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Woodland Establishment Reduces Nutrient Losses to Waterbodies in Urban Catchments: A Review of the Evidence

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Key Points:

- A synthesis of evidence from peer-reviewed literature found substantial benefits of urban trees in terms of reduced nutrient transfer
- Trees brought about 44.2% and 47.0% reduction at plot scale for total nitrogen and total phosphorus respectively
- Leaf litter is an important pathway of nutrient transfer to waterbodies, and riparian trees introduce complex effects

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Abstract

Systematic review of peer-reviewed literature was undertaken to establish benefits of urban forests on reducing nutrient concentrations in adjacent or downstream waterbodies. Following screening, a small number of articles (40) were found relevant, representing studies quantifying non-point source nutrient losses from urban and peri-urban environments. Evidence was split between plot- and catchment-scale. Plot-scale studies often included evaluations of engineered nature-based solutions. At catchment-scale, studies of streamwater quality typically investigated influence of contributory catchment nutrient sources. Wide ranges of beneficial reductions were apparent, and at both scales not all studies identified significant benefits. Summarizing against this backdrop, at plot (micro-) scale woodland reduces mean concentrations in runoff, soil or groundwater by an average of 44.2% for total nitrogen (TN) and 47.0% for total phosphorus (TP). At catchment (meso-) scale, evidence suggests a 20% areal addition of forest at the expense of mixed urban fabric can reduce mean concentrations by 15.7% and 12.6% for TN and TP respectively. Additionally, some articles reveal potential drawbacks reducing benefits provided specifically by street trees and riparian woodland. Leaf litter falling on impervious surfaces can heighten risk of TP leaching to streams, but has little impact on TN. Riparian woodland was found to have complex water quality impacts. Canopy cover suppresses stream channel biological nitrogen uptake, which based on all evidence appears considerable. However, unshaded headwaters can foster accelerated primary productivity with undesirable downstream consequences. Overall, gathering further evidence is encouraged, given current uncertainties, especially to address differences between impervious, permeable and riparian urban woodland settings.

1. Introduction

Woodland is increasingly recognised as providing a range of ecosystem services, for example, regulating air pollution, enhancing soil quality and reducing flood risk (Burton et al., 2018). In urban environments in particular, nature-based solutions (NBS) are increasingly recognised as having capability to address many societal challenges and provide economic, societal and environmental benefits in a sustainable manner. Implementation is especially advanced for the primary purposes of stormwater mitigation. A wide range of engineered solutions are adopted such as green roofs, bioswales, rain gardens and permeable pavements (McGrane, 2016), but usually the most commonly adopted approach is tree planting (e.g., as summarized across 100 European cities by Almassy et al. (2018)). A spectrum of tools are available to support practitioners in evaluating the potential benefits of urban NBS. These range from tools for rapid and extensive quantification of ecosystem services (e.g., InVEST: Redhead et al., 2018) to detailed mechanistic models of urban water resources (e.g., SWMM: Baek et al., 2020).

Urban areas are exposed to increasing flood risk (Kundzewicz et al., 2018). Elevated nutrients are of widespread concern in aquatic ecosystems (Smith & Schindler, 2009) and in drinking water supplies. It is widely recognised that woodland can provide benefits for flood alleviation. For example, Stratford et al. (2017) show consensus in reductions in river flood peaks by woodlands in temperate oceanic and sub-polar oceanic climatic regions. Likewise inverse relationships at a range of scales between streamwater nutrient export and woodland cover in the catchment contributing area are long recognised. In a comprehensive review, Beaulac and Reckhow (1982) identified export rates of TN and TP to be 50% and 80% lower respectively in natural forested compared to urban watersheds. Therefore, reduction in nutrient concentrations by woodland is potentially important for suppressing eutrophication of waterbodies. Trees in riparian settings may provide unique water resource and quality benefits (Feld et al., 2018). However, specific evidence for stormwater benefits in urban woodland environments remains surprisingly scarce. Although identifying robust local scale evidence, Baker et al. (2021) find evidence of runoff reduction at larger scale to be patchy with a paucity of studies incorporating adequate control conditions. Regarding water quality benefits, a synthesis of literature evidence is lacking. This is despite the recognised severity of non-point source urban nutrient pollution signatures in addition to those of wastewater effluent (Groffman et al., 2004). A coherent understanding of urban water quality response is needed, especially since urban trees are subject to more acute and chronic environmental stressors than rural counterparts (Baxter et al., 2002; Falxa-Raymond et al., 2014). It may be incorrect to assume tree planting in urban settings provides equivalent benefits to those achieved elsewhere.

The objective of the present study was to identify evidence for the benefits of trees in reducing TN and TP transport specifically to urban waterbodies. It did not set out to comprehensively review relationships between trees and water quality in a more general context, for which readers are referred to other reviews (e.g., Neary et al., 2009). Literature was collated systematically, assessed using ratified approaches for screening and exclusion, and framed using the following primary and secondary questions: (Q1) How much improvement in water quality in urban runoff arises from a specified increase in urban forests? (Q2) Does the occurrence of trees in specific types of urban setting bring about differing consequences for water quality? From the evidence identified, we summarized findings by:

- An evidence mapping exercise covering a range of key characteristics including geographic distribution, morphological setting (impermeable [e.g., street trees], permeable [e.g., in parkland] or riparian), tree species and whether or not the woodlands studied were part of NBS initiatives,
- A meta-analysis to derive best estimates of quantified effects of urban woodland on hydrological nutrient transport, with a view to directly improving the rigor of the scientific evidence underpinning modeling tools for urban NBS evaluation.

2. Methodology

2.1. Evidence Gathering

Literature searches were undertaken in Web of Science (WoS) and Scopus databases on 17 August 2021 using the following Boolean "topic search" term: "(urban* OR cit* OR town*) AND (tree* OR forest* OR wood* OR canop*) AND (("water quality" OR pollut*) AND nutrient*)." The searches yielded a return of 1,118 papers excluding articles not written in English and those published prior to 1 January 1990. The Population-Intervention-Comparator-Outcome (PICO) structure (Collins et al., 2015) was used to facilitate screening at abstract and full-text level. The PICO scheme originated in medical science has been shown demonstrably preferable to other approaches (Methley et al., 2014). It represents an industry standard approach in environmental science (James et al., 2016). At each screening stage, those articles clearly failing to meet the requirements of the four PICO elements (Table 1) were not retained for further analysis. Emphasis with PICO is usually on impacts of management interventions, and whilst the scope of the present review is wider, the structure PICO provides for defining screening criteria is suitable for the process of excluding material not directly relevant. Separately, a set of 10 publications were collated which passed the full-text screen of 19 potentially relevant abstracts previously identified from a search cited in a review by Baker et al. (2021) which had been tailored to find evidence specifically in an NBS context (topic search term: "(urban* OR cit* OR town*) AND (tree* AND ("green infrastructure" OR "green space" OR "nature based solution*" OR NBS OR "low-impact development" OR LID)) AND (("water quality" OR pollut*) AND (nutrient* OR metal*)." In addition to those already identified by Baker et al. (2021), a total of 94 of the 1,118 newly found papers passed the abstract level screen of which 30 were retained following full-text screening. The complete set of 40 papers retained for analysis were then assessed for categorization (Table 1: Column 4 criteria) along with further elements of critical appraisal (criteria in Table 2). Together as a whole these were to be used in an evidence mapping exercise to describe the extent of the knowledge base. Additionally, key results which specifically addressed the primary and secondary questions above were summarized for subsequent meta-analysis.

The results were organized into four different preliminary categories (Figure 1) upon which interpretative meta-analysis was undertaken. The objective of the meta-analysis was to define quantitative benefits of trees on nutrient water quality. These were presented as box-whisker plots (Figures 2b and 2d).

For articles to contribute to our objectives it was necessary for findings to be readily extractable from data reported in the main article or from Table A1. In a number of cases where papers passed screening at the

Table 1
PICO Elements, With Definitions and Criteria for the Screening Process

1. Item	2. Definition	3. Criterion	4. Additional details and categories
Population	subject of study, that is, freshwaters	water in urban areas not influenced by treated sewage effluents[a]	Surface runoff, leaf litter leachate, soil water, groundwater, stream water, standing water (e.g. wetlands)
Intervention	proposed management technique	tree planting or presence in urban areas	
Comparator	control or difference in tree cover	absence or a significantly different level of trees in urban areas	Types of comparison: (1) upslope/downslope, (2) before/after, (3) nearby contrasting urban land use
Outcome	effects observed as a result of the intervention	nutrient content in water	Concentrations (e.g. event mean) or loads (e.g. annual flux) of total nitrogen or total phosphorus, or constituent species (ammonium, nitrate, dissolved phosphate etc.)

[a]Decision as to whether or not an area of study was urban was reliant on the primary authors' description, combined sewer overflows were not excluded.

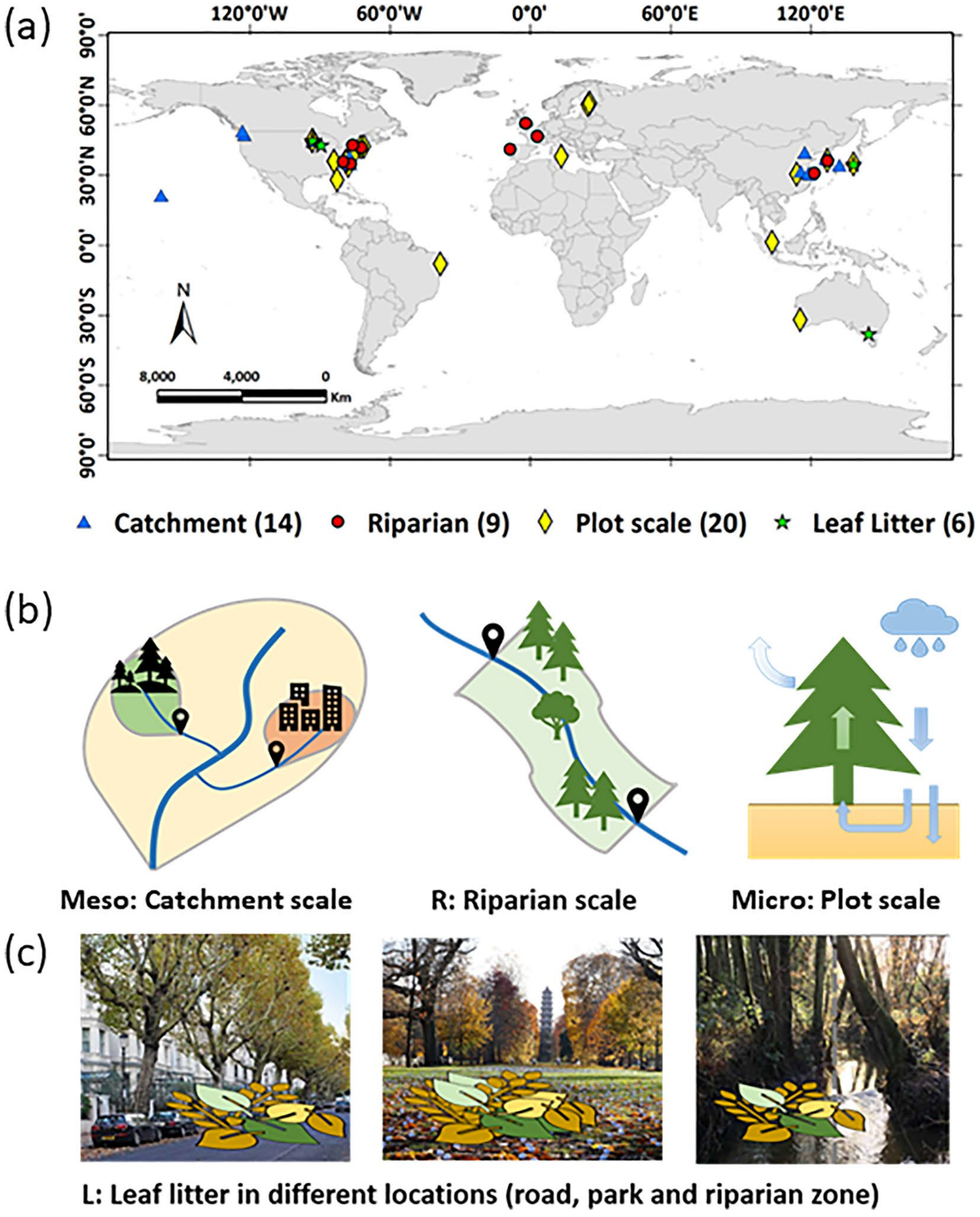

Figure 1. Description of the evidence base: (a) a map of distribution of studies, (b) conceptual distinction between catchment (Meso), plot (Micro) and riparian (R) study types (c) contexts for the fate of leaf litter (L study type) on streets, lawns or in rivers.

abstract level it proved difficult to extract the required information with confidence. Making inordinate efforts to achieve this might have been successful but would have greatly detracted from the systematic nature of the exercise. Common examples of this were where comprehensive presentation of raw data had not been made, with focus instead on key summaries related to the specific objectives of the study. Exclusion of articles was not reflective of their overall quality and value. Similarly, assigning low scores for weighting purposes (see Section 2.2) should not be regarded as a criticism of the quality of the research but merely a reflection of its suitability for extracting the specific evidence we sought.

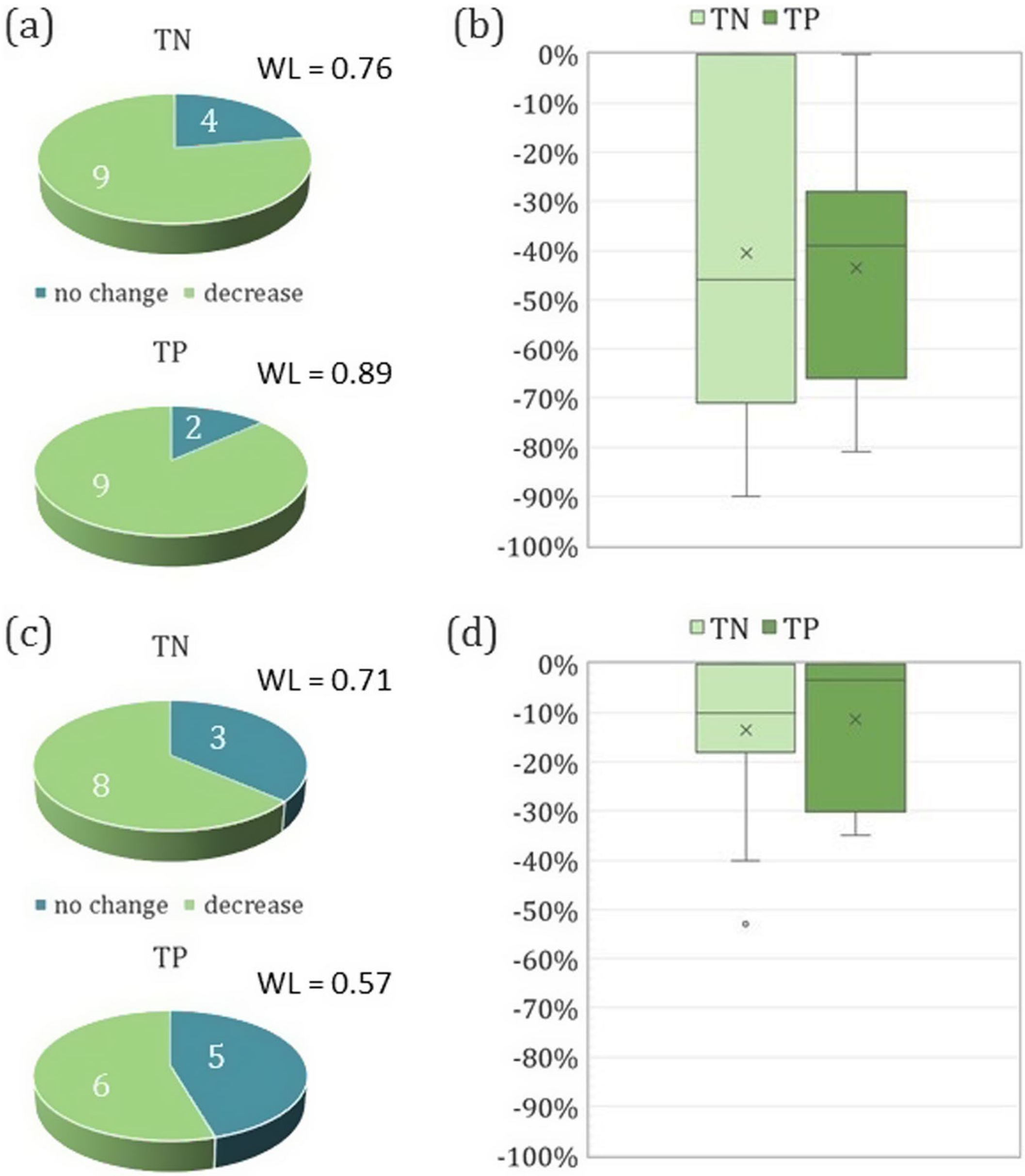

Figure 2. Evidence for decrease in nitrogen (TN) and phosphorus (TP) nutrient concentrations due to forest establishment in place of mixed urban land use fabric. Concentrations usually represent event mean concentrations in storm runoff or annual mean concentrations in soil solution, groundwater or stream water (for details see Table A1): (a) proportions and numbers of Micro-studies showing no change or a decrease; using the weightings described in Section 2.2 this equates to weighted likelihood of change (WL) of 0.76 for TN and 0.89 for TP, (b) range of impact of forest on nutrient concentrations in surface runoff, soil solution or groundwater (from Micro-studies, where $n = 10$ for TN and $n = 9$ for TP) (x: unweighted mean); median TN and TP benefit is 46% and 39% respectively, (c) proportions and numbers of Meso-studies showing no change or a decrease; using the weightings described in Section 2.2 this equates to weighted likelihood of change (WL) of 0.71 for TN and 0.57 for TP, (d) range of impact of a 20% areal addition of forest within a catchment on nutrient concentrations in stream water (as derived from Meso-studies, where $n = 11$ for TN and $n = 11$ for TP) (x: unweighted mean); median TN and TP benefit is 10% and 6.5% respectively. NB: upper whiskers are obscured by the upper quartiles which have identical values (0%) in panel (b and d).

2.2. Categorization, Meta-Analysis and Weighting of Evidence

In preparation for establishing aspects of urban forest benefit in quantitative terms (Section 3.2), information pertaining to the criteria (Tables 1 and 2) together with other details (e.g., basin size) were used for broad thematic

Table 2
Critical Appraisal Criteria

Criterion	Appraisal entry
Study type	Primary quantitative observational (QO)
	Primary quantitative experimental (QE)
	Review (R)
Forest as NBS	Yes/No
Tree location (if known)	Urban in-situ
	Urban ex-situ
Riparian tree location	Yes/No
Geographic location	Continent (plus city/country)
Inclusion of modeling	Statistical model (SM)
	Deterministic model (DM)
	None
Study area size	Descriptive
Monitoring period	3 = long (>2 years)
	2 = moderate (1–2 years)
	1 = short (<1 year)
Monitoring frequency	3 = high (>fortnightly)
	2 = moderate (fortnightly—seasonal)
	1 = low (<seasonal)
Number of sites including control	3 = many (>6)
	2 = moderate (3–6)
	1 = few (<3)

categorization to map the evidence (Figure 1) including its geographic distribution. Categories of evidence were identified: (a) plot scale work or findings related to individual trees (termed Micro-studies), (b) catchment-scale findings broadly discriminated from Micro-studies by drainage basin size (Meso-studies), (c) studies relating the impact on water quality of urban woodland setting including riparian environments (as described further in Section 3.1). The categories are not mutually exclusive.

Whilst many studies included observations of various nutrient species, the majority of studies (26) presented data on total nitrogen (TN) and total phosphorus (TP). For representing wider water quality health and its consequences, we argue these are the most useful nutrient indicators. Where individual species were reported rather than TN or TP, we assumed total nutrient concentrations would respond similarly. In each study (Table A1) the temporal characteristics of the underpinning quantitative water quality evidence was placed in one of three classes (storm event-based, campaign-based or annual). To answer Q1 above, information between studies was assessed for direction of change and where possible specific magnitude of change. Regarding direction, this involved a basic establishment (from primary authors' assertions) of whether or not findings demonstrated statistically significant changes or differences related to woodland influence. Regarding magnitude, the bringing together of findings between studies was, out of necessity, harmonized and rationalized. For all studies, this process involved the re-casting of the primary question in more specific terms. Findings from Micro-studies were expressed in terms of the level to which woodland affected nutrient concentration in soil solution, surface runoff or groundwater samples. For Meso-studies, the quantity established was the amount of change in stream water nutrient concentration arising from a 20% areal addition of woodland in a catchment, which represents a substantial yet realistically achievable level of landuse change.

To summarize findings as representatively as possible by giving greater weight to more comprehensive and reliable evidence, we weighted the results using a value range of 3–10. Each study was assigned a weighting defined as the sum of scores from the three data criteria describing monitoring period, monitoring frequency and number of sites (Table 2). Where specific data criteria were not defined, a score of 1 was assigned by default. To represent an additional level of confidence in findings an extra point was awarded for studies which used either deterministic or statistical models. Modeling applications are generally effective in accounting for confounding factors, so this proxy for confidence was used as it could readily be assessed objectively. For each permutation of study type (Micro- or Meso-) and nutrient (TN or TP), the weighting approach was applied to all contributing studies, including those not showing significant change. The weighted likelihoods of decrease in nutrient concentrations (WL values: Figures 2a and 2c) were defined as the ratios of the aggregated total weighting for studies showing change to the aggregated total weighting for all studies.

3. Results and Discussion

3.1. Evidence Mapping

The evidence base was summarized (Figure A1) and details of the findings in each individual article tabulated (Table A1). The prevalence of relevant studies has increased greatly in recent years with 35 of the 40 studies published since 2010. Of the remainder, only 1 was published before 2000. Geographically at continental resolution (Figure 1a), the distribution of evidence is weighted toward North America (20) with substantial numbers in Asia (10) and the majority of remaining studies in Europe (4) and Australasia (5). Of the 40 studies, 12 related specifically to woodland as NBS. Experimental studies (QE) comprised 8 of the 40 studies, all others being observational (QO, including modeling-based studies). No review articles passed full-text level screening. In a number of studies, either process-based (9 studies) or statistical (11 studies) model applications were fundamental for quantitative determination of the water quality benefits of woodland. Not all statistical modeling applications were recorded in the primary studies. Use of statistical modeling was only deemed of relevance to our objectives where it was applied directly to explore relationships between land use assemblage (including woodland) and nutrient concentrations.

Micro-studies (e.g., Tirpak, Hathaway, & Franklin, 2019) often included research addressing impacts of engineered NBS and typically comprised measurements of soil solution, groundwater or surface runoff, as opposed to studies of stream water and larger standing waterbodies. A number of Micro-studies included throughfall measurements and often contrasted these to bulk rainfall and stemflow. Unless including observations in other media (surface runoff, soilwater or groundwater), these were omitted as findings could not be readily related to transport in surface waters. Many of the articles classified as Meso-studies (e.g., Shupe, 2017) used statistical modeling to bring together earth observation of landcover with surveys of streamwater quality across a range of catchments covering urban and forest gradients.

Regarding urban morphological setting (Q2), some studies were deemed representative of impermeable settings. Whilst these theoretically might relate to parking lots and playgrounds, they were unanimously focused on streets (i.e., street trees). These primarily addressed leaf litter, and associated rapid leaching and transport pathways on impermeable surfaces. Hence these were denoted L-studies, a group worthy of particular emphasis. Activity in this area appears very geographically focused in central USA. The impact of leaf litter is of potentially high significance, with distinct implications for urban environmental management. In contrast to impermeable settings, trees on parklands, lawns, gardens or other permeable land were not additionally assessed in any specific way and were not categorized as such. Other studies were specifically related to river riparian settings (classified as R-studies). These largely fell into two sub-sets. First, we found those which identified longitudinal water quality changes along a river stretch attributable to differing levels of riparian canopy coverage. In contrast, a second set provided information on the varying efficacy of woodland riparian buffers depending on their width or species composition.

3.2. Primary Question: How Much Improvement in Water Quality in Urban Runoff Arises From a Specified Increase in Urban Forest?

3.2.1. Plot-Scale Findings

Due to their small spatial extent, Micro-studies represented the core data set from which to identify effects of woodland most likely to be unequivocal, therein having absence of or suitable control of confounding factors. Four R-studies focused on riparian woodland buffers (Line et al., 2002; Matteo et al., 2006; van Looy et al., 2013; Xu et al., 2021) but provided evidence of terrestrial nutrient retention at a plot scale akin to those classified as Micro-studies. Therefore they were included in a meta-analysis of 19 studies.

Overall, the evidence showed the presence of woodland has resulted in significantly lower nutrient concentrations in a majority of studies (Figure 2a). Of those 15 studies covering both nitrogen and phosphorus, 13 demonstrated lower concentrations for both nutrients. The other two identified lower phosphorus concentrations attributable to woodland but no discernible reduction in nitrogen (Barr et al., 2017; Nidzgorski & Hobbie, 2016). In some cases, quantitative plot-scale effects were not readily extracted, mostly those where studies of riparian buffers revealed different and distinct findings which are discussed separately later. The overall range of magnitude of effect was considerable (Figure 2b). The respective WL scores (Figure 2a) indicate more confidence in the existence of significant beneficial effects for TP than for TN.

The majority of experimental studies characterizing stormwater nutrient retention considered trees as part of NBS installations. These typically involved controlling stormwater inputs and soil hydrological conditions in mesocosms, either representing modular (Lim et al., 2021) or street-scale bioretention systems (Denman et al., 2016; Tirpak, Hathaway, & Franklin, 2019) including those initiatives forming part of suspended pavement installations (Page et al., 2015; Tirpak et al., 2019b). The studies largely showed NBS to be beneficial, although those of Tirpak, Hathway & Franklin (2019), Tirpak, Hathway, Franklin, et al. (2019) were exceptions, in notable contrast to the others measuring ortho-phosphate rather than total phosphorus. In a study primarily assessing green roofs, Barr et al. (2017) also identified beneficial stormwater TP retention by woodland. Otherwise, and unrelated to NBS, Hathaway et al. (2012), Line et al. (2002) and Zhao et al. (2007) all observed nutrient reductions due to woodland in stormwater runoff in sets of very small catchments of contrasting levels of tree cover. Some studies used spatial deterministic models. Revelli and Porporato (2018) identified lower nitrogen loads in areas influenced by urban street trees, although deriving quantified estimates of these from the study was not possible. For both TN and TP, model prediction for NBS establishment gave substantial forest benefits of over 60% in one case (Tsegaye et al., 2018) but much smaller benefits (6%–7%) in another where street and riparian tree buffers were simulated in an 80% urban area (Matteo et al., 2006).

Other plot scale findings were related to soil water or groundwater compartments. Parkland lysimeter studies revealed considerable soil solution nutrient benefits of woodland compared to grassland and attributed these differences to soil moisture effects (Setälä et al., 2017). However, these were only achieved in sufficiently mature deciduous plantations. Oldest trees also gave unclear effects. Nidzgorski and Hobbie (2016) found similar benefits for soil phosphate and studied implications for groundwater quality using hydrological modeling. Nitrogen impacts were inconsistent, seemingly differing between years due to climate variability (Nidzgorski & Hobbie, 2016), although Wang et al. (2018) identified some evidence of urban forest benefits for groundwater dissolved organic nitrogen. Whilst Decina et al. (2018) studied nutrients in throughfall and soil solution for individual trees, they did not report soil concentrations under contrasting landcover, so data were not included in meta-analysis.

3.2.2. Catchment-Scale Findings

From the articles passing the full-text screen, 14 studies were classified as Meso-studies. Compared to the Micro-studies, which with a few exceptions are confined to less than a few hectares, these cover a much wider range of spatial extent and mostly represent stream water sites. Most sites drain areas between 10 and 100 km^2. It was useful to isolate these studies as they represent integrated effects of woodland nutrient retention in a basin-wide context. Compared to the Micro-studies, a larger proportion of Meso-studies did not show significant benefits of woodland (Figure 2c). Of those studies covering nitrogen and phosphorus, 5 of 9 demonstrated lower concentrations for both nutrients. In the remaining studies, 2 solely showed TN benefits with the other 2 solely showing TP benefits. Due to their larger spatial extent it was less easy to take account of confounding factors. Most commonly it was uncertain whether the influence of point source pollution from wastewater effluents had been avoided in site selection or removed during analysis. Brett et al. (2005) explain these issues in detail but few studies were explicit, hence it was usually not possible to account for confounding influences of this type. Arable land uses with high nutrient signatures were often also the source of confounding factors. In studies where quantification of change was possible, the spread of benefits was displayed (Figure 2d).

As to be expected from the larger scales involved, the majority of studies focused on stream waters. Two studies (Janke et al., 2014, 2017) covered a range of domains (soils, groundwater and surface waters) and are concerned with impacts of leaf fall on water quality at a range of scales. These are discussed in more detail in Section 3.3.1. In addition, three studies reported stormwater runoff (Alfonso et al., 2015; Kumar et al., 2016) and soil solution (Zhang et al., 2019), the latter two studies using process-based modeling. Kumar et al. (2016) focused on inorganic nitrogen and ortho-phosphate. A further study reported modeling of stream quality (Li et al., 2018). A number of studies used statistical techniques which helped us ascertain effects of woodland on nutrient water quality (Brett et al., 2005; Haidary et al., 2015; Middleton et al., 2020; Shupe, 2017; Viau et al., 2011). The inclusion in studies of modeling techniques, either deterministic or statistical, can help isolate confounding factors and gave more confidence when identifying the specific relationships between urban forest and nutrient concentrations, acting amongst the myriad of other influences in a catchment. On the other hand, model skill was not always reported. Unreported and poor model performance undermined our objectives of attributing forest effects.

3.3. Secondary Question: Does the Occurrence of Trees in Specific Types of Urban Setting Bring About Differing Consequences for Water Quality?

We found detailed evidence in two respects, first on how leaf litter affects nutrient export (L-studies) and second the influence riparian woodland has on within-channel aquatic processes (R-studies). Otherwise, we also recorded tree species information, but detailed assessment of its influence on nutrient fluxes proved complex and out of scope of the present study. Evergreen trees did give comparably less benefit than deciduous trees in some studies (Nidzgorski & Hobbie, 2016; Setälä et al., 2017).

3.3.1. Effects of Leaf Litter and Riparian Canopies

The fate of nutrients in leaf litter greatly depends on where it falls, either on impervious surfaces, grassland or directly into waterbodies (Figure 1c). Six articles, mostly from central USA, assessed leaf litter decomposition and associated nutrient release. Of these studies, 5 of 6 identified clear dis-benefits of leaf litter on leaching of TP to waterbodies. Only 1 of 5 studies identified TN dis-benefits. Compared with phosphorus there are many other substantial sources of nitrogen to impervious surfaces (e.g., atmospheric deposition and vehicles) (Janke et al., 2017) making for more complex relationships.

Much higher rates of leaching of soluble reactive phosphorus were found from litter across a range of tree species than from grass cuttings (Wallace et al., 2008). We found minimal comparable information on release of nutrients from litter falling directly into rivers. Rapidity of leaf litter decomposition increases with fragmentation (Wang et al., 2020) and half-lives appear much shorter on roads (a few days) than on lawns (up to 3 months) (Bratt et al., 2017; Hobbie et al., 2014). With this understanding of leaching rates, budgeting studies in small urban basins can potentially identify significant leaf fall contributions. From a controlled study comparing nutrient export with and without leaf removal, Selbig (2016) found that leaf litter contributed 64% of the entire TP load to an urban river in a small basin where 13% of the woodland comprised street trees. Similarly, Janke et al. (2017) implied a leaf litter contribution of 58% to TP from an urban basin with 17% street tree fraction, and Bratt et al. (2017) attributed 40% of stream water TDP to leaf litter in a basin with a similar street tree fraction. The findings of Selbig (2016) equated to an annual leaf litter contribution of 244 mg TP m^{-2} canopy, whilst Bratt et al. (2017) estimated a lower flux of 84 mg TP m^{-2}. Both these estimates markedly exceeded the reported benefits of parkland trees compared to grassland. As derived from lysimeter drainflow observations, retention under parkland tree stands exceeded that under grassland by approximately 17 mg TP m^{-2} (Setälä et al., 2017). Across 19 urban catchments, Janke et al. (2017) identified a strong relationship between the fraction of streets with overhanging canopies (covering a gradient 0–0.45) and stream TP concentrations during storm events. The calculations of leaf litter influence by Bratt et al. (2017) and Selbig (2016) represented the higher end of this street canopy gradient (between 0.36 and 0.57). Yet, as none of the Micro- and Meso-scale studies defined relative contributions of street trees to total woodland, it was not possible to put evidence from the L-studies of street tree TP export pathways in context. Of the articles surveyed, only Zhang et al. (2019) and Shupe (2017) appeared to use sufficiently high-resolution earth observation to facilitate this distinction.

Four of the 9 studies classed as riparian (R) provided evidence for plot-scale retention and contributed data for meta-analysis (Figure 2). All 9 studies also contributed other types of evidence. Characteristics of woodland buffers enabling effective nutrient mitigation were revealed (Matteo et al., 2006; Moon et al., 2013; van Looy et al., 2013; Xu et al., 2021). Line et al. (2002) observed beneficial effects from 9 to 15 m of riparian woodland. Some studies used models. Matteo et al. (2006) predicted small levels of nutrient retention (3.5%–4%) in urban environments under 60 m riparian buffers. To achieve a 10% reduction in nutrient load, Moon et al. (2013) used modeling to prescribe 70–80 m wide deciduous buffers but narrower (60–70 m) evergreen buffers. Significant positive effects on nutrient retention of the presence of forest within 200 m of urban stream channels were predicted (Xu et al., 2021).

Relations between riparian canopy cover and longitudinal change in river water quality have been found pervasive across disparate studies assessing impacts of organic pollution (Ledford et al., 2017), river restoration (Ramião et al., 2020) and stream habitat (Sudduth et al., 2011). Light blockage by canopies, despite suppressing undesirable filamentous algae, curtailed autotrophic nitrate uptake and resulted in much higher nutrient concentrations than in corresponding open stretches of river (Ledford et al., 2017; Sudduth et al., 2011). Strong seasonal variation is apparent. Only 200 m of shaded river brought about 8-fold increases in summer concentration, whereas rapid denitrification of leaf litter from riparian trees suppressed autumn elevations in nitrate (Ledford et al., 2017). However, findings of Ramião et al. (2020) appear contradictory; with increasing nitrate concentrations observed along urban reaches and decreases along natural forested reaches.

3.3.2. Management Implications Related to the Secondary Question

In all settings, urban trees provide benefits by lowering TN and TP concentrations in soils and runoff and reducing nutrient transfer to waterbodies. Trade-offs are identified in impervious and riparian environments; and although based on limited evidence, these require specific management considerations.

The specific pathways of nutrient loss from leaf litter to urban rivers are important and unique. Impervious surfaces act as highly connected and ephemeral headwater conduits, with capacity to intercept and accelerate the transport of atmospheric pollutants and derivatives of leaf litter to waterbodies (Fork et al., 2018). From a planning perspective, this has a strong bearing on whether tree planting might be preferentially focused in permeable areas (Decina et al., 2018). More frequent street sweeping is recommended (Selbig, 2016), although risk of nutrient delivery from leaf litter will remain substantial even if undertaken every week. In summary, whilst there is considerable evidence for mechanisms by which water quality dis-benefits of street trees arise, at catchment scale the extent to which leaf litter export is exacerbated in street settings compared to urban parkland is currently unknown.

The R-studies show woodland buffers effectively preventing nutrient input to rivers, but they also illustrate complex trade-offs for water quality brought about by presence or absence of riparian canopies. Unshaded rivers may foster localized benefits in the growing season and reduce overall levels of net ecosystem respiration. They may however contribute to detrimental effects further downstream in urbanized river systems where nutrients are in excess. Photosynthetic uptake only represents a temporary sink of nutrients, and reaches fed by headwaters which have been warmed by direct sunlight and contain elevated phytoplankton biomass will become more susceptible to excessive eutrophication and its unwanted secondary impacts. Sudduth et al. (2011) reflectively summarize the difficulty and uncertainty in how to best manage urban rivers and riparian zones, which necessitates balance between enhancement of ecosystem function (demonstrated by faster nutrient uptake) and habitat restoration.

3.4. Synthesis of Overall Effects and Provision of Coefficients for Modeling Applications

The evidence collated for assessing the influence of woodland on nutrient losses to waterbodies reflects a heterogeneous mix of study types. These include comparative studies of different land cover (e.g., Nidzgorski & Hobbie, 2016), effects of land use change (such as establishment of NBS: e.g., Tirpak et al. (2019b)) and process studies along hydrological pathways. Whilst this provides for a diverse set of comparators and reference conditions, any significant benefits will all arise from the same mechanisms. These comprise an interactive set of hydrological and biogeochemical processes, whereby woodlands reduce precipitation inputs via interception, detain surface water and take up water and nutrients through the root system (Baker et al., 2021; Lucash et al., 2007). This serves to reduce runoff and the attendant nutrient transfers to waterbodies.

Summary presentation of woodland nutrient retention in Meso-studies (Figure 2d) involved standardizing results to a relatively small 20% change in total land use to forest. Standardization to 20% change reflected the weight of evidence in the papers passing the screening process. The evidence base only covers relatively small variability in landcover in mixed urban settings with a paucity of studies from catchments strongly dominated by one land use. As the range of land use assemblage comprising the evidence was limited and because we took measures to exclude from the synthesis any data reflecting the most polluting sources of nutrients (intensive agriculture and wastewater effluent), we assume: (a) stream nutrient response to a change in woodland coverage to be linear and independent of the initial proportion of woodland, and (b) insubstantial locational variability in the sensitivity of stream nutrient response to change in woodland. Interpretation and application of the findings is only recommended in environments within the bounds covered by the evidence base. Furthermore, we stress that carrying out a synthesis across studies involves bringing together information that is heterogeneous in many respects. These heterogeneities encompass a range of temporal characterizations of water quality that have contrasting levels of focus on storm events as opposed to baseflow conditions. The type of ground cover beneath canopies may also act as an important factor controlling water quality response, yet few studies identify whether underlying ground is permeable let alone if the surface is thickly vegetated or bare soil. These features introduce substantial known and unknown sources of uncertainty and we emphasize the need for caution when using the synthesis.

In order to quantify likely benefits of NBS, geospatial models of urban areas are often used. Typically, individual model applications require single values to define inputs or retention coefficients rather than a distribution. Spatial models typically use nutrient delivery ratios, which reflect the retention capacity of specific land use types. InVEST includes urban and sub-urban land uses. In a similar manner, the SWMM model requires inputs of typical pollutant runoff loadings for a more detailed set of specific urban landuses. For evaluation of prospective urban tree planting using numerical modeling approaches, we recommend incorporating findings from our synthesis as follows:

- To quantify reduction of nutrient loads in runoff due to trees, use Figure 2b to define retention coefficients, scaling them accordingly to represent the proportion of a land use unit being converted to woodland.
- As process-based catchment hydrological models such as SWMM include runoff dynamics and river network representation, validate the level of reduction in nutrient concentration simulated downstream at small urban basin outlets against summary information from Micro-studies (Figure 2d).
- In cases where modeling covers a larger downstream spatial extent, use Micro-studies to characterize urban tributary inputs, by applying Figure 2d to quantify the influence of differing tree coverage in contributory basins on nutrient concentrations.

Benefits appear more limited at catchment scale (Figure 2d) than at plot scale (Figure 2b). For each permutation of study type (Micro- or Meso-) and nutrient (TN or TP) the following was undertaken to summarize benefit. For the subset of studies showing significant decrease, a single weighted mean percent change was calculated. As change is by definition unidentifiable in studies not showing significant benefit, these were attributed a change of zero. Therefore, to include consideration of the non-significant studies in the overall estimates of change, the single weighted mean percent change (for studies showing significant decrease) was multiplied by the weighted likelihood of decrease (WL: see Section 2.2).

Using the weighting approach, the overall summarized results of the meta-analysis are 44.2% and 47.0% decrease in mean concentrations for TN and TP respectively in Micro-studies. For Meso-studies the decreases in mean concentration are 15.7% and 12.6% respectively for TN and TP. Introduction of weighting slightly increases the mean estimate of change in all cases. Within the possible range (3–10), slightly higher quality scores were found for Meso-studies (mean: 7.5) than Micro-studies (mean: 6.6) although monitoring was typically less frequent in Meso-studies. The approach minimizes the influence of outliers, as does use of median values, which are also reported (Figures 2b and 2d). The weighted means are slightly higher than the median values, especially for TP Meso-studies. As well as those showing significant change, studies not showing significant change in TN and TP were included in derivation of medians. Prior expectation for scaling-up of results was that Meso-studies would show only one-fifth the level of retention in Micro-studies, based on the assumption that catchment-scale confounding factors such as other land uses and groundwater sources balance out. Greater than expected retention in Meso-studies arose, perhaps implying that riparian-related nutrient retention is substantial. This was especially the case for TN.

4. Conclusions

A number of conclusions are drawn from the review:

- The body of evidence identifying relationships between forest and water quality from diffuse sources in urban settings is relatively limited. This followed exclusion of numerous studies having tenuous relevance, which looked at wider chemical and ecological water quality impacts of land use change in larger mixed land use river basins.
- Benefits of urban tree planting are considerable. Weighted mean and median TN and TP concentrations are reduced by 39%–47%. Summarized findings can be incorporated into numerical models. In this context it is important to emphasize the wide range of response found and the substantial number of studies not identifying significant benefits.
- Although riparian tree planting reduces nutrient transfer to waterbodies, there is some evidence that it brings about a complex set of additional water quality benefits and trade-offs. This requires further investigation, especially the downstream consequences and for establishing a holistic picture of river health including for example, ecosystem metabolism estimates.
- Whilst effectively taking up nutrients, street trees are a source of rapid transport of degraded leaf litter. Albeit based on limited evidence, this can potentially be a very important pathway for TP to waterbodies. Establishment of NBS does not always have positive consequences for all affected ecosystem services, and the introduction of urban woodland, especially roadside planting, is no exception (Taguchi et al., 2020).
- The extent of the evidence about specific effects arising from trees in riparian and impermeable settings is limited to very few articles, and the need for further studies of these environments is very strongly recommended.
- Overall, rather than providing robust conclusions, these are preliminary findings from limited available data and set a strategic forward-looking direction for necessary activity in the field.

As priorities for future research we recommend:

- Given the relative dearth of information, further gathering of general evidence for links between urban woodland and attenuation of polluting nutrients. For effective synthesis, it is important that future studies are suitably designed to conform to the uniformity of reporting we have outlined.
- Investigation of the contribution of leaf litter to nutrient leaching especially in parkland and riparian environments. This would place understanding of leaf litter leaching on impervious surfaces in wider context.
- Catchment-scale studies, which discriminate between street trees, parkland trees and riparian trees when attributing land use influences on water quality.

Appendix A

Word cloud and descriptive evidence base arising from literature search (Figure A1 and Table A1).

Figure A1. Word cloud.

Table A1
Evidence Base for 40 Papers Passing the Full-Text Screening Process

Source	[1]Study type	Forest as NBS	Location	[2]Inclusion of modeling	[3]Evidence scores (A, B, C)	[4]Study category	[5]Summary findings	[6]Decrease in TN	[6]Decrease in TP
Alfonso et al. (2015)	QO	N	Yongin, South Korea	N	1, 2, 1	Meso	(A) Speciation of P studied in watersheds with land use gradients. TP leaching in 100% urban watershed higher than in mixed land use watersheds. Mean concentration across 6 storms over 5 months summer period is 0.58 and 0.84 mg TP L^{-1} in 59% and 0% forest respectively. Forest reduces P concentration by 30%.		Y, 10
Allison et al. (1998)	QO	N	Melbourne, Australia	N	1, 2, 1	L	(A) Minimal leaching of nutrients from leaf litter into stormwater relative to total loads.		
Barr et al. (2017)	QO	N	Philadelphia, USA	SM	3, 1, 2	Micro	(A) Comparison of nutrient concentrations from green roofs with other NBS and other urban land uses. No significant difference in between woodland, grassland and mixed land use (44% impervious) for TN or NO_3. Woodland has 58% lower TP than grassland (or 28% lower than a 50/50 mix of grass and mixed).	N	Y, 58
Bratt et al. (2017)	QO	Y	St Paul Minnesota, USA	DM	2, 3, 3	L	(A) Stormwater outfall and leaf litter study. Based on litter bag losses from 10 g dry weight leaves, litter contributes negligible N but 40% of annual TDP to streams. Modeling enables catchment scale estimate of 3.4 kg $year^{-1}$ P leached (36% canopy cover) equates to 55.7 mg TDP m^{-2} canopy.		
Brett et al., 2005	QO	N	Seattle, USA	SM	3, 2, 3	Meso	(B) Watersheds with land use gradients. A 10% increase in forest at expense of urban reduces TP by 15% and SRP by 27%. Total change (within bounds of observations) shows reduced TP by 41% and SRP by 62%. N changes statistically insignificant.	N	Y, 30
Decina et al. (2018)	QO	N	Boston, USA	N	1, 2, 3	Micro	(B) Study of sequestration of nutrients by tree canopies compared to bulk precipitation. TN 150% and TP 500% higher loads in throughfall than bulk precipitation. In soil solution no significant concentration difference (TN 15% higher).		
Denman et al. (2016)	QE	Y	Australia	N	2, 2, 3	Micro	(A) Street trees reduced storm runoff TN loads by 59% (84%) 85% and 82% for low medium and high wetness soils respectively.	Y, 70	
Haidary et al. (2015)	QO	N	Hiroshima, Japan	SM	1, 1, 3	Meso	(B) Subset of 5 highly urbanized catchments. Significant logarithmic relationships derived between forest and seasonal nitrogen species concentrations in wetlands.	Y, 18	

Table A1
Continued

Source	(1)Study type	Forest as NBS	Location	(2)Inclusion of modeling	(3)Evidence scores (A, B, C)	(4)Study category	(5)Summary findings	(6)Decrease in TN	(6)Decrease in TP
Hathaway et al. (2012)	QO	N	Raleigh, North Carolina, USA	N	2, 2, 1	Micro	(A) A range of storm sizes captured and EMCs calculated in non-point source urban environments. Increase in forest by 20% results in reductions for TP, TRP and TKN of 66% and NO_3 and NH_3 of 43% in runoff.	Y, 66	Y, 66
Jang and An (2016)	QO	N	Dongjin River, South Korea	N	3, 2, 2	Meso	(B) For sub-catchments of approximately 15% urban cover a 20% increase in forest at expense of arable leads to 31% and 10% reduction in TP and TN respectively.	Y, 10	Y, 31
Janke et al. (2017)	QE	N	Minneapolis and St Paul, USA	SM	3, 2, 2	L Meso	(A) Increase in street tree canopy fraction from 0 to 0.3 leads to approximately 100% increase in TP and 25% increase in TN (EMCs); this leaf litter effect which outweighs influence of trees on runoff reduction.	N	N
Janke et al. (2014)	QO	N	St Paul, Minnesota, USA	N	3, 2, 3	L Meso	(B) Litterfall an important source of particulate and organic nutrient forms, street canopy fraction an important predictor of TP in stormwater.	N	N
Kumar et al. (2016)	QO	N	Northern Virginia, USA	DM	3, 3, 2	Meso	(B) Water quality model (SPARROW) applied over 5-year period simulated reversion of non-point source urban pollution to forest. Taking subset of catchments with minimal agricultural influence a 22% increase in forest at expense of urban results in 11% (3% wet year 21% dry year) and 38% (20% wet 59% dry) less TIN and OP loads to waterbodies respectively.	Y, 10	Y, 35
Ledford et al. (2017)	QO	N	Syracuse, New York, USA	N	2, 3, 3	R	(B) Baseflow sampling fortnightly for 1 year along an urban stream without wastewater inputs only groundwater influences possibly carrying nutrients originating from leaky sewers. After 200 m of riparian shade autotrophic uptake of nitrate ceases. 0.8 mg N L^{-1} without uptake, 0.1 mg N L^{-1} with uptake. Riparian shade prevents filamentous algae. Some seasonal variation: leaf litter in autumn promotes denitrification (0.6 mg N L^{-1}).		
Li et al. (2018)	QO	N	Tianjin, China	DM	3, 2, 3	Meso	(B) Modeling study (SWAT) in per-urban watershed showed forest and urban to be nutrient sink and source landscapes respectively. 20% increase in forest at expense of urban results in load reductions of approximately 7% TN and 6.5% TP.	Y, 7	Y, 6.5

Table A1
Continued

Source	[1]Study type	Forest as NBS	Location	[2]Inclusion of modeling	[3]Evidence scores (A, B, C)	[4]Study category	[5]Summary findings	[6]Decrease in TN	[6]Decrease in TP
Lim et al. (2021)	QE	Y	Singapore	N	2, 3, 1	Micro	(A) EMC removal for TN of 46% and TP of 32% in modular bioretention system at low input concentrations. Efficiency depends on input concentrations. High concentrations may give higher removal rates especially for TP due to higher particulate fraction.	Y, 46	Y, 32
Lin et al. (2019)	QO	Y	Anji, China	N	1, 1, 3	Meso	(B) Study of microbial diversity in natural restored forest and degraded urban streams. No difference in TP, 50% lower TN under forested cover.	Y, 10	N
Line et al. (2002)	QO	N	North Carolina, USA	N	2, 2, 3	R Micro	(A) Runoff storm events monitored in sites across urban and forest gradients. EMC reduction from residential to woodland was 80%, 7% and 38% for NO3, TN and TP respectively. A 12 m forest buffer reduces runoff EMC by 38% for TN and 18% for TP.	Y, 7	Y, 38
Matteo et al. (2006)	QO	Y	Springfield, USA	DM	1, 1, 2	R Micro	(A) Five-year GWLF modeling study simulated effectiveness of woodland riparian and road buffers. For 27%, 55% and 80% urbanized catchments paired TN and TP load reductions are 26.1% and 20.0%, 0.2% and 14.5% and 6.6% and 6.6% respectively.	Y, n/a	Y, n/a
Middleton et al. (2020)	QO	N	Perth, Australia	SM	1, 1, 3	Meso	(C) Reach scale and catchment scale analyses of 14 sites. Subset of 6 small urban basins do not show clear low or high flow effects of riparian or catchment forest for TP or TN (0%–11% forest in otherwise urban basins). Riparian woodland beneficial for TN. Only significant forest effect at catchment-scale is lower DIN at baseflow.	N	N
Moon et al. (2013)	QO	N	Daejeon, South Korea	DM	3, 3, 1	R Micro	(B) For two sub-catchments of over 15% urban cover, a reduction of TN and TP loads by 10% requires 70–300m and 60–140m deciduous tree buffer strips respectively. The width depends on catchment topographic characteristics. Evergreen buffer strips are more effective.	Y, n/a	Y, n/a
Nidzgorski and Hobbie (2016)	QO	N	St Paul, Minnesota, USA	DM	3, 3, 3	Micro	(B) Compared to turf grass P leaching was 33% and 59% lower per unit area under evergreen and deciduous trees respectively. With respect to grass, soil water concentration reductions for SRP are 55% and 81% for evergreen and deciduous respectively. They are insignificant for TDN and NO_3-N which showed lower N leaching in forest than turfgrass in 2012 but higher N leaching in 2013. Model-based scale-up of measurements to an urban sub-watershed.	N	Y, 81

Table A1
Continued

Source	[1]Study type	Forest as NBS	Location	[2]Inclusion of modeling	[3]Evidence scores (A, B, C)	[4]Study category	[5]Summary findings	[6]Decrease in TN	[6]Decrease in TP
Page et al. (2015)	QE	Y	Wilmington, North Carolina, USA	N	1, 3, 1	Micro	(A) Comparison of inflow and outflow shows EMC TN and TP to be reduced by 76%. Nitrate is reduced by 47%. This is comparable to conventional bioretention systems but suspended pavements do not impair tree health	Y, 76	Y, 76
Ramião et al. (2020)	QO	N	Portugal	SM	1, 1, 3	R	(C) Nutrient changes along river reaches studied. NH_4 showed large decreases. Any changes in P are unclear. Along an urban river a 0.75 mg NO_3-N L^{-1} increase per km occurred in an urban reach compared to a forest reach showing 0.25 mg NO_3-N L^{-1} decrease per km.		
Revelli and Porporato (2018)	QO	N	Durham, Minneapolis, Palermo and Serra Talhada	DM	2, 1, 2	Micro	(B) Ecohydrological model simulated enhanced uptake of soil nitrogen by urban street trees.	Y, n/a	
Selbig (2016)	QO	N	Madison, Wisconsin, USA	SM	3, 3, 1	L	(A) Sampled integration of EMCs to determine mass losses in storm sewer outfalls in two small urban catchments (50% impervious, 50% canopy) one with the other without leaf litter removal. Confounding factor of lawn fertilizer means N results unreliable. leaf litter and other organic detritus from trees contributes 64% of TP load to river, equates to 244 mg TP m^{-2} canopy. 66% of TP is TDP.		
Setälä et al. (2017)	QO	N	Helsinki and Lahti, Finland	SM	2, 2, 3	Micro	(B) Lysimeter studies showed 64% and 95% lower soil water loads of TP and TN in woodland compared to lawn. Woodland showed 50% less soil moisture (i.e. equating to 28% and 90% lower TP and TN concentration). Only effective reductions in 40–60 year old parks. Less benefit from older trees. Young parks are much less effective. Evergreen trees give large dis-benefits (TN and TP).	Y, 90	Y, 28
Shupe (2017)	QO	N	Vancouver, Canada	SM	3, 2, 3	Meso	(B) High spatial resolution stream water quality assessment with many repeat samplings. Overall differences in mean NO_3-N concentrations were 0.66 mg L^{-1} in urban dominated basins and 0.31 mg L^{-1} in forest-dominated basins.	Y, 53	N

Table A1
Continued

Source	(1)Study type	Forest as NBS	Location	(2)Inclusion of modeling	(3)Evidence scores (A, B, C)	(4)Study category	(5)Summary findings	(6)Decrease in TN	(6)Decrease in TP
Sudduth et al. (2011)	QO	N	North Carolina, USA	N	3, 2, 3	R	(C) Restoration involved removal of riparian trees to increase light to the channel leading to higher nitrate uptake velocities in restored stream reaches during summer. Temperature and canopy cover explained 80% of the variation. There were no differences in winter. Stream metabolism did not differ between stream types.		
Thornhill et al. (2017)	QO	N	West Midlands, UK	N	1, 1, 3	R	(B) Survey of ponds and their bordering landcover discriminated 4 types of pond and from statistical analysis showed that landuse at local scale was more important determinant than at catchment-scale. Two types related to local urban surroundings both showed higher nutrient concentrations. The more shaded urban pond type had highest NH_4, with high algal biomass and poor macroinvertebrate diversity.		
Tirpak, Hathway & Franklin (2019)	QE	Y	Knoxville, Tennessee, USA	N	1, 3, 2	Micro	(A) Root uptake by trees in bioretention mesocosms is not significant. Magnitude of hydrological effects related to differences in tree species.	N	N
Tirpak, Hathway, Franklin, et al. (2019)	QE	Y	Knoxville, Tennessee, USA	N	3, 1, 2	Micro	(A) In suspended pavement bioretention systems with trees no significant difference found between inflow and drainage samples for all nutrient species.	N	N
Tsegaye et al. (2018)	QE	Y	USA	DM	1, 1, 1	Micro	(A) Infrastructure planning tool used to assess effectiveness of tree BMPs at reducing storm runoff. Derived respective TP and NO_3-N model export coefficients of 0.15 and 0.17 for forest and 0.39 and 0.6 for road.	Y, 72	Y, 62
Van Looy et al. (2013)	QO	N	France	N	3, 2, 3	R	(B) Study of influence of different widths of riparian tree canopies on nutrient concentration. An extensive national study that did not specifically focus on urbanized sites. 60% riparian forest cover in the 10 m buffer is needed to achieve good physicochemical status. For wider 30 m buffer, riparian forest coverage above 45% appears necessary.	Y, n/a	Y, n/a

Table A1
Continued

Source	[1]Study type	Forest as NBS	Location	[2]Inclusion of modeling	[3]Evidence scores (A, B, C)	[4]Study category	[5]Summary findings	[6]Decrease in TN	[6]Decrease in TP
Viau et al. (2011)	QO	N	Hawaii, USA	SM	3, 1, 3	Meso	(C) Survey related land use to bacterial concentrations and water quality. Of sites with low agricultural contribution site with 79% urban has highest DIN (388 μg N L^{-1}). At lower urban areas 18%–45% any decreasing DIN trend is unclear. Decreases in DIN related to forest percentage from 54% to 78% (around 150 μg N L^{-1}) to above 80% (below 100 μg N L^{-1}) were found.	Y, 40	
Wallace et al. (2008)	QE	N	Adelaide, Australia	N	1, 3, 2	L	(A) Leaching rates from litter of range of different tree species and grass cuttings. Very high (approximately 700 mg kg^{-1} SRP) leaching released from London Plane and river red gum litter compared with other trees species and grass.		
Wang et al. (2018)	QO	Y	Swan Coastal Plain, Australia	SM	3, 2, 3	Micro	(B) Groundwater DON concentration comparison in urban, pastural and natural area. Statistical modeling and sensitivity analysis showed lowest DON is located in natural region, higher in urban, highest in pastural. In addition, riparian trees showed relatively lower DON than in both shallow and deep samples of the groundwater but these represent a combination of pasture and urban samples.	Y, 55	
Xu et al. (2021)	QO	Y	Shanghai, China	N	2, 2, 2	R	(B) In stretches along an urban river, proportions of forest and wetland in riparian zones of 100, 200, 400, 800 m consistently show negative relations with nutrient concentrations whereas agriculture and industry show positive relations. The strength of the relationships are greatest for the narrower buffers.	Y, n/a	Y, n/a
Zhang et al. (2019)	QO	N	Jiangsu, China	DM	3, 2, 3	Meso	(B) SPARROW model used to identify TP sources in headwater watershed. Forests were main sources of P loads from higher elevations, but cropland was the main lowland contributor. Forest-to-tea and cropland-to-urban conversions over time have enhanced runoff and promoted more P loss.		Y, 16

Table A1
Continued

Source	[1]Study type	Forest as NBS	Location	[2]Inclusion of modeling	[3]Evidence scores (A, B, C)	[4]Study category	[5]Summary findings	[6]Decrease in TN	[6]Decrease in TP
Zhao et al. (2007)	QO	Y	Wuhan, China	N	2, 2, 3	Micro	(A) Pollutant loading rates for stormwater runoff were lowest for the woodland region, highest in the animal yard. Relatively the woodland site (around 75% tree coverage) had much lower EMCs for TN, TDN (3–4 times lower) and similar or slightly lower TDP. Within impervious sites, lower (22% compared to 51%) tree coverage has higher annual TN (108 compared to 68 kg hm^{-2}). Similarly, in the animal yard area, site with more trees (30% compare to 9%) has less annual nutrient loss (61–88 kg hm^{-2}).	Y, 46	Y, 39

Note. Where: (1) QE = quantitative experimental, QO = quantitative observational (2) MD = deterministic model, MS = statistical model; (3) A = monitoring period score, B = monitoring frequency score, C = number of sites score; (4) study categories are L (leaf litter) Micro (plot-scale) Meso (catchment-scale) and R (riparian) (some studies span multiple categories); (5) as related to Q1 ("How much improvement in water quality in urban runoff arises from a specified increase in urban forest?") rather than overall findings; representative mean concentrations determined from the following categories of result output: (A) event mean concentration (e.g., from storm runoff), (B) annual mean, (C) campaign-based mean (e.g., seasonally targeted); (6) decrease or no change in mean concentration due to forest establishment relative to mixed urban fabric, in most cases only applicable for Micro- and Meso-studies (significance (Y/N), % (with "n/a" entered where level of change not quantifiable), for Micro- and Meso-studies entries are blank where the pollutant was not studied). TN = total nitrogen, TP = total phosphorus, EMC = event mean concentration, TDP = total dissolved phosphorus, SRP = soluble reactive phosphorus, TRP = total reactive phosphorus, TKN = total Kjeldahl nitrogen, NO_3 = nitrate, NH_4 = ammonium, NH_3 = free ammonia, TIN = total inorganic nitrogen, OP = organic phosphorus, TDN = total dissolved nitrogen, DIN = dissolved inorganic nitrogen, DON = dissolved organic nitrogen, BMP = best management practice, NBS = nature based solution, For further details of process-based models cited (SPARROW, GWLF, SWAT) see source reference. Full references are listed at the end of main article.

Data Availability Statement

All data derived from published articles for use in data mapping exercises and meta-analysis are provided in Appendix Table A1. The data on which this article is based are available in Alfonso et al. (2015), Allison et al. (1998), Barr et al. (2017) Bratt et al. (2017), Brett et al. (2005), Decina et al. (2018), Denman et al. (2016), Haidary et al. (2015), Hathaway et al. (2012), Jang and An (2016), Janke et al. (2017), Janke et al. (2014), Kumar et al. (2016), Ledford et al. (2017), Li et al. (2018), Lim et al. (2021), Lin et al. (2019), Line et al. (2002), Matteo et al. (2006), Middleton et al. (2020), Moon et al. (2013), Nidzgorski and Hobbie (2016), Page et al. (2015), Ramião et al. (2020), Revelli and Porporato (2018), Selbig (2016), Setälä et al., 2017, Shupe (2017), Sudduth et al. (2011), Thornhill et al. (2017), Tirpak et al. (2019a), Tirpak et al. (2019b), Tsegaye et al. (2018), Van Looy et al. (2013), Viau et al. (2011), Wallace et al. (2008), Wang et al. (2018), Xu et al. (2021), Zhang et al. (2019) and Zhao et al. (2007).

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