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Article

Delivering a Multi-Functional and Resilient Urban Forest

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Abstract: Tree planting is widely advocated and applied in urban areas, with large-scale projects underway in cities globally. Numerous potential benefits are used to justify these planting campaigns. However, reports of poor tree survival raise questions about the ability of such projects to deliver on their promises over the long-term. Each potential benefit requires different supporting conditions—relating not only to the type and placement of the tree, but also to the broader urban system within which it is embedded. This set of supporting conditions may not always be mutually compatible and may not persist for the lifetime of the tree. Here, we demonstrate a systems-based approach that makes these dependencies, synergies, and tensions more explicit, allowing them to be used to test the decadal-scale resilience of urban street trees. Our analysis highlights social, environmental, and economic assumptions that are implicit within planting projects; notably that high levels of maintenance and public support for urban street trees will persist throughout their natural lifespan, and that the surrounding built form will remain largely unchanged. Whilst the vulnerability of each benefit may be highly context specific, we identify approaches that address some typical weaknesses, making a functional, resilient, urban forest more attainable.

Keywords: urban; forest; tree; resilient; resilience; ecosystem services; scenarios; systems; futures

1. Introduction

Greening our cities might be thought of as the archetypal urban sustainability solution. The potential of trees, in particular, to deliver a range of social, environmental, and economic benefits is recognised by both researchers and practitioners, yet it is clear that the dynamic nature of urban areas may threaten the survival of trees to maturity and/or undermine their delivery of key benefits to society. Here we demonstrate an approach that: (i) integrates different disciplinary perspectives on the benefits and drawbacks of urban street tree planting; (ii) identifies system conditions upon which these depend; and (iii) tests the vulnerability of these conditions using contrasting scenarios for urban futures.

1.1. The Benefits of Urban Tree Cover

In recent years a multitude of large-scale urban tree planting campaigns have been initiated in cities around the world (e.g., the New York City Million Trees program, the UK Big Tree Plant, and Global ReLeaf), and support for urban greening can be found at both local and national levels of government [1–7]. Whilst the financial [8] and natural resource [9] costs may be considerable, such planting programmes typically claim that a wide range of sustainability benefits will be delivered; including, but not limited to: building energy savings, improved air quality, carbon capture, increased biodiversity, improved water quality, and direct improvement of human health and wellbeing [7,9,10]. Discipline-specific studies provide evidence to support these claims [11–18] and the broad identification, quantification and valuation of potential ecosystem services supplied by the urban forest has received substantial attention [8,19–25]. There are also drawbacks associated with increasing urban tree cover that need to be considered, typically referred to as disbenefits or disservices [22,23]. These include: health and safety risks (and associated fears), public nuisance (e.g., fallen leaves sticking to parked cars), financial costs from maintenance and infrastructure damage, and environmental impacts relating to waste, pollutants and the introduction of pests [23].

1.2. Threats to Urban Tree Cover

Tree cover within some cities has undergone periods of expansion and contraction in recent decades [26–29], and the level of tree cover in several US cities has been found to be in decline [30]. Estimates of annual tree mortality rates are highly variable [31], with reported losses of 3% to >50% for newly planted street trees, depending on local land-uses and social influences [32,33]. This raises the question of whether large-scale urban tree planting can succeed in delivering benefits over the long-term, given the impermanence of past urban tree cover. A diverse range of factors influence urban tree survival, ranging from vandalism or removal of the tree itself, to restricted access to key resources such as soil moisture [34]. Threats are also emerging or intensifying as a result of globalisation, urbanization, and population growth [34,35]. A recent review of the success of large-scale urban tree planting initiatives in the US points to the problem of uncertainties regarding long-term funding and political support [7]. Future risks from factors such as pests, diseases, and climate change have been addressed at many levels by researchers [35], urban forestry and arboriculture professionals [34], and regulatory organisations. For example, the European Parliament is currently considering a revision of its Plant Health Regime to address concerns about emerging risks related to pests, diseases, and the spread of non-native species. In addition, databases exist to help identify pests and diseases that are considered a risk to tree health [36] and to support more climate and disease resistant choices for urban tree planting [37]. However, threats to trees associated with changes to the built form, urban governance, and social values appear less well-addressed.

1.3. Contextual and Temporal Sensitivity of Ecosystem Services Supplied by Trees

The nature and magnitude of the sustainability benefits delivered by urban trees can be strongly influenced by their urban context, in its broadest sense (*i.e.*, their built, cultural, ecological, or economic context). It should therefore be recognised that large-scale urban tree planting projects may include a wide variety of planting locations and tree types, and involve a pool of stakeholders with different motivations, expectations, and resources [38]. Recognising this context is important, as key biophysical processes can be influenced by local land-covers, land-uses and social practices (Supplementary Information S1). For example, transpiration and shade from trees can benefit people and infrastructure via summertime cooling [39,40], but may be disrupted in situations where built infrastructure damages tree roots or where sealed surfaces reduce soil moisture levels [25]. The presence of receptor groups (beneficiaries) is also an important consideration. For example, trees planted in residential neighbourhoods may deliver benefits through the cooling of houses in summer, which they would be unable to deliver if planted within other land-use types [41]. In addition, the degree to which urban trees affect net urban carbon emissions depends not only on their size, health, and species, but also on the surrounding land-use, on the energy requirements of adjacent buildings, and on how the resulting green "waste" is managed [42].

Given that the benefits delivered by urban trees can vary depending on their context, what happens when this context changes? Are some benefits particularly sensitive to future social, environmental, or economic changes? Redevelopment, densification, population increases, and demographic shifts are common characteristics of many cities [43], potentially impacting the production and consumption of urban ecosystem services. In addition, the ways that citizens value trees may change over time [44]. Even if the built and social context of an urban tree were to remain stable and supportive over the short term, some benefits may still take many years to accumulate [41], as they often scale with the size or maturity of the tree [8]. A key challenge is, therefore, to ensure that the potential benefits of urban tree planting are realized over the following decades and centuries, in the face of a complex, uncertain and changing urban context [45].

1.4. Trees, Urban Systems and Resilience Thinking

Studies that consider threats to the longevity and performance of urban trees often focus on technical questions and solutions related to the tree itself, such as identifying planting techniques that will improve the chances of long-term survival and growth [44]. This reflects a broader pattern within sustainable urban forestry, to focus on technical and numerical standards related to the trees themselves [42]. However, a much broader range of social, environmental, and economic factors are clearly relevant to the persistence and functioning of urban trees [7,9], as evidenced by the variability in tree cover and survival between land-use types [32], built densities [28], and land ownership [27]. There is, therefore, a need for approaches that can explore the current and future performance of the urban forest in a way which acknowledges its diverse range of values [42], and also the dynamic nature of the landscape within which these are embedded.

Cities are complex, metastable systems with highly-coupled flows of mass, energy, people, and capital [45,46]. Analyses of the risks to the ecosystem services supplied by urban trees must therefore recognise that trees are embedded within this broader "system of systems" and may benefit from identifying key system components, dependencies, processes, and outputs. For any given benefit to be sustained, a set of system conditions needs to persist which extends beyond the simple presence of an urban tree [8,9,22,47,48]. A culture of planting "the right tree in the right place" recognises the importance of context and is clearly embedded in the psyche of many arboriculturists and foresters [34,49]. However, systematic recording and analysis of these contextual dependencies and their vulnerability has thus far been absent.

Addressing sustainability challenges within urban areas typically requires the integration of a variety of perspectives within analyses and decision-making, and calls have been made for more interdisciplinary research and collaboration in relation to urban ecosystems [3,50]. However, such interdisciplinary collaboration in both research and practice can be extremely challenging [5,38,46]. "Resilience" is a concept that can be used to stimulate interdisciplinary research, to support understanding, management and governance of complex linked systems of people and nature, and to guide development pathways in changeable and uncertain environments [51]. Resilience has multiple definitions, but here it is used to mean continuity in the desirable aspects of system performance, despite disturbance or re-structuring of the system itself. When applied to sustainability in cities it helps to emphasise the inherent instability of urban spaces and their uses, and that the performance of an idealized sustainable urban form may depend on its capacity to tolerate, adapt, or even to provoke change [50]. An urban tree could therefore be conceptualised as being part of, and intimately linked to, a broader socio-economic and biophysical system, which, if disturbed sufficiently, may prevent the tree from delivering key benefits to society. Using the concept of resilience to frame a discussion about risks to urban tree performance also helps to highlight the difference between the intervention (*i.e.*, the planting of a tree), its intended benefits, and the conditions upon which these benefits depend. Distinguishing the intervention from its intended benefits makes explicit that it is the benefits that the tree delivers that need to be resilient, even if the tree itself, and the urban system within which it is embedded, undergo changes in the future.

This study aims to illustrate an approach that can be used to integrate different perspectives on the risks to the long-term performance of urban tree cover, and to provide insight into the resilience of potential benefits associated with street tree planting in the UK. We apply a recently developed method for analysing urban "sustainability solutions" [52,53] that: (i) explicitly pairs a sustainability solution (in this case urban street tree planting) with its intended benefits; (ii) identifies system conditions necessary for the delivery of each benefit; and (iii) uses future urban scenarios to systematically test the vulnerability of these conditions.

We conclude that the potential benefits of urban street tree planting are often dependent on the presence of system conditions related to the level of tree maintenance, public values, local government policies, and the density and configuration of the surrounding built form. Key conditions may not persist within future urban scenarios where market forces are more dominant, where individualist attitudes prevail or where poverty and inequality are high. We suggest that resilience might be increased by broadening planting locations to include private green spaces immediately adjacent to streets and improving the co-management of street trees by individuals, NGOs and municipal departments. This could be supported by the introduction of market-based systems to incentivise the participation of a broad range of stakeholders in the long-term protection and management of urban street trees. In addition, planting techniques that reduce the need for supplementary watering, reduce maintenance requirements, isolate roots from potentially polluted urban soils, and that facilitate transplantation, have the potential to improve the resilience of urban street tree benefits.

2. Materials and Methods

2.1. Diverse Perspectives on Threats to the Benefits of Urban Street Trees

In order to explore how urban street tree performance might become vulnerable over time we followed steps 1–4 of the Designing Resilient Cities Method [47–49], as outlined at www.designingresilientcities.co.uk. At the heart of this method is the recognition that cities are complex systems, and that the success of urban interventions may depend on multiple factors. It is therefore desirable to seek input from a broad range of perspectives at each methodological step

(Figure 1). In the present case, we sought UK practitioner input from experts in the fields of architecture (Royal Institute of British Architects), town planning (Lancaster City Council) and the built environment (Building Research Establishment), via workshops led by members of the Urban Futures project [48]. Participants were invited to question the resilience of specific development proposals [50] or previously implemented solutions [47], and to identify conditions upon which their performance depended. Participant numbers ranged from approximately 20–40 and were selected by making contact with professional groups/institutions and local municipalities. Our final workshop included the entire Urban Futures academic team and covered the following disciplines: Forestry, Air Quality, Design, Architecture, Civil Engineering, Spatial Planning, Environmental Psychology, Human Geography, Ecology, Utility Services, and Economic Development. At this workshop, participants drafted a formal list of the intended benefits of urban street tree planting and associated necessary conditions, drawing upon the outcomes of earlier workshops, as well as their own knowledge from related research and practice. This draft list was then circulated for comments to a wider pool of academic and practitioner project partners.

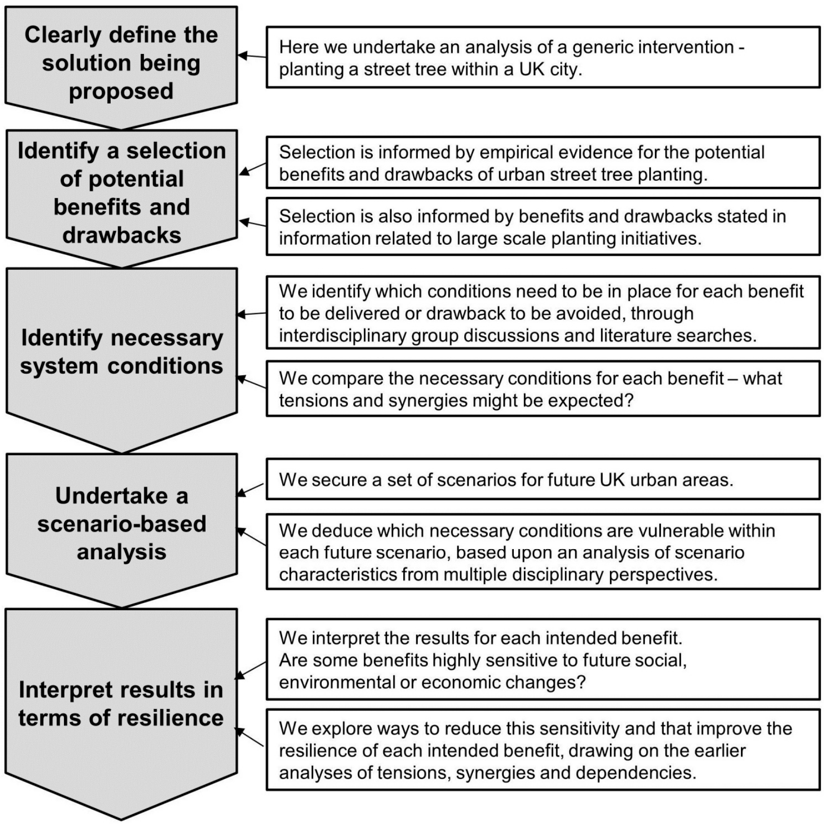

Figure 1. An overview of key steps within the methods.

2.2. Urban Street Trees and Their Intended Benefits

The first step within this methodology is to clearly define the "sustainability solution" that is being tested and to state explicitly its intended benefits. Tree planting within urban areas can be highly varied, from commercial forestry within a large temperate park to amenity planting within the business district of a tropical city. We therefore narrowed the scope of our analysis by analysing a generic solution of planting a single street tree within a UK urban area. We define a street tree as any tree growing immediately adjacent to a road. In the UK such trees are often planted in pits dug directly into the paved pedestrian walkway that runs parallel to the road. Previous authors have identified a need for increased planting within UK cities [51] and urban greening has received considerable support at the UK government level over recent decades [35]. In addition, urban street trees are associated with a large set of benefits and challenges [25,52] that would be interesting to explore from a systems perspective. This solution was considered broad enough to capture many of the likely threats to urban tree performance, whilst providing sufficient context to make the results useful to those addressing concerns about the legacy of today's urban planting initiatives.

Urban street trees are multi-functional [25], and are therefore introduced or retained in cities for a variety of reasons, by a variety of actors [34]. This multi-functionality is both desirable and unavoidable, but it may also create confusion about which ecosystem services a particular street tree is being managed to deliver, and which services should be prioritised. We developed a list of potential benefits and drawbacks associated with urban street tree planting, based upon group discussions and workshops, claims within publicity material for large-scale urban tree planting initiatives, and evidence from the academic literature (Supplementary Information S1), and then screened these to ensure their relevance to UK urban areas.

2.3. Necessary System Conditions

Next, we identified conditions that would need to be in place in order for each of these benefits to be delivered, and for key drawbacks to be avoided. These "necessary conditions" can be as simple as the continued presence of a tree, or as specific as a particular type of on-going maintenance. For example, street trees planted adjacent to a building can reduce heating requirements during cold weather, on the condition that they are an evergreen species and that they are positioned so as not to inhibit possible solar gain. For each intended benefit, the necessary conditions were initially identified through group discussions and workshops, followed up by literature searches. This process of identifying necessary conditions is subjective and partial, given the many dimensions of the urban system; furthermore, outcomes will be influenced by the professions and disciplines contributing to the process. However, it has the advantage that assumptions about dependencies are made explicit and recorded. Revision in light of new data is straightforward and indeed recommended. Care was taken to avoid duplication and overlap as much as possible (*i.e.*, listing a condition that implicitly includes another listed condition), although this is difficult to eliminate completely when considering such a complex system. Whilst it would not compromise the efficacy of the methodology, avoiding duplication is important, both for simplifying the analysis and for clarifying thinking about which characteristics of the urban system are most relevant. The list of benefits, drawbacks and associated necessary conditions was then arranged as a matrix, similar to the score-matrix method used to support design decision-making in engineering. This benefit-condition matrix was used to identify particular conditions that were necessary for certain benefits to be delivered, conditions that might be required only in particular contexts, and those which had the potential to compromise the delivery of other benefits. This process facilitates the identification of synergies in, and tensions between, delivering multiple benefits from urban street tree planting. The literature evidence base to support this analysis is given in Supplementary Information S2.

2.4. Scenario-Based Resilience Analysis

We then undertook a scenario-based resilience analysis to identify those necessary conditions that might not be supported in the future, and to make the reasons for their vulnerability more apparent. Four plausible and internally consistent scenarios for UK urban areas in 2050 were considered, derived from a broader scenario set developed by the Global Scenarios Group [53]. The broad characteristics of these four global scenarios were retained (Figure 2). However, as part of the Urban Futures project [47] their characteristics were adapted and expanded to make them more relevant to UK urban areas, covering themes such urban form, natural environment, technology, policy, governance, social values and economy. These urban UK scenarios had been created to allow for the pressure-testing of sustainability solutions against an uncertain future [48,54]. Such scenarios are distinct from predictions, extrapolations, or any other formal forecasting method [55,56], and have the advantage that they allow for the inclusion of shocks, phase changes and tipping points that can occur within complex socio-ecological systems (*c.f.* [55,57,58]). Whilst climate change is considered, its nature is identical within each scenario. However, its impacts on urban trees may vary between the urban scenarios depending on their capacity to respond to this threat. The use of multiple urban scenarios recognises that the future cannot be predicted with any degree of certainty, whilst still providing a framework for exploring whether solutions put in place today could still function within a future that we may not necessarily expect or desire. The combinations of drivers that underpin these scenarios are intended to differ from those typically found within UK cities and in some cases they result in radically different visions of the future. These scenarios can be mapped to fall along a gradient of social values that range from an individual to a community focus, or a gradient that ranges from an open and globalised economy to one that is much more localised [56]. We contend that together these scenarios define the boundaries of a likely plausibility space for UK urban areas in 2050. The future scenarios we used are described briefly below, with further details provided in Boyko *et al.* [54]. The scenario characteristics we consider particularly relevant to urban trees are given in Supplementary Information S3.

(a) Policy Reform (PR). Government action attempts to reduce poverty and social conflict within the confines of a globalised free market. Individual behaviours are slow to move from materialistic self-interest, although it is widely accepted that markets require strong regulation to avert economic crisis, social conflict, and environmental degradation. Tensions continue to grow between continuity of the dominant social values and the desire for greater equity to address key sustainability goals.

(b) Market Forces (MF). There is strong belief in the "hidden hand" (*i.e.*, self-correcting logic) of the free market as key to resolving social, economic, and environmental problems. Individualism and materialism are core human values. This scenario assumes that the global system in the twenty-first century evolves without major surprise. Incremental market adjustments have (so far) been able to cope with major social, economic and environmental problems as they have arisen.

(c) Fortress World (FW). As a result of the (partial) breakdown in world order, powerful and self-interested actors protect their resources whilst an impoverished majority are (literally or effectively) disenfranchised and live in ghettos. In this divided world, the elite live in an interconnected network of enclaves and the impoverished majority scratch a living outside.

Armed forces impose order, protect those parts of the environment valued by the elite, and prevent complete collapse of society.

(d) New Sustainability Paradigm (NSP). An ethos of sustainability (of "one-planet living"), has taken root throughout society, bringing with it a fundamental questioning of materialism. New socio-economic patterns follow from these fundamental changes in values. In order to maintain global communication and economies of scale, cities are transformed rather than abandoned or replaced.

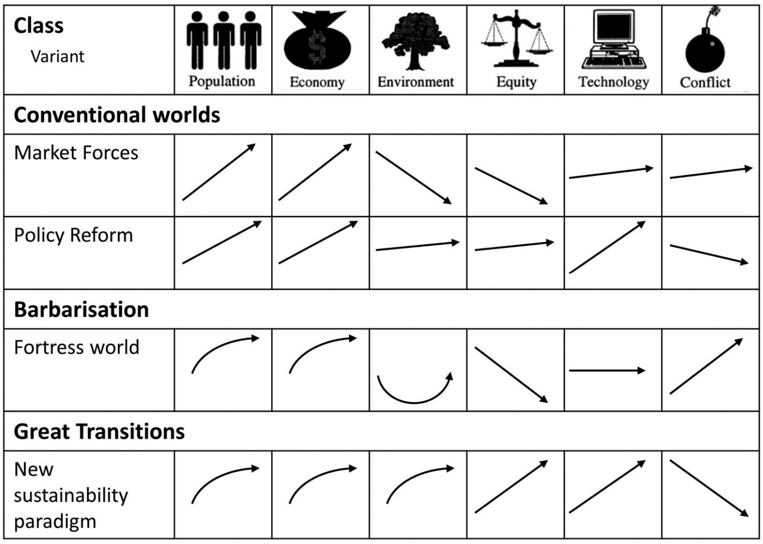

Figure 2. Broad characteristics of the future scenarios used within this analysis. Edited and reproduced with permission of Gallopin *et al.* [53].

For each necessary condition, we searched the database of scenario characteristics for those that were deemed to be most relevant. The characteristics of each scenario that were considered to either support or undermine each necessary condition are given in S3. Using these characteristics, we deduced whether each necessary condition was likely to be "Vulnerable", "Partially Vulnerable", or "Supported" within a particular scenario. The classification of "Partially Vulnerable" was used where a condition was considered likely to be supported in some urban contexts but not in others, within the same scenario. By using multiple scenarios with a wide range of characteristics, we were able to subject the necessary conditions to a much more rigorous test of vulnerability than would be the case if only current conditions, or those conditions pertaining to predictions for a single future scenario, were considered.

Finally, the results of this scenario analysis were interpreted in terms of resilience. Those benefits whose necessary conditions were found to be vulnerable under a range of future scenarios were identified as potentially lacking resilience. Options for addressing these vulnerabilities are explored in the discussion.

3. Results

3.1. Necessary Conditions

Overall, the most common conditions that were identified as being necessary for delivering particular benefits were those that related to the presence and health of the street tree (Table 1), such as access to sufficient light and water. Other frequently identified conditions were that the tree is large or mature, that high levels of canopy cover exist in the surrounding urban area, that the tree is maintained for amenity, that people are present nearby, and that the tree is visually accessible to the public. However, several conditions that are necessary for delivering one intended benefit are considered likely to undermine the delivery of other benefits. These conditions include those that relate to the presence of a large or mature tree, the presence of large-scale tree cover, the tree being maintained for wildlife, the surrounding area being built to high-density, and the tree being physically accessible to the public. As a result, it is clear that delivering any of the benefits considered here has the potential to undermine other benefits, or to result in drawbacks.

3.2. Scenario Analysis

When subjected to the scenario based resilience analysis, all necessary conditions were considered to be vulnerable to some degree and most were found to be at least partially vulnerable within three of the four future scenarios (Table 2). These vulnerabilities are most evident within the Market Forces (MF) and Fortress World (FW) scenarios, where economic and security interests (respectively) are prioritised over environmental concerns. Several conditions relating to the species of street tree appear to be particularly vulnerable. Even in the Policy Reform (PR) and New Sustainability Paradigm (NSP) scenarios, where careful consideration is given to the most appropriate tree species for a particular location, the large-scale replacement of street trees with more appropriate species is unlikely to take place. This means that the species of street trees planted as part of current initiatives are those that would broadly be expected to be present in 2050 under these scenarios. In addition, within the MF and FW scenarios, the species of tree that are retained and planted are likely to be those that happen to be in fashion or that have particular value in terms of timber or fuel. Other conditions which appear particularly vulnerable are the continued presence of a street tree at the original planting site, the tree's roots not spreading excessively, its maintenance to benefit wildlife, and its structural connectivity to a broader tree network. Whilst a necessary condition may be vulnerable in several scenarios, the reasons for this were not always the same. For example, the structural connectivity of tree networks may not always be supported within the PR scenario because high-density land redevelopment to deliver key social goals takes priority over environmental concerns. In this scenario, tree networks may become structurally fragmented as policies are implemented to achieve a more compact urban form and to deliver new public transport systems. Although policy would specify the need for mitigation, trade-offs would be expected where infrastructure projects have a particularly high social value. Tree networks may also be removed in the MF scenario, but for different reasons such as the avoidance of damage to built infrastructure, the reduction of litigation risks, and the widening of major transport corridors. The protection and management of urban tree networks is also less likely within the FW scenario, in which a "tragedy of the commons" has unfolded within much of the city; street trees in many areas are illegally taken for timber and fuel by the impoverished citizens, with the government unable or unwilling to prevent this.

Table 1. Conditions necessary for securing key benefits from urban street trees and avoiding drawbacks. See Supplementary Information S2 for supporting justifications.

Benefits to Achieve and Drawbacks to Avoid	Necessary Conditions																										
	Consistent water supply for healthy growth	Tree's access to light is maintained	Low stress from soil pollution	Low stress from air pollution	Root growth not substantially impeded	A tree is still present	Tree is large or mature	People are present nearby	Tree is visually accessible to public	Tree is maintained for amenity	Large-scale tree-cover across urban area	Tree is maintained for wildlife	Surrounding area built to high-density	Tree is physically accessible to public	Tree not in a street canyon with busy road	Tree does not overhang road or pavement	High canopy	Tree blocks solar access to building	No artificial lighting	Tree is part of a densely-vegetated barrier	No persistent noise	Tree is connected to a broader tree network	Species is native	Species is a low VOC emitter	Lateral root spread not excessive	Tree is growing in a pervious surface	Species is evergreen
Provide feeding resource for native birds and bats	*	*	*	*	*	√	√	!		!	√	√	!	!	√				√		√	√	√			*	
Cool buildings (shade)	√	√	√	√	√	√	√								!			√									*
Reduce heating requirements during cold weather	√	√	√	√	√	√	√	√					!				!	!		√							√
Attenuate noise throughout the year	√	√	√	√	√	√	√			!							!			√						*	√
Reduce net CO_2 emissions	√	√	√	√	√	√	√			!	√															*	
Reduce stormwater runoff rate/volume	√	√	√	√	√	√	*				√															√	*
Summertime cooling	*	√	√	√	√	√	√				√				!	!		√									
Reduce exposure to air pollutants (NO_2, O_3, PM)	√	√	√	√	√	√	√	√		*	*				√									√			*
Reduce psychological stress	√	√	√	√	√	√	*	√	√					*			√										
Decrease perceptions of overcrowding	√	√	√	√	√	√	*	√	√			!	√		!	!											
Create desirable environments for recreation	√	√	√	√	√	√	*	√	√	√		!		√			√					√			√		
Improve urban aesthetics	√	√	√	√	√	√	*	√	√	√		!													√		
Increase property values	√	√	√	√	√	√	*	√	*	√		!															
Reduce crime	√	√	√	√	√	√	!	√	√	√	√	!					√		!	!							
Increase economic investment within surrounding area	√	√	√	√	√	√		√	√	√	√	!							!		!						

Table 1. *Cont.*

Benefits to Achieve and Drawbacks to Avoid	**Necessary Conditions**																										
	Consistent water supply for healthy growth	**Tree's access to light is maintained**	**Low stress from soil pollution**	**Low stress from air pollution**	**Root growth not substantially impeded**	**A tree is still present**	**Tree is large or mature**	**People are present nearby**	**Tree is visually accessible to public**	**Tree is maintained for amenity**	**Large-scale tree-cover across urban area**	**Tree is maintained for wildlife**	**Surrounding area built to high-density**	**Tree is physically accessible to public**	**Tree not in a street canyon with busy road**	**Tree does not overhang road or pavement**	**High canopy**	**Tree blocks solar access to building**	**No artificial lighting**	**Tree is part of a densely-vegetated barrier**	**No persistent noise**	**Tree is connected to a broader tree network**	**Species is native**	**Species is a low VOC emitter**	**Lateral root spread not excessive**	**Tree is growing in a pervious surface**	**Species is evergreen**
Stabilise cuttings/embankments						√	√							!													
Avoid root interference with built infrastructure/paving	√	!	!	!	!	!	!				!		!					!				!			√		
Avoid shrink-swell damage to buildings/infrastructure	√	!	!	!		!	!				!		!													√	
Avoid public hazard due to leaf/fruit fall	√	!	!	!	!	!	!			*	!	!		!		*											
Avoid injury/damage due to branch/tree fall	√	√	√	√	√	!	!			√	!	!	!	!		√	!										

KEY √ = Condition is typically necessary for delivering intended benefit. * = Condition may be necessary in some contexts; ! = Potential conflict between condition and a particular benefit.

Table 2. A summary of the results of the scenario based resilience analysis.

Necessary Conditions	Future Scenarios			
	PR	**MF**	**FW**	**NSP**
Species is native	*	*	*	*
Species is a low volatile organic compound (VOC) emitter	*	*	*	*
Species is evergreen	*	*	*	*
A tree is still present	*	*	x	√
Lateral root spread is not excessive	*	x	x	√
Tree is connected to a broader tree network	*	x	x	√
Tree is maintained for wildlife	*	x	x	√
Tree is not in a street canyon with busy road	*	*	x	√
Tree is maintained for amenity	*	√	*	x
Consistent water supply for healthy growth	*	*	*	√
Root growth not substantially impeded	*	*	*	√
Tree's access to light maintained	*	*	*	√
Tree is large or mature	*	*	x	√
High canopy	*	*	x	√
Tree is part of a densely-vegetated barrier	*	*	x	√
No persistent noise	*	*	*	√
No artificial lighting	*	*	*	√
Tree blocks solar access to building	*	*	*	√
Surrounding area built to high-density	√	*	*	*
Tree does not overhang road or pavement	*	√	√	x
Low stress from air pollution	√	*	x	√
Low stress from soil pollution	√	*	*	√
Tree is physically accessible to public	√	*	*	√
Tree is growing in a pervious surface	√	*	*	√
Tree is visually accessible to the public	√	*	*	√
People are present nearby	√	*	√	*
Large-scale tree cover across urban area	√	√	x	√

Those necessary conditions considered vulnerable within a particular scenario are marked with "X" in the corresponding column. "*" represents those considered partially vulnerable, whilst "√" is used to indicate where a condition is likely to be supported. PR = the Policy Reform scenario, MF = Market Forces, FW = Fortress World, NSP = New Sustainability Paradigm. The scenario characteristics used to support this analysis are given in Supplementary Information S3.

4. Discussion

The analysis presented here is based upon a generic proposal to plant a single street tree within an urban area in the UK, and would therefore need to be adapted for a more specific planting proposal and for a particular geographical location. The outcomes of the analysis are also sensitive to the variety of disciplines involved in identifying key benefits and their dependencies, and to how they interpret the scenario characteristics. Our aim was to consider the broad range of benefits that might be derived from urban street trees in the UK and to capture the diverse system conditions upon which they depend over time. There is evidence that studies of ecosystem services tend to focus on biophysical or economic dimensions and much less on socio-cultural services and drivers [59,60]. To a great extent this bias results from the difficulty in quantifying the latter. We argue that by ensuring a range of disciplinary "voices" were at the table and that by using highly contrasting future scenarios, we forced a broader questioning of the social, technological, economic, environmental, and political dependencies. However, we acknowledge that our analysis may still be limited by deficiencies or biases within academic and practitioner knowledge. This is a fundamental problem in the study and synthesis of complex systems. This knowledge gap has been recognized, and participatory research processes have been proposed as one mechanism for improving our understanding of the social-cultural dimension of ecosystem services [59]. Despite these caveats, the outcomes are considered to be broadly indicative of how the benefits delivered by urban street trees might be vulnerable to loss over time.

4.1. Benefits, Necessary Conditions, Synergies and Tensions

The variety of necessary conditions, synergies and tensions identified in Table 1 illustrates both the diversity of factors that may influence street tree performance, and the complexity of the urban system within which they are embedded. It raises questions about whether urban tree planting programs are able to realise such a broad range of intended benefits in the short term, and then to sustain them until 2050, a timeframe that is still significantly less than the potential lifespan of most tree species planted in urban areas.

We find that environmental benefits, which are often cited as the rationale behind urban greening programmes due to the relative ease of their monetisation, depend on system conditions which are not always mutually compatible. For example, using a street tree to reduce summertime air temperatures and to cool an adjacent building (via shading) may conflict directly with a desire to warm the building in winter, should the tree also limit solar gain in this season. Likewise, whilst it is desirable to block cool air flows in winter, the opposite may be desired in summer in continental climate zones. This clash has long been recognised in urban tree planting literature [10], where it is recommended that deciduous trees be used for shade, and evergreen trees be used to provide wind shelter along the northern perimeter of a building (in northern hemisphere sites), providing an example of how tensions can be resolved by careful planning, as long as such benefit trade-off information is recorded and built into management plans. Spatial incompatibilities of intended benefits may also occur in areas such as busy street canyons, where street trees may be effective at providing useful shade and reducing perceptions of overcrowding, yet perform poorly in relation to air quality, where they can trap air pollutants emitted within that canyon, increasing population exposure [61]. This may be at least partially resolved by high levels of canopy thinning [62], although pruning, combined with street noise, lighting and moving vehicles would be expected to undermine many of the tree's potential biodiversity benefits [63]. Such synergies and tensions are, however, not universal, and careful analysis of the local context can reveal ways to reduce some potential conflicts. For example, in a busy street canyon where only electric vehicles were permitted or where trees are heavily pruned, conflicts between improving air quality and delivering shade would be much reduced.

What we broadly term as "social" benefits, such as: creating desirable environments for recreation and health, improving urban aesthetics, increasing residential and business property values, increasing inward investment in the area, and decreasing perceptions of overcrowding, are often compatible with each other. However, the conditions that support social benefits are often incompatible with those necessary for ecological benefits, such as providing effective feeding resources for urban bird and bat communities. This incompatibility is partly due to the more aggressive maintenance that trees in streets tend to be subjected to (e.g., the removal of insect-rich standing dead wood [64]), which is also linked to how local people value different forms of tree cover [52,65]. In addition, trees in areas of high population density are at risk of being subjected to artificial lighting and noise, which are known to have negative impacts on urban invertebrates, birds and mammals [63,66–68]. As a result, tensions between social and ecological benefits would be expected to make street trees vulnerable to removal/functional-simplification under certain future scenarios.

4.2. Scenario Analysis and Resilience Implications

Scenarios have been used in a variety of ways to consider how ecosystems and the services they provide might change in the future [55,69–71], although this approach has rarely been applied at the city or sub-city scale (*c.f.* [72]). Their purpose here was to broaden the debate about urban street trees and resilience, to include not only threats that are expected to increase over time (e.g., climate change, pests and diseases [35]), but also socio-political changes that may be much less predictable. Many of these scenario characteristics can be recognised in urban areas around the world. The contrasts between these scenarios can be used to highlight and question the implicit assumption within today's urban planting proposals that key urban conditions will persist. For example, the initiation of "Million Tree" planting schemes by politicians implies that there is currently broad public support for large-scale urban tree planting, yet public attitudes to urban trees are highly variable [11,65,73,74]. In this case, our scenario analysis helps provide a structure for questioning whether key benefits would be sustained if local people become less supportive of urban street trees in the future. Some planting initiatives also appear to depend on broad public involvement, as they rely in part on residential and other private land owners for providing planting sites and subsequent tree maintenance [27,74]. In a future where the management responsibilities for urban street trees shifts further from the municipal to the individual level, long-term success may well depend on a sustained shift in public attitudes regarding responsibilities for urban tree stewardship [75] and on improved participatory democracy in the form of a greater/more formal integration of volunteers into city management functions [9]. Similarly, given that funding for the maintenance of urban trees is often considered inadequate [8,52] and likely to be further reduced in many areas in the context of fiscal austerity [7,74,76], our methodology prompts the user to consider whether current planting strategies and techniques are sufficient to ensure that street trees planted today could survive in a future where maintenance budgets were virtually non-existent.

The vulnerabilities identified during this process might be addressed in a variety of ways; our analysis aims to initiate a broad-based discussion about potential risks to the long-term delivery of urban ecosystem services and to help structure the response. Essential to this is the recognition that urban trees are part of a complex social-ecological system [9] and that their delivery of benefits over the long-term relies on more than simply the persistence of the trees themselves. Broad strategies proposed for improving resilience in cities include maintaining high response diversity, multi-functionality, redundancy and decentralisation [77]. These themes are explored within the sections below, with suggestions for areas of future research. Our analysis highlights three classes of system conditions which appear to be particularly important: (i) retention and survival to maturity; (ii) large-scale planting; and (iii) social context. We discuss vulnerabilities and the resilience implications for key benefits below.

4.3. Retention and Survival to Maturity

The presence of a tree is a self-evident requirement for the delivery of each benefit (Table 1) and it is therefore unsurprising that various forms of direct protection for individual street trees are commonly put in place within UK urban areas [34,52] and elsewhere. However, from this analysis street trees are still considered to be vulnerable to removal within their natural lifespan, either directly or via the degradation of key growing conditions; in some scenarios these trees may not be replaced (Table 2). Retention of tree cover over long time periods by the replacement of dead trees [78] might help to improve the resilience of some benefits. However, many benefits are most effectively delivered by large or mature trees, as they are often highly visible, can have disproportionally high ecological value [79], and exert a considerable influence over microclimates.

Long payback periods may be required before the benefits of urban trees have covered the initial costs of planting [8], yet half of urban street trees may die before they reach 13–20 years old [31]. Those trees that do survive to maturity can generate a variety of tensions in urban areas (Table 1, and refs [52,65,80]), creating pressure for their removal. There is a perception amongst practitioners that large street trees are already being lost in UK urban areas [52,76], and such trees appear even more vulnerable under the MF and FW scenarios (Table 2). Key drivers for tree loss, restricted growth, or periodic replacement, include direct impacts from climate change (MF, FW), pests and disease (MF, PR), competition for space within high-density developments (PR, FW, NSP), and concerns about the costs of infrastructure damage (MF), litigation (MF), health impacts (MF, PR), and maintenance (MF). This implies that to reduce the risk of tree loss, careful attention should be given to the precise location of planting. Areas to avoid are sites where threats to public safety might reasonably be expected now or in the future, where high densities of utilities are present/expected, or where physical (re)development is a realistic risk during the natural life-span of the tree. Resilience to climate and disease impacts will also be increased by ensuring a diversity of genotypes, species and genera are planted [34]. This “response diversity” can be achieved through an approach that identifies ecological niche function and that selects several species that deliver similar benefits, but that respond differently to shifts in growing conditions, pests and anthropogenic pressures.

In some cases, more fundamental changes to how urban trees are valued, owned and managed may be required [7,76]. In a future where market forces dominate, high land-values combined with the risks posed to valuable built infrastructure may create pressures to remove urban street trees that social and governance systems are unable to resist. Resilience might therefore be improved through the development of market-based systems that enable the multiple functions of an individual street tree to be better captured within decision-making processes. Payment for ecosystem services [81] has been proposed as a tool for their management in urban areas [82] and long-term funding for non-profit and community actors has been identified as an important route for securing the stewardship of urban trees [7]. However, we found no evidence that market-based systems have been considered as a tool for increasing the resilience of any of the large-scale urban tree planting initiatives listed in Supplementary Information S1.

The availability of sufficient water and root space are also key conditions that must be sustained in order for urban street trees to reach maturity, both in terms of promoting tree growth and avoiding conflicts from the lateral expansion of their roots. Protecting these conditions may be challenging in a future where the local built density has broadly increased (PR, FW, NSP) or where the levels of protection and maintenance for urban trees have declined (MF, FW). However, technical solutions implemented at the time of planting could provide some resilience, such as the use of dedicated soil cells, suspended permeable pavements and the integration of planting sites with surface water drainage systems [25,34]. In addition, planting techniques that make the likelihood of future translocation more successful may provide useful flexibility. This decentralised approach may help to isolate individual trees from broader changes to the water table and pollutants within urban soils. Whilst such solutions may not be practical for all urban planting situations, they may be cost-effective for high-value trees in high-density locations, where large numbers of people may benefit and where the potential costs of damage to built infrastructure are considerable.

4.4. Large-Scale Tree Cover

Several benefits that are claimed for urban tree planting require the presence of large-scale canopy cover in order to be effective, e.g., CO_2 assimilation, providing feeding resources for wildlife, and reduced stormwater runoff. In effect, the planting of a single street tree will have little impact on delivering these benefits if it is located within a landscape that is largely devoid of tree cover. Our futures analysis shows that although in most scenarios large-scale urban tree cover is maintained, considerable changes might be expected at the neighbourhood scale. Losses are likely in scenarios where infill development is common and where redevelopment typically occurs at higher built densities (PR, FW, NSP), and in poorer neighbourhoods where the maintenance of urban trees has become less of a priority (MF, FW). Large-scale planting also greatly increases the chances of drawbacks being realised (Table 1), with the potential for economic and social costs due to infrastructure damage, litigation and health impacts. Once again, improved methods for capturing the value of key benefits within economic and governance systems [3] may incentivise the retention of broad-scale tree cover under scenarios where markets have greater power and where social attitudes to the environment are less supportive. High tree-species diversity at the neighbourhood scale, as well as a large number of nodes within tree networks may also provide useful ecological redundancy, ensuring that alternative feeding resources and dispersal routes exist for bird and bat communities, should some be lost over time.

4.5. Social Context

For many of their potential benefits to be delivered, urban trees need to be located near to people, yet trees can also result in a range of negative impacts on human wellbeing [11,23]. Our analysis highlights the added complication that the magnitude of some social costs and benefits could vary over time and may be highly sensitive to changing social values [44]. In a future scenario where market forces dominate (MF), or consumerist and individualist attitudes prevail (MF, PR, FW), street trees are vulnerable to removal if the (perceived) risks to health, safety or nuisance are high. Increased pressure to remove street trees might also be expected, as a response to litigation risks and infrastructure damage. One strategy to improve the resilience of urban tree planting could be to target parcels of private land that have relatively low densities of buried infrastructure, yet are still close to busy public streets. Gardens/yards and small amenity green spaces within high-density residential developments might therefore prove to be more resilient planting sites than paved areas immediately adjacent to roads, delivering higher rates of survival and growth [8]. However, homeowner support for such planting locations is not universal [9,65] and would be much reduced within the Market Forces scenario. This tension might therefore be reduced by making direct payments to residents/housing managers for hosting and managing urban street and yard trees and the ecosystem services provided; analogous to the practice of paying residents to create "rain gardens" for stormwater interception [83]. Such payments might be best targeted at economically deprived areas, where urban tree cover is often poor [84], and where its benefits may be most needed.

Large tree planting initiatives have had short-term success in engaging volunteers with site identification, planting and the management of urban trees [7,78], often on private land. However, our analysis flags up the risk that public support might decline in the future. The active engagement of individuals, organisations, agencies and institutions in urban tree planting campaigns is already common practice in the UK [34] (e.g., TreeBristol [85], The Mersey Forest [86], and Plymouth Tree Partnership [87]). Yet meeting the different needs and aspirations of stakeholders within large planting projects can be challenging [9,38]. Resolving these tensions could increase management "response diversity", by ensuring sufficient social capital is sustained over time [88] to adapt to the changing needs of urban street trees. Whilst resolving long-term funding issues is clearly important [9], co-management might also be strengthened by greater clarification of the roles and responsibilities of different actors [88].

5. Conclusions

Our analysis makes explicit the conditions that are necessary to realise many of the potential benefits of urban street tree planting within a UK urban context. It identifies synergies and tensions between these benefits, and questions the implicit high-level assumption within many planting campaigns that trees will survive and provide ecosystem services far into the future. We argue that by focusing on the system conditions upon which these benefits depend (rather than the tree itself), we are better able to examine the underlying mechanisms that drive their compatibility and resilience. Benefits are often dependent on conditions such as continued levels of tree maintenance, on public values and policies which are supportive, and on a built form which remains largely unchanged. However, we have illustrated that these conditions may not be supported within plausible scenarios for future cities and that some changes to current practice are required in order to make the desired benefits of urban tree planting more resilient.

We suggest that large-scale urban tree planting projects should include explicit statements about which benefits will be prioritised and the timescales over which they are intended to be delivered. As with other pieces of urban infrastructure, risks to long-term performance should then be identified and holistically addressed. Ensuring the replacement of "lost" street trees is necessary but insufficient; tree survival to maturity is also vital for the delivery of many benefits. Although current best practice is to ensure urban tree planting is compatible with its social and built context, we suggest that this be broadened to consider the impact of plausible changes to the tree's context over its natural lifespan. The main aim of this paper is to illustrate how such an analysis could be undertaken. We also make some recommendations for how the resilience of urban street tree planting might be improved:

- Broaden planting locations to include private gardens and residential amenity green spaces immediately adjacent to streets, to reduce potential conflicts with people and built infrastructure and to reduce tree mortality due to environmental extremes.
- Introduce annual direct payments for local residents and business owners, to incentivise their involvement in the long-term protection and management of trees, in neighbourhoods where benefits are most needed.
- Develop more formal partnerships between the individuals, NGOs and municipal departments that are involved in the co-management of street trees in urban areas, to increase their legitimacy, accountability, and ability to access and share resources.
- For planting in heavily developed areas such as urban centres, incorporate soil cells integrated with surface water drainage systems, and use planting techniques that facilitate the transplantation of trees at a later date if necessary.

Such changes would involve the broadening of current practice, requiring a greater integration of urban foresters and arboriculturists with the long-term spatial planning, funding, governance and infrastructure management processes within urban areas.

Supplementary Materials

Supplementary Information S1: Identifying benefits and drawbacks of urban tree planting for use in the scenario-based resilience analysis, Supplementary Information S2: Justifications used to support the necessary conditions identified in Table 2 of the main manuscript, Supplementary Information S3: A scenario-based analysis of the vulnerability of the conditions required for an urban street tree to deliver its intended benefits.

Supplementary materials can be accessed at: http://www.mdpi.com/2071-1050/7/4/4600/s1.

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Author Contributions

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Christopher Rogers and Jon Sadler generated the data on benefits and necessary conditions and initiated the resilience analysis. James Hale and Thomas Pugh led the analysis. James Hale, Rob MacKenzie, Thomas Pugh and Jon Sadler wrote the paper. Silvio Caputo, Richard Coles, and Russell Horsey provided additional text and substantial feedback on an early manuscript draft. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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