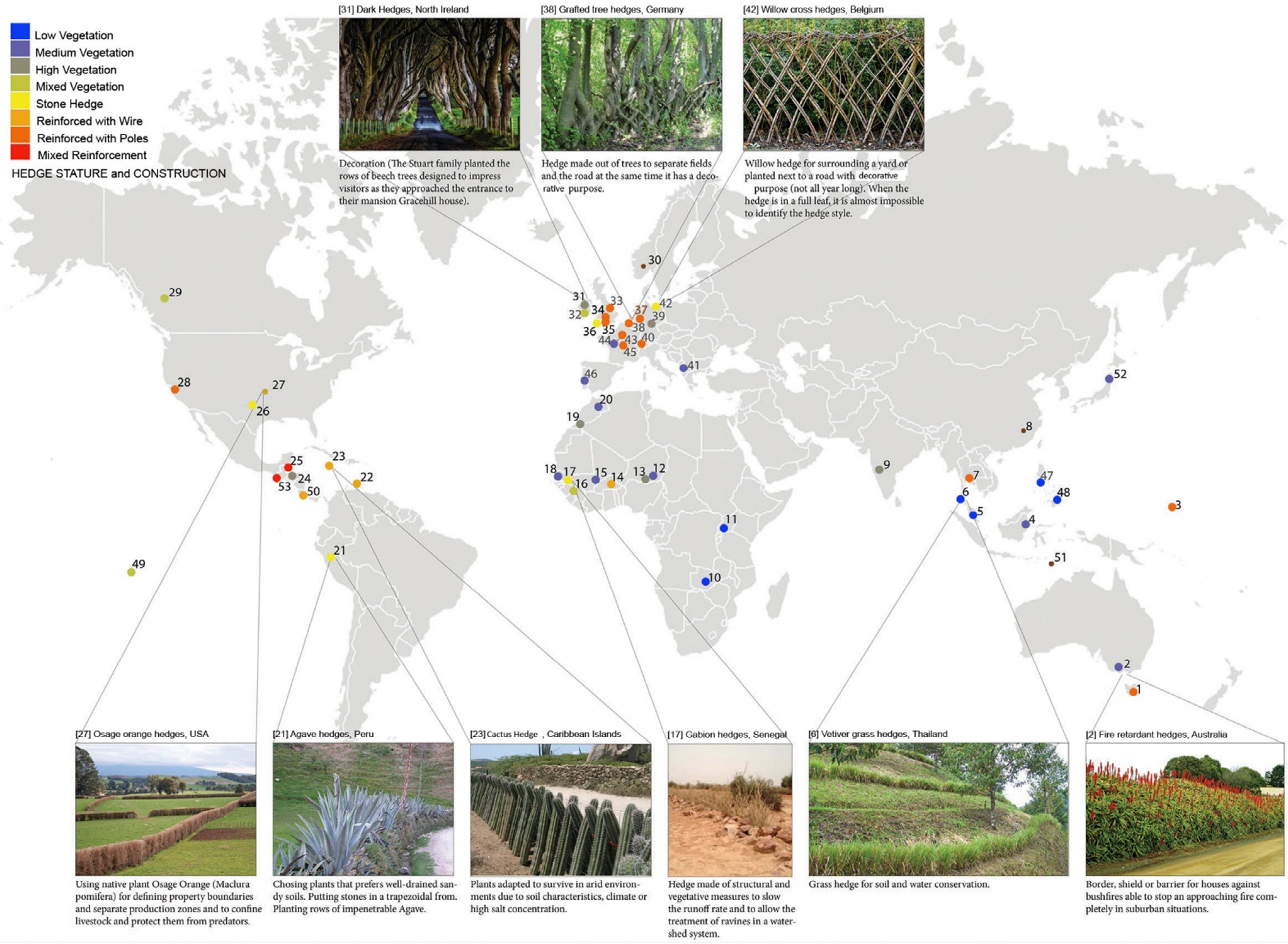

Figure 8. Map of the selected 53 historical rural hedge types from all over the world used as the initial dataset for building a hedge database for design. "Hedge Database for selection" by Senta Badovinac Bajuk and Nouhaila Karroum, GTLA at TUM, winter semester 2019, Urban Hedges Seminar. Numbers in square brackets in the figure are codes of the hedges (see Table 1).

3.2.2. Rethinking the Urban Green Systems and Hedges

The gathered information forms the initial dataset that will be analyzed and supported with information from further research and related studies. This will then be structured to be used in design experiments focused on the development of novel urban hedge systems. Some of this work has already begun in the form of systematic and comparative analyses of the interventions that contribute to the generation of these hedges. This involved mapping the generative processes along a timeline as a particular combination and sequence of plant selection, manipulation, management, and maintenance decisions. One such comparison was made between the three rural hedge types and corresponding traditional practices: (1) Midland Hedges, UK [34]; (2) Devon Hedges, UK [35]; and (3) Contour Hedges of the alley cropping systems in the Philippines [36] (Figure 9).

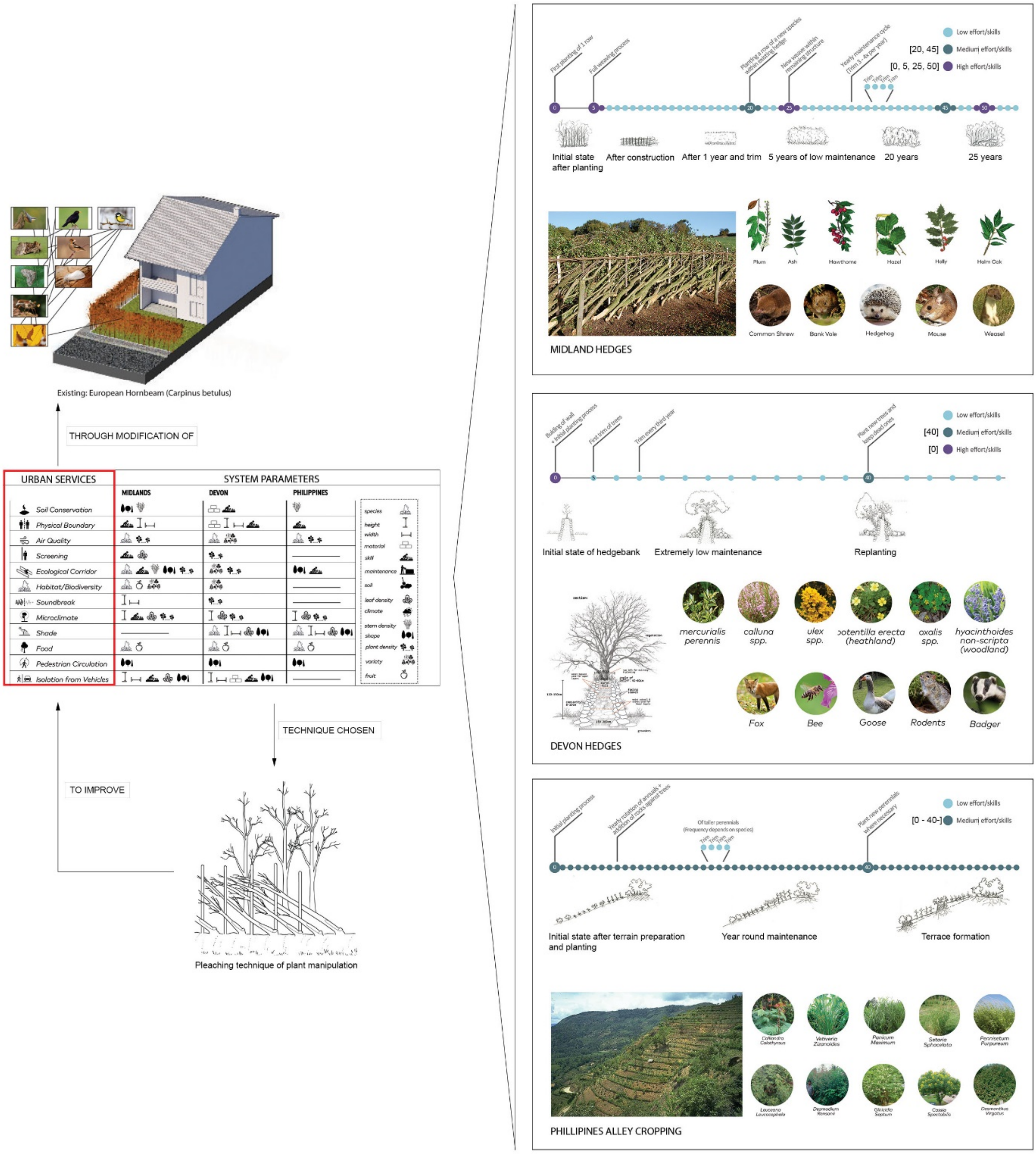

Figure 9. Comparative study of the three traditional rural hedge types, the related planting, manipulation, management, and maintenance decisions mapped along a timeline, planned and associated biodiversity, and potentials for transfer of solutions to improve urban hedge performance; GTLA at TUM, winter term 2019, Urban Hedges Seminar, work by Arda Cosan and Carling Sioui, including work of Kianu Goedemond and Marco Alonso Hsu.

The linkages between the system parameters and services were identified in principle terms and studied to examine whether services delivered in one context (i.e., rural environment and agricultural purposes) can be relevant for delivery in another setting (i.e., urban environment and architectural purposes). Many of those benefits observed in traditional systems were found to also be beneficial for urban contexts. These studies confirmed that the functions made possible by traditional practices are diverse and range from wind protection to prevention of wildfire spread and promotion of soil formation and conservation. In comparison, urban hedges deliver limited functions and services, partly due to their homogeneous plant structure as well as low plant species diversity, as selection favors plants that can withstand and meet urban conditions and needs. For this reason, it is of interest to study the possible adaptation of traditional hedgerow types to urban settings.

To pave the way for such a transfer, surveys were carried out on a number of sites in Munich to study and characterize (a) site boundary conditions, (b) the hedgerows that are currently there, and (c) performance gaps. The latter concerns the various additional benefits that could potentially be delivered through improvements in hedge design, as well as an assessment of the variability and adaptability of several of the solutions found in traditional systems to the complex and diverse needs and conditions found in cities. Ackermannbogen in Munich was chosen as a study site to test the potentials of transfer of insights gleaned from historical case studies (Figure 10). Ackermannbogen is an area where a wide range of residential building types, semi-public areas, public areas of the Olympiapark, private gardens, and major roads are found and establish diverse boundary conditions. Cities generate hard borders unlike the environmental gradients found in rural areas. The border types found on the site were mapped and classified to establish the existing boundary conditions, as well as the existing urban green infrastructure and hedges. This was followed by a study for identifying the areas which offer opportunities for plantation, the types of species and locations where they can be established, as well as the target areas which could be improved through implementing history-inspired urban hedges. This design exercise highlighted the importance of coordinating decision-making at the landscape scale (related to urban forestation and the planting of trees and shrubs), with hedgerow interventions planned at the local scale according to ecosystem service needs, especially to address some of the factors that limit hedgerow performance in cities. This includes the negative impact of adjacent sealed surfaces, habitat fragmentation, and homogeneity of the living plant structures on hedge performance. The hedges that were sampled are all confined to a limited number of plant species that grow easily in continental climates, are mono-species hedges rather than mixed-species, and are maintained to keep their topiary pruned forms rather than utilizing sophisticated techniques that work with growth processes. Evergreens are often favored due to their ability to provide privacy to houses and gardens all year round, although this could easily be achieved with deciduous plants using plant manipulation techniques similar to weaving or pleaching for example.

Plant selection and plant establishment are critical in the design of hedges. Several challenges concern encouraging seed dispersal and colonization of high-value/non-invasive plant species in cities, and detecting and expanding areas for urban forestation and green infrastructure. Another challenge regards tailoring the design and performance of the hedge to the different local needs and conditions, i.e., simultaneous provision of weather protection (i.e., wind, sun), noise attenuation (especially traffic), and privacy (an increasing challenge in densely built areas), while at the same time generating new possibilities for food production in cities. Some studies focused on the design link that can be formed between urban trees and buildings to facilitate a better local response to different combinations of design requirements. This included assigning specific pruning techniques to achieve the necessary moderation of wind speed, sound attenuation, privacy, and solar access through careful manipulation of vegetation and canopy density (Figure 11, bottom).

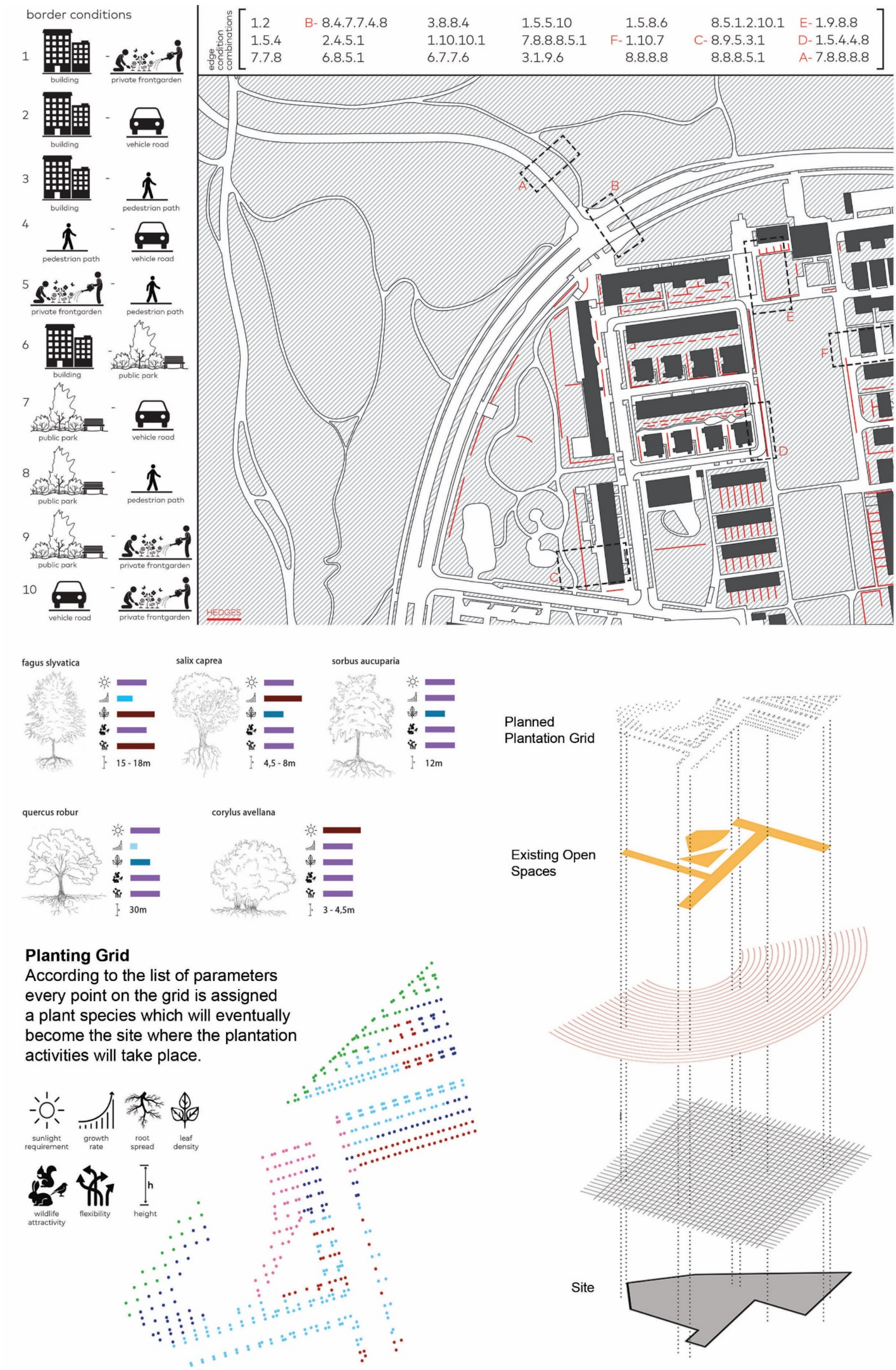

Figure 10. Analysis of urban hedges and urban boundary conditions found in Munich (top left column: types of land use

indexed and top row: numerical combinations denoting border conditions on site) and design exercises with focus on plant selection and distribution for urban hedge interventions informed by historical case studies; GTLA at TUM, winter term 2019, Urban Hedges Seminar, works of Elementary Application of Rural Hedging into Urban Functionality by Arda Cosan and Carling Sioui.

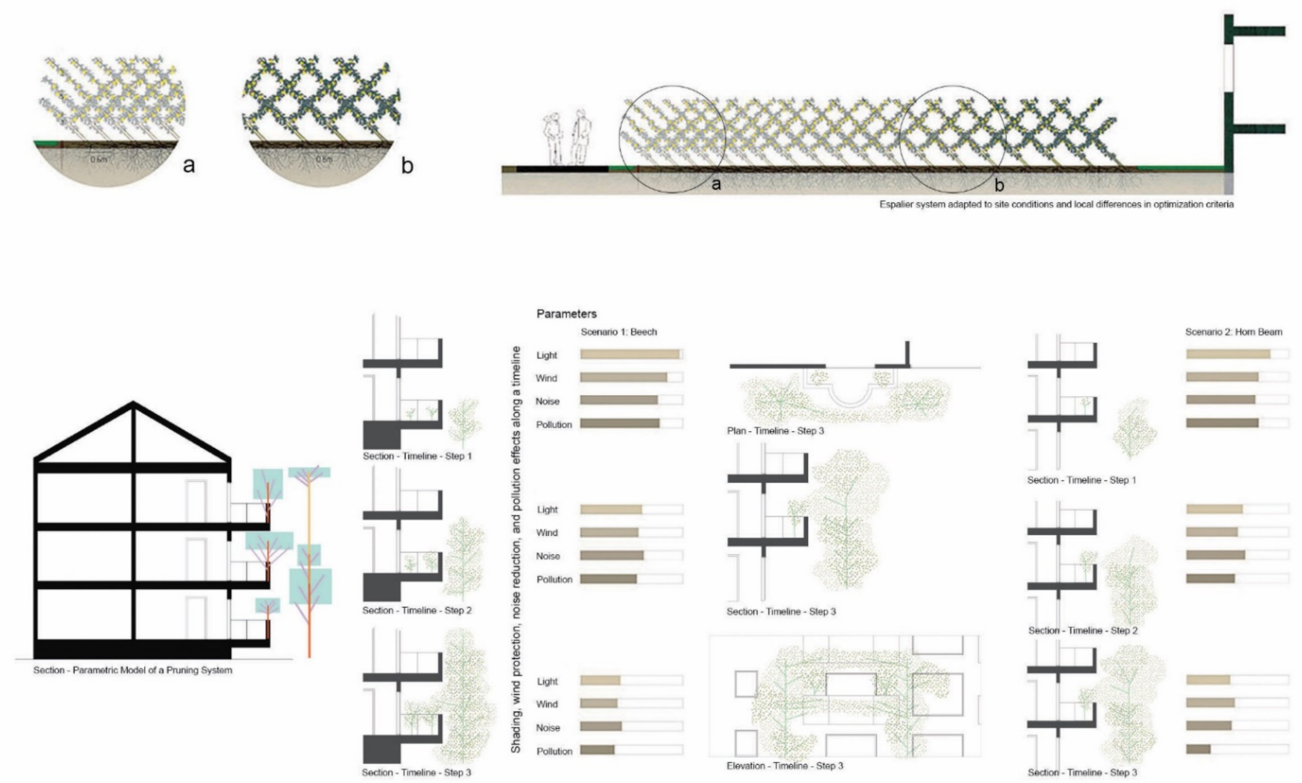

Figure 11. Basic system variability to cope with diverse needs and conditions based on tree pruning techniques for beech and hornbeam and the espalier method; GTLA at TUM, winter term 2019, Urban Hedges Seminar, works of Community Green Densification by Carlos Martinez, Pablo Giobellina, and Andres López, and Fruit Production in the City with Espalier Hedges by Alice Lahourde and Simon Ochott.

The espalier method is a hedge type invented and advanced by the Romans to improve the cultivation of fruit trees through a combination of training and pruning techniques. This technique was initially adopted due to its advantages for vertical production along walls where space is limited, such as in dense settlement areas, and later for food production at the industrial scale (U.F.O. System—Upright Fruiting Offshoots System). Another reason for using the espalier is to provide maximum sunlight exposure throughout the height of the tree, especially at higher altitudes where conventional orchard methods are not suitable for fruit production. One interesting example is the espalier technique developed in the 1920s by the French arborist Edmond Bouché-Thomas in the city of Angers in Brittany in France. This urban study focused on the variability of the espalier method by examining its adaptability to three different urban sites. The goal was not only to optimize the system for fruit production, but also to respond to the individual priorities, different sets of objectives, and challenges specific to each site (Figure 11, top). Once the critical design parameters (i.e., distance between each individual plant and branches/chords, the angle of branches, hedge height) were determined, the ability of the design to improve multifunctionality, performance constraints, and further research questions could be established.

The studies indicate that it can be useful to couple knowledge with computational modeling, simulation, and decision support. For this reason, a line of work on computational modeling of hedges and simulation of manipulated plant growth was initiated.

The initial work on this topic focused on adapting L-system (originally developed to model plant growth and development by Aristid Lindenmayer in 1968) for the purpose of evolving and analyzing diverse and context-specific hedge structures (Figure 12). The application of L-systems requires instituting rules of stem internode expansion, and the predisposing condition, position, and direction of outgrowth and development of leaves. This method and rules can lead to useful modeling for erect growth shoots and could generate recommendations for the position of pruning treatments.

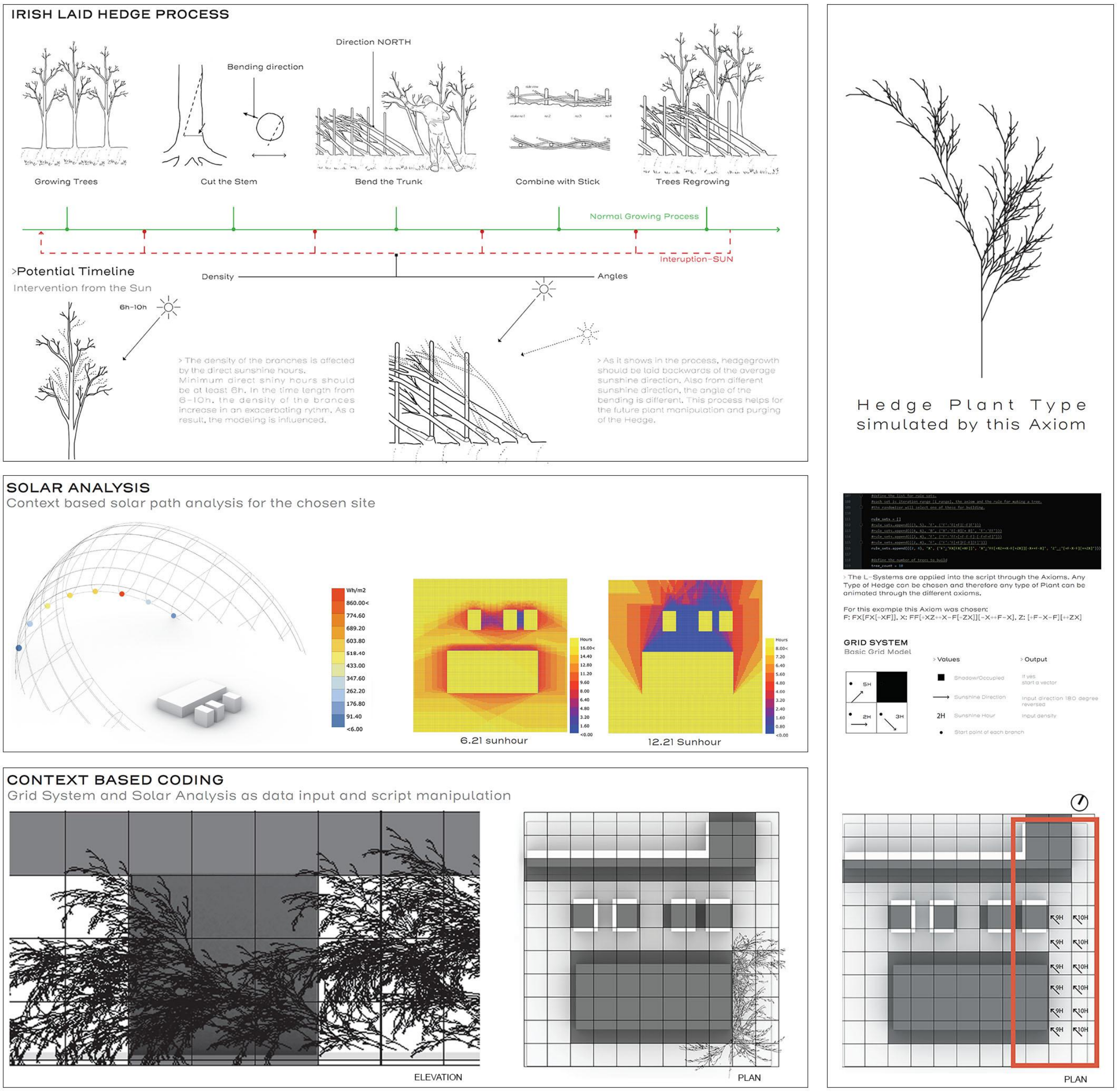

Figure 12. Analysis of rural hedges and urban boundary conditions found in Munich and translation as input for modeling and simulating such systems using L-system. Potential timeline takes into consideration the hedge-laying angle established according to the predominant direction of sunlight (second panel from the top); GTLA at TUM, winter term 2019, Urban Hedges Seminar, work of Context Specific L-System: Colonization of Hedge Under Solar Analysis by Dafni Filippa and Fan Wan.

3.3. Hedges in Contemporary Design Projects

A number of contemporary design projects feature hedges and/or hedging techniques as a distinct feature on the scale of individual buildings or clusters of buildings. Architectural scale projects that focus on single buildings frequently deploy one of three approaches:

(a) hedges as surface cover, (b) hedges as spatial elements that delimit and define spaces, and (c) Baubotanik projects that deploy hedging techniques as growing, living architecture. The latter can incorporate multiple functions ranging from defining space to structural elements. All three approaches inherently, but not always explicitly, include modulation of the microclimate.

Examples of projects using hedges as surface covers include, for instance, the holiday houses in Jupilles by Duncan Lewis and Edouard Francois (Figure 13) and the Kö-Bogen II commercial and office building in Düsseldorf designed by Ingenhoven Architects. The holiday houses in Jupilles by Duncan Lewis and Edouard Francois feature a tree hedge as a second skin of a two-story building.

Figure 13. A tree hedge as a living façade for a holiday retreat. Design by Duncan Lewis and Edouard Francois. (photography: © Maison Edouard François)

By densely planting different species close to the façade and framing the crown volume with wire nets to guide regular pruning, a formal but lively and ever-changing element creates the visible façade of the house. The tree hedge is narrow, entailing that windows and the lower part of the building are kept free from branches and foliage. This kind of green façade combines the advantages of the self-supporting structure of trees with the microclimate and cooling effects of the foliage [37]. A much larger project is the Kö-Bogen II commercial and office building in Düsseldorf designed by Ingenhoven Architects. The project features Europe's largest green façade, consisting of 8 km of evergreen Hornbeam hedges. The ecosystem services include urban heat reduction, carbon dioxide binding, moisture storage, and biodiversity support [38].

Examples of projects using hedges as spatial elements that delimit and define spaces include, for instance, the Spidernethewood house in Nimes, designed by R&Sie(n) or dense low-rise living quarters such as the Verdi-Siedlung in Vienna designed by Harry Glück. The Spidernethewood house in Nimes is located on a site with natural vegetation. Outdoor spaces are defined by nets in addition to the trees and shrubs that are trimmed along these nets. As trees and shrubs grow, their dense foliage provides protection from outside views. Moreover, the dense vegetation over large parts of the plot moderates microclimate and promotes biodiversity [39]. In the densely built Verdi-Siedlung by Harry Glück, hedges are used as living fences to delimit plots, embodying a green solution that reduces the perception of the built density of the living quarters [40].

Baubotanik projects that deploy hedging techniques as a growing living structure include, for instance, the "Green Room" in Ludwigsburg designed by ludwig.schönle. In this project, plane trees are used to grow a stable wall and a shading roof structure to improve local climate, employing the hedging technique of inosculation [41]. The "Plane Tree Cube" in Nagold, Germany, uses the same technique to foster stability and structural reliability of cross grown and interconnected trees [42,43] (Figure 14).

Figure 14. Plane Tree Cube, Nagold, Germany. The design by ludwig.schönle is based on the hedging technique of inosculation. (photography: © Ferdinando Iannone)

3.4. Hedgerow Networks—Approaching the Landscape Scale

Forman and Baudry posited that agriculture and hedgerows co-developed over human history in landscapes with moist temperate climates, today co-existing on circa 10% of the earth's surface [2]. This constitutes a significant amount of land surface and highlights the importance of hedgerows and their expansive use as hedgerow networks that characterize landscapes on the territorial scale (Figure 15). Examples of such landscapes include, for instance, the Northern German Knicklandschaft and the bocage in France and the UK. Hedgerows and hedgerow networks are studied in landscape ecology [2], with a focus on the role and functions of hedgerow networks as extensive and locally specific systems. One line of research focuses on landscape structures, dynamics, and their impact on species diversity in hedgerow networks across related spatial and temporal scales, using a multiscale approach of analysis [44]. Another line of research focuses on habitat connectivity on the landscape scale and, more specifically, the potential role of hedgerow networks as corridors between fragmented woodland habitats [45]. It has been shown that habitat loss and habitat fragmentation is detrimental to species' survival, often leading to isolated pockets of habitat that cannot support viable populations [44,46,47]. Hedgerows can facilitate the persistence and migration of species due to benign microclimatic conditions as some research has shown [48]. These different lines of research address aspects that are likely central to the adaptation and use of hedgerow networks in urban environments, including questions of biodiversity support and the ability of such networks to act as effective green corridors.

Urban environments are often heavily fragmented due to land use, road networks, and sealed surfaces, thereby creating difficult conditions as well as often insurmountable boundaries for different plant and animal species. For this reason, notions of adapting and using hedgerow networks as extensive UGS in cities would require comprehensive planning with the aim of counteracting fragmentation and diminishing excessive boundaries and unsuitable conditions. Therefore, projects that employ hedgerows on larger scales are few. Nonetheless, several contemporary projects have emerged in recent years that propose utilizing hedgerow networks as key elements of green infrastructure on a territorial scale. Located in the UK, the proposed National Hedge project by the US-based consultant group, PORT, envisions a nationwide system that links the electricity network with hedgerow networks to reconnect the fragmented landscape, employing a culturally specific system of landscape management. To achieve this, the project includes a series of different scenarios related to specific land use: woodland, agricultural, industrial, suburban/residential [49].

Figure 15. The bocage landscape in France as an example of a well-connected hedgerow network. (Aerial photo from 1944, https://www.flickr.com/photos/photosnormandie/2994957914 CC BY-SA 2.0) (accessed on 3 March 2021).

4. Discussion

On first sight, many historical and contemporary hedge types seem to utilize singular hedging techniques, such as pruning, injuring, bending, or joining. However, upon closer examination, it appears that for the purpose of combining specific benefits, different practices were executed concurrently or in different stages of the development of a hedge. The Monschauer domestic hedges, for example, used laying, interweaving, and pruning at certain phases of the development, whereas the diagonal hedges combined bending, fixing, and inosculation simultaneously. The systematization of hedge types and hedging techniques described above illustrates a first attempt to understand differences between techniques and their consequences. However, the concurrent or sequenced utilization of hedging techniques needs to be studied at much greater depth and detail to approach the complex functions and services that traditional systems can deliver. Moreover, further research is needed to gain deeper insights into their adaptation to different contexts and conditions and into their fulfillment of different performance requirements. The series of seminars and explorative design studios held at the Professorship for Green Technologies in Landscape Architecture (GTLA) at the Technical University of Munich (TUM) described in this paper have explored some of these questions. However, a deeper and more systematic study on influencing parameters in different settings should be carried out, additionally involving a stronger element of research by design and intensified field experiments.

A complex combination of plant manipulation techniques that protect and improve plant health and performance, as described above, is rarely used in urban hedges. If such techniques are applied, it is usually performed in a simplified and formalized manner, i.e., rectangular topiary. In fact, the shapes created by hedging techniques seem to have an aesthetic appeal that tempts not only amateur gardeners but also designers to utilize a more formal and less performance-minded approach. Yet, in view of the fact that the urban context is characterized by complex and diverse conditions and demands, the generic urban hedge that we are accustomed to is no longer adequate to meet the complex challenges of our time. In order to deliver the needed level of multifunctionality for implementation in cities, we are currently studying the various types and combinations of functional plant manipulation techniques that generate a wide range of hedge typologies and ecosystem effects.

Extensive systematic research on rural hedges provides a rich source of historical knowledge, but critical differences between the historic rural and the contemporary urban context make it difficult to use the information from one to understand the other. It is precisely these differences, first and foremost between their multifunctionality, ecosystem and service benefits, and economic value, that draws attention to the rural hedge as a model for the urban hedge. This historical knowledge provides a wealth of information concerning time-tested land use systems, solutions, practices, and processes; these can be harnessed and integrated into city planning procedures as well as landscape and architectural design to improve the urban environment and provide the benefits offered by vegetation and urban green infrastructure to urban dwellers. However, the initial design studies undertaken so far indicate that a direct design transfer is not sufficient since designs need to be able to meet changing and diverse urban needs, conditions, and challenges, in addition to creating new possibilities. Nonetheless, harnessing historical knowledge to better understand the new problems and solutions that determine and influence the multifunctionality of hedges is a learning step towards the design of contemporary hedgerows as a novel UGS that delivers multiple ecosystem functions and services. The functional traits and the intertwined natural and human induced growth processes that generate them are not always obvious.

The transfer of traditional knowledge for adaptation and innovation in cities necessitates further in-depth systematic analysis and comparisons between the rural and urban hedges. This will serve to gain insights into how plant species choice, plant manipulation techniques, and maintenance regimes influence multifunctionality and response to environmental context and specific needs, which determine performance. The knowledge derived from historical analysis and surveys from urban contexts points towards a performance gap and direction for validation, experimentation, and development of novel urban hedge systems with tailored performance. This includes considering specific trade-offs and gains, feasibility, necessary method and technology innovation, long- and short-term implications, and the challenges of coordinated and systematic intervention needed to achieve net positive cumulative impact. As such, this necessitates the integration of design, management, and planning decisions and processes. In the next phase of this research, further theoretical, experimental, and field study research is necessary to capture more insights about hedge systems and their multifunctionality. At the same time, historical case study research needs to be complemented with systematic analyses of contemporary urban hedge designs, contexts, and specific needs, as well as design research and field experiments to not only test and validate information derived from case studies but also to expand design solutions in response to today's urban challenges.

Historical hedge systems evolved over centuries through experiential trial-and-error and inherited traditional practices, in addition to local ecological knowledge and geographic diffusion. These practices have been developed specifically for their contexts and uses with the aim of achieving diverse but precisely defined functions. The rich diversity of hedge types emerged out of various combinations of a number of techniques—such as coppicing, pollarding, and pleaching—and rules, which are context-specifically applied in different forms and structures. These practices often require complex, predictive, and sophisticated maintenance schemes. Novel methods and tools in the areas of 3D scanning, data-driven modeling and simulation, computer-aided design, information modeling and knowledge engineering, decision support systems, and robotics can address this complexity and facilitate a meaningful translation and transfer. This will serve design and design evaluation, as well as systemic and combinatory adaptation and maintenance strategies.

In contrast to green areas where nature is protected from the impact of human intervention, urban green systems in general and urban hedges in particular, result from deliberate designs where plant selection, manipulation, and management play an important role in determining ecosystem functions and societal benefits. Moreover, the condition in rural and urban contexts are considerably different. In a rural context, hedges are typically bordered by crop, pasture, or small roadways, while urban hedges and their adjacent land use is often much more abrupt. Such differences have an impact on hedges and the conditions inside them. Consequently, expectations need to be different and informed by the actual conditions in which a hedge is placed. Specific expectations should be evidence-based to the extent that this is possible. This may be hard to accomplish when a significant change in context from rural to urban is intended. Nevertheless, historical and systematic case studies, field experiments, and research that covers the geographic breadth and variability are crucial to establish a starting point. This needs to be combined with studies on urban hedges, as current research concerning green infrastructure, urban ecology, and biodiversity often only implicitly cover urban hedges. Nevertheless, studies in this area confirm that rural hedges score higher for wildlife, as plant species are more commonly reported in rural areas. In comparison, urban hedges are found to provide fewer resources (flowers, seeds, fruit) for animals (and for people) than their rural counterparts [50]. However, plant traits have not been the only main subject of research so far [51]; another key research subject concerns functional plant manipulations, which have yet to be linked with ecosystem functions and services that are important for promoting a better habitat.

On the largest scale there exists obvious and considerable obstacles for the implementation of hedgerow networks in cities. This includes first and foremost the lack of land area required for extensive continuous UGS. This aspect is not easily solved in dense cities, as any solution will necessitate allocation of municipal land, as well as land that is currently privately owned. Some form of compensation or benefits for implementation would need to be introduced to ensure long-term planning outcomes. Wherever this is not possible, expectation might need to be moderated and scaled to available options for implementation. Therefore, contemporary projects that make extensive use of hedges in inner cities are frequently confined to restricted areas due obvious surface area constraints. This can be seen, for instance, in projects such as the Kö-Bogen II building by Ingenhoven Architects. While the project features 8 km of hedges, they are all concentrated on the surface of the building, thereby not providing the green corridors of typical hedgerow networks. Therefore, it can be concluded that it is obviously much easier to implement hedges on the local scale in contained sites, and that the implementation of larger systematic interventions faces various obstacles and thus lags behind. An initial solution to overcome this could involve linking the reduction of vehicular networks in urban core areas with the allocation of continuous bands for urban green systems (especially hedgerows). However, the distribution of road networks follows different considerations and fulfills different needs than the ones for UGS and especially hedgerow networks. For this reason, the suggested possibility above is only a starting point that will need to be supplemented and amplified by adding land for the implementation and densification of hedgerow networks. Wherever an initial network cannot feasibly be established, an initial approach could entail a dense distribution of "hedge-islands", i.e., areas in which significant local stands of hedges are implemented, similar to the example of the traditional L-shaped hedges in Shimane Prefecture in Western Japan [52]. Since implementing hedgerow networks in urban settings will require long-term planning and implementation, this might entail different combinations of rather punctual, linear, and interconnected hedge implementations that can, over time, become continuous urban hedgerow networks. With this approach, different context specific strategies for land allocation can be developed that take advantage of and are coupled with locally specific adaptations of urban fabric and land use.

A second key problem associated with implementing and maintaining hedgerows is the associated high level of resource and labor intensity. This is not a new realization, as exemplified by an extensive entry on hedges in the *Economic Encyclopedia* by J.G. Krünitz that was published between 1773 and 1858 [53]. In this early period of change towards an industrial society, the difficulty of providing the necessary resources to implement and maintain hedgerows is elaborated in some detail. The entry outlines the need for broad collaboration between affluent land owners and poor farmers to replace "dead fences" with "self-growing fences", i.e., hedges. In this context, "dead" fences were deemed to be too demanding in terms of material resources, i.e., wood. The materials decayed too fast and were needed for other purposes. The entry promoted a broad consideration of resources and combined short- and long-term perspectives on the advantageous performance of hedges.

A third major issue that requires solutions is the question of design, initiation, monitoring, and maintenance (monitoring and manipulation) of urban hedgerow networks. For this purpose, state-of-the-art technology can be adapted and utilized, i.e., stationary sensor systems or unmanned aerial vehicles with multiple sensors for monitoring and human expertise in hedge maintenance may be complemented with robotics technology for some level of hedge maintenance in conjunction with experts. It is possible to already witness the use of robotics in agriculture, and more specifically the emergence of robotic technology coupled with Artificial Intelligence in fruit harvesting.

Furthermore, the aspect of maintenance will require new types of skills from the human actors involved in these processes, as well as a fundamentally interdisciplinary approach to broad questions of environmental sustainability, ecology, urban microclimate, and design. Currently, the validation of ecosystem services by UGS requires further research and development, especially in terms of relevant key performances. This needs to be advanced alongside the physical aspect of hedge management. However, the return value of improved urban microclimate, enhanced ecosystem services, and related aspects of human health and well-being would justify the necessary efforts in terms of rethinking urban landscape planning (together with its vital linkages to peri-urban and rural areas in which such green networks can play a significant role) and landscape management. This can be informed by the re-emergence and adaptation of traditional green systems such as hedgerows and their use in urban environments in the age of rapid land use change and urbanization.

5. Conclusions

Traditional rural hedges constitute a fascinating example of how natural history is intertwined with and inseparable from cultural history. A lot has been written about the natural history of plants and animals, but evaluations of human-made living structures from a natural history perspective is more sparse. Wright's account [54] on hedgerows as a distinct feature of natural environments in rural landscapes is novel and timely but unfortunately stops at the urban edge. A natural history of urban hedges has yet to be written, especially at a time when humans increasingly depend on sustainable nature-based solutions to meet the challenges of urbanization. In comparison to their rural counterparts, there is relatively little known about past, present, and future urban hedges. In this article, we examined traditional hedges, hedgerows, and hedgerow networks with the aim to uncover the potential of adapting hedges to urban contexts to provide an extensive and continuous addition to existing UGS. This involved examining hedge types and related hedging techniques, hedgerows and their ecosystem functions and services, as well as their functions as green corridors. Furthermore, this involved examining the principal obstacles that will likely be faced when seeking to implement hedgerows as continuous green systems in urban contexts. In general, we view this as an exemplary case for adapting traditional systems as novel UGS and for conceptualizing how other traditional systems can be thought through in a similar manner. We examined the approach on three correlated scales: the plant scale, the scale of hedgerows, and the scale of hedgerow networks. The development of hedgerow networks as novel and ultimately continuous urban green systems requires further substantial research and the implementation of real-life experiments to gather insight into the particularities of the various significant contributions that multi-species urban hedges can provide. In addition, there is a need to establish governance aspects related to urban landscape planning—i.e., land allocation, decision support, and evaluation aspects (especially concerning the delivery of ecosystem services)—and methods, tools, and technology development for the entire chain from design to implementation, maintenance, and adaptation of urban hedgerows to anticipate and meet changing requirements over time. We aim to pursue these lines of inquiry further, placing emphasis on the interdisciplinary scope of this research and the need to establish a trans-scalar approach and workflow that can be adapted to local conditions and circumstances.

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