Supplementary Information S1

Identifying Benefits and Drawbacks of Urban Tree Planting for Use in the Scenario-Based Resilience Analysis

The purpose of this supplementary information is to provide a broader introduction to the multiple benefits, drawbacks and dependencies associated with urban trees (Section S1), and to provide an evidence base for the set of benefits and drawbacks selected for our analysis of street trees in UK urban areas (Section S2).

S1. The Multi-Dimensional Benefits and Drawbacks of Urban Trees

As living organisms, trees affect, and are affected by their environment; that is, they have an ecological presence. Because trees share the space within which we build, they may also be considered to have a geotechnical presence. Trees also have a strong social presence, with a wide range of influences on human behaviour, and are themselves influenced by cultural practices. This multi-dimensionality corresponds to previous descriptions given in the context of socio-ecological research [1]. The UK National Ecosystem Assessment [2] recognizes that these various influences can be cast in terms of service provision for those living with the urban forest and hence in some cases monetised [3].

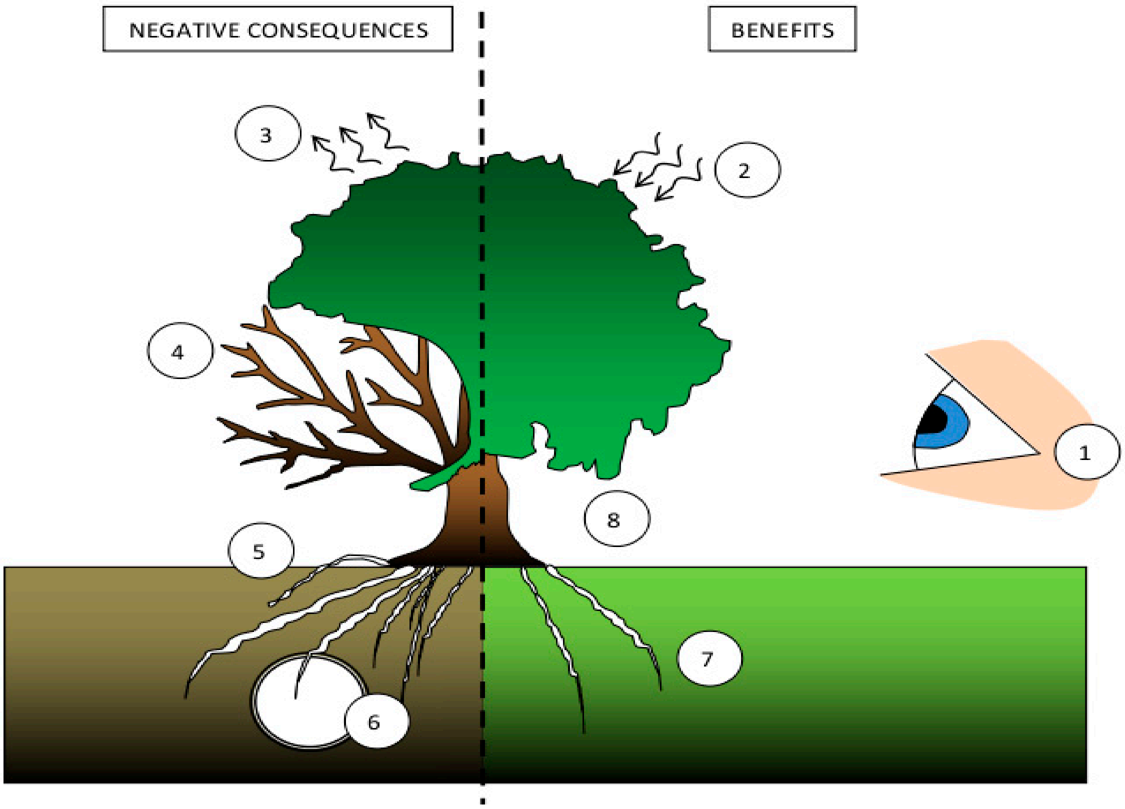

Figure S1. Positive and negative impacts of trees within the urban environment. Numbers 1–8 represent different classes of impacts that are explored within the text below.

The social presence of the tree as a visible feature (Figure S1, class 1) has a number of generally beneficial impacts. There is much evidence to support the hypothesis that humans can have strong, positive emotional responses to the natural world [4], and that opportunities for such contact are much reduced within urban areas [5]. Greater feelings of wellbeing as a result of urban tree cover may be manifested in a more positive perception of the local area and improved local identity [6], lower levels of crime and increased social interaction [7–9], reduced stress and faster hospital recovery times for those with views of trees [10,11]. Street trees may also play a positive role in traffic calming [12]. However, visual impacts may also be negative; fallen leaves or unhealthy trees may reduce aesthetic qualities, and reduced visibility may lead to an increased fear of crime [13]. Fallen leaves and fruit, as well as standing dead wood, have a range of potential ecological benefits [14,15], adding further to the increased biodiversity that the tree may provide directly (4). Yet such debris may constitute a nuisance, potentially creating a slip hazard or damaging property. Falling branches and trees may therefore create a litigation risk [16] and the removal of debris also imposes maintenance costs.

Poor tree growth has been associated with a lack of (or poor quality) root-penetrable soils, which are prevalent in areas that have been compacted and paved to achieve increased bearing capacity [17,18]. Given time, tree roots will however reinforce the soil and can stabilise embankment slopes, preventing erosion [19]. Soil channels created by roots can also facilitate water penetration (7) [20,21], reducing surface runoff and potentially increasing aquifer recharge [22,23]. Transpiration of water drawn up through the roots may also have a cooling effect on the surroundings (8). However, this water demand may also be a problem in arid climates or extensively paved areas, where the tree may require supplementary watering. Further, variations in the suction effect exerted on the soil by transpiration can result in building/infrastructure damage in clay soils (6) [24]. Roots can also directly damage building foundations and infrastructure (e.g., water pipes and sewers), particularly as most root systems occupy the top 60 cm of soil [25] (6) which is extensively used for siting utility service pipelines and cables. Competition for space beneath urban streets (both roads and adjacent pedestrian areas) is accompanied by the considerable potential for utility service damage due to lateral and vertical shrink – swell movements of these linear structures. Moreover, surface heave due to shallow tree roots may constitute a trip hazard where pavements are damaged (5).

As well as the basic ecophysiological effect of evapotranspiration, the urban forest canopy provides shade and shelters high-heat-capacity urban surfaces [26] (8), thereby reducing air temperature. Canopy effects may be considered positive or negative for people within urban areas depending on the local climate and context. Shading by trees reduces daylight penetration to lower building floors, which may increase the need for artificial light in both the urban outdoor environments and in adjacent buildings. In addition, tall trees could compromise local energy generation by solar panels or wind turbines. The canopy can also provide shelter from the wind, increasing pedestrian comfort on windy days, but reducing comfort on hot days when a breeze would be welcome, although the latter could be countered by evapotransiration and shade effects. The same principles apply to buildings; trees may be used as a barrier against cold winds [27] and can also be used to attenuate noise [28].

The interaction between the urban forest canopy and its environment extends to air pollution; trees can act as an effective removal surface for airborne particulate matter [29] improving air quality. Uptake of trace gases through leaf stomata (2) can also improve air quality, with nitrogen dioxide and ozone being efficiently removed [29–31]. A net intake of carbon dioxide through stomata also occurs due to photosynthesis. This carbon dioxide is removed from the atmosphere until the biomass into which it is converted decomposes, thus offsetting a small amount of anthropogenic carbon dioxide emissions. It should be stressed though that above-ground carbon stock in urban trees is small, when compared against urban emissions [32] and fraught with uncertainties over the lifecycle of the biomass [33]. Trees also emit volatile organic compounds (VOC's) which can contribute to ozone formation in urban areas (3), and thus worsen air quality [30]. The level of this emission varies with species and environmental conditions [34]. In addition, the reduction in airmass mixing rates caused by trees in street canyons can reduce air pollutant dispersion [35]. Overwhelmingly however, trees are present and valued in cities for aesthetic reasons [36], even if our aesthetic pleasure in urban trees may derive in part from assumptions about the services they are providing.

S2. Intended Benefits and Drawbacks of Urban Trees to be Used in the Resilience Analysis

Our analysis focuses on those benefits which are commonly cited in the academic literature or as the motivation for large-scale urban planting programmes (Table S1 below). It is not intended to be all encompassing, but rather to identify key benefits that may be reasonably expected from urban trees, particularly those planted along streets. We take as our base the benefits accounted for in the widely used UFORE model [37]: air pollution reduction, carbon assimilation, building insulating effect of evergreen trees in winter due to wind shelter and building cooling effect of trees in summer. This subset is chosen primarily due to the relative ease of quantification. In addition to these we analyse the following benefits, deemed to be potentially significant in recent reviews [28,38–40]: reducing rate and volume of stormwater runoff, providing habitat for wildlife, reduced air temperature, noise attenuation, creating desirable environments for recreation, reducing psychological stress (including faster recovery times from illness), improved aesthetics, increased property values, increased business turnover. These studies also list the avoidance of carbon dioxide and air pollutant emissions from power plants due to reduced energy demand for heating and cooling. Likewise evaporative hydrocarbon emissions can be reduced by lowering temperature. We do not consider these indirect benefits separately in our analysis. Similarly, improvements in water quality are a result of decreased runoff [23] and are therefore not considered separately. As many visions of sustainable cities involve high population densities and a compact urban form, we also consider the benefit that trees may decrease perceptions of overcrowding in high-density developments [41]. The benefit of stabilisation of cuttings and embankments [19] is also included.

Benefits claimed on the websites of several urban greening programmes are listed in Table S1 along with the number of websites citing each benefit. The most commonly-cited benefits are those discussed above: biodiversity enhancement, energy savings, reductions in air pollution, improvements in water quality, reduced noise pollution, improved aesthetics, higher sales in business districts and increased property value. Thus our list of benefits covered those most commonly claimed as justification for tree planting. We note that these 'benefits' may not be desirable in all situations—e.g., increased biodiversity bringing increased numbers of, or concerns about, animal pests—but assume, for simplicity, that the benefits are uncontested.

In addition to the sustainability benefits, we also consider important drawbacks that may arise from planting street trees in urban areas and which must be avoided or minimised. One of the most common reasons for tree removal in urban areas is as a result of conflicts with infrastructure [39]. Thus in our analysis we consider the avoidance of interference with underground infrastructure through root growth and through transpiration-driven soil shrink-swell effects. The avoidance of leaves and fruit creating negative aesthetic or safety effects is also considered, as is the avoidance of injury or infrastructure damage through branch or tree fall. The complete list of benefits and drawbacks used in the analysis is given in Table 1 of the main manuscript. We do not quantify the effectiveness of urban trees in achieving any or all of these benefits. That is the subject of the many issue-specific cost-benefit and case study analyses already in the literature [42–44], and is an area of on-going research. Rather, we seek to assess whether the various benefits are compatible with one another, and to explore the resilience of such benefits to future changes in the urban system.

Table S1. Benefits listed in support of large-scale urban greening programmes.

Benefit	Number of Citations	Programme Ref.
Attract wildlife (biodiversity)	3	1, 3, 4
Mitigate against climate change	1	1
Carbon capture	2	3, 4, 6
Save energy	5	1, 2, 3, 5, 6
Reduce power plant emissions (through lower energy use)	1	3
Reduce greenhouse gases	1	4
Reduce summer air temperature	1	3
Shade	1	1
Shelter	1	1
Increased longevity of street surfaces	1	2
Reduce air pollution	6	1, 2, 3, 4, 5, 6
Reduce asthma and respiratory diseases	1	3
Reduce flood risk/capture stormwater	2	1, 5
Improve water quality (stormwater interception)	3	3, 4, 6
Reduce water consumption	1	4
Aquifer recharge	1	6
Reduce erosion	1	6
Reduce noise pollution	3	1, 2, 5
Improved aesthetics	3	1, 3, 4
Higher sales in business districts	3	2, 3, 5
Increase property value	3	2, 3, 5
Increased productivity among employees	1	2
Faster hospital recovery times	1	2
Lower crime	2	1, 2
Increased community pride	1	3, 4
Encourage physical activity	1	3
Create amenity spaces	1	4
Reduce stress	1	5
Calm traffic	1	5

1 The Big Tree Plant, UK, http://www.defra.gov.uk/bigtreeplant/ [Access: March 2015]; 2 Mile High Million, Denver, USA, http://milehighmillion.org [Access: March 2015]; 3 Million Trees NYC, USA, http://www.milliontreesnyc.org [Access: March 2015]; 4 Million Trees, South Australia, Adelaide, http://www.milliontrees.com.au [Access: March 2015]; 5 Million Trees LA, USA, http://www.milliontreesla.org [Access: March 2015]; 6 Million Trees, London, Ontario, http://milliontrees.ca [Access: March 2015].

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