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PERSPECTIVE ESSAY

Resolving intractable soil constraints in urban forestry through research–practice synergy

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Abstract
In compact urban areas, grey infrastructure tends to prevail over green infrastructure. The tight urban fabric challenges tree growth and restricts development of greener and healthier cities. The admirable forest-city goal demands innovative methods and solutions tailor-made to tackle inherent constraints. Research findings could be more proactively transformed and transferred into practices. The aerial tree growth space, relatively less difficult to ameliorate, attracts more attention. The more intractable subterranean constraints of confined soil volume acutely restrict root growth, root spread and tree health and contribute extensively to premature decline and tree hazard. Soil surface sealing by impermeable paving is associated with compaction, organic matter deficit, low nutrient and water holding capacity and meagre nutrient stock. Scanty application of research findings has kept practice quality at a low level, rendering the persistent soil problems in the bane of urban forestry. A systematic survey of state of play provides hints on novel solutions derived from existing knowledge and proposes new research practice. A package of measures with generic connotations has been distilled from the survey of chronic, critical yet widely neglected urban soil management issues. Urban forest managers and researchers can jointly adopt out-of-the-box thinking and generate actionable translational research. Policy makers and practitioners can more promptly be informed by new harvests of research–practice synergy. Intimate and reciprocal interactions between science and practice can be proactively nurtured to raise the quality of urban landscape.

Keywords Urban soil constraint · Bane of urban forestry · Soil volume limitation · Soil sealing · Re-naturalization in urban forestry · Landscape altruism

1 The intractable soil constraints and the knowledge–practice gaps

In dense city areas, the artificial paving and structures dominate the land cover (Arnold and Gibbons 1996, pp. 245–247; Salvati et al. 2016, pp. 424–425). Trees are sequestered and literally squeezed out of the compact built-up fabric (Jim et al. 2018, pp. 3–6). The conflicts between trees and the urban matrix have attracted the attention of urban forest researchers (McPherson et al. 2001, pp. 22–23; Jim and Chan 2016, pp. 77–79), often focusing on the above-ground part and neglecting the below-ground soil component (Haan et al. 2012, pp. 318–319; McGrath and Henry 2014, pp. 111–113).

The limited urban soil management tends to concentrate on chemical properties, especially soil fertility, echoing a legacy from agricultural practice (Sarah et al. 2015, pp. 395–396; Musielok et al. 2018, pp. 274–276). The physical soil properties have been studied extensively by researchers, yet they are commonly neglected at the practice front (Perry 1994, pp. 4–7; Sanders and Grabosky 2014, pp. 302–303). The critical tree growth issues include soil structure, aggregate stability, bulk density, porosity (Jim 1998a, pp. 237–242; Puskás and Farsang 2009, pp. 270–271), soil volume restriction and soil sealing (Jim 2017, pp. 274–278; Just et al. 2018, pp. 143–144). Their prevention and amelioration have remained scanty and ineffectual (Koeser et al. 2013, pp. 655–656).

The lack of soil volume for tree roots is a common problem facing tree managers in compact urban areas (Urban et al. 1988, pp. 59–61; Casey Trees 2008, pp. 2–3; LANDCOM 2008, pp. 16–18). The critical soil attributes, associated constraints and consequences on soil properties and

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root growth are summarized in Table 1. The gaps between current knowledge and practice are identified in the same table. Some notable cases of soil limitations leading to poor tree growth and tree collapse are depicted in Figs. 1, 2, 3, 4, 5 and 6.

1.1 Natural composition

Soil volume restrictions could be inherited from pre-urbanization soil profiles. Natural soil may contain plenty of stones, subsurface stone layer or stone pan to impede air and water movement and root growth (Table 1a). The effective soil volume for roots is confined, thus limiting the capacity to supply plant available water and nutrients. Root growth is correspondingly suppressed in terms of density, spread and vigour. The limited root extension, especially of strong structural roots in the lateral direction, jeopardizes tree anchorage. The presence of large boulders or a shallow rocky base is even more restrictive by imposing physical barriers to roots. Too much sand- or clay-sized particles bring extreme soil textures which are unfavourable to moisture storage and supply.

Existing research findings offer practical solutions (Table 1a). The site soil can be improved by ameliorating the soil restrictions or by replacing poor-quality soil with an imported soil mix prepared according to a dedicated urban tree soil specification. Subsurface or surface drains can be installed before tree planting in conjunction with sustainable urban drainage design. Planting site design can tackle some negative issues, such as raising the soil level using imported soil to tackle difficult stony or rocky problems. Selecting tree species that can tolerate the stresses allows planting without substantial ameliorative measures. The key concern is whether practitioners can make good use of the knowledge base and translate it into practices to resolve inherent shortcomings at the site planning, design and pre-planting stage.

1.2 Material organization

Soil volume could be confined by organization of materials (Table 1b). Soil materials could be densely packed due to natural but more often artificial causes. If the bulk density exceeds the extreme threshold of about 1.9 Mg/m^3, soil moisture storage and transmission, aeration and root growth are hampered (Jim and Ng 2018, pp. 368–369). The packing density of soil in the urban setting is often increased considerably by intentional compaction to satisfy engineering stability requirements. Sometimes, the increase in density is due to trampling by pedestrian or vehicular traffic (Jim 1998b, pp. 149, 1998c, pp. 174–176, 1998d, pp. 687–689).

Textural discontinuity commonly occurs in disturbed sites where soil materials of different particle size distributions are laid down in clearly demarcated layers. The sharp textural interface blocks downward water movement until the upper layer is saturated (Hill and Parlange 1972, pp. 699–700; Craul 1985, pp. 337–338). It implies that light rain or irrigation does not allow water to enter the lower layer, whereupon root growth is confined mainly to the upper layer with little penetration into the lower part (Weaver and Stipes 1988, pp. 111–112). A high water table reduces the effective or usable soil depth as the continually wet soil is avoided by tree roots.

A naturally shallow solum has less usable soil volume (Table 1b). Subsurface hardpan could be formed by natural pedogenesis due to translocation of fine clay-sized materials from upper horizons and concentrated deposition in a lower horizon, often associated with in situ cementation. The hardened and dense layer restricts water, air and root penetration. These inherent limitations need to be identified by soil assessment before planting with the help of trained personnel. A simple field method could be developed to evaluate suitability of site soils for tree planting based mainly on available soil volume and key soil quality attributes (Handkard et al. 2005, pp. 203–205; Scharenbroch et al. 2017, pp. 202–204). Soil amelioration such as deep ploughing, fracturing and subsoiling can tackle the problems (Sax et al. 2017, pp. 151–152). If the site soil is too poor, replacing by a well-prepared soil mix can enhance tree growth (Watson et al. 1996, pp. 169–170). The extensive experience in agricultural tillage in terms of method and machinery could be more proactively transferred with suitable modifications to urban soil management (Craul 1991, pp. 26–27).

To prevent the above restrictive properties due to material organization from dampening tree growth in the long term, the ample basic research in soil science regarding impacts on tree growth can be translated into practical measures (Table 1b). Additional research practice may be necessary to convert scientific findings to practical mitigation measures, with reference to soil amelioration and choice of species to match site conditions. Knowledge on root growth habits and requirements of urban tree species could be enlisted to match species to site constraints. In the global south, such knowledge unfortunately is insufficient, and relevant research capacity and funding are needed to fill the gap (Jim 1990, p. 1–6).

1.3 Structure and porosity

Soil volume available for edaphic functions and root exploration is often limited internally at the micro-scale (Kozlowski 1999, p. 600) due to inadequate porosity (Table 1c). If soil structure is inherently unstable due to shortage of aggregating agents, notably humus, it is susceptible to degradation by external forces (Quirk 1978, pp. 6–8). Often, the soil structure could be damaged during soil handling and storage (Dhar et al. 2018, pp. 4–5). Poorly structured soil suffers

Table 1 Main neglected physical constraints of urban tree planting and proposed research–practice agenda to fill the knowledge–practice gaps

		Consequence													Knowledge-practice gap					
		Soil									Root									
Soil attribute	Constraint	Confined soil depth	Confined soil width	Limited available moisture	Restricted infiltration	Restricted permeability	Restricted evaporation	Poor drainage	Limited aeration	Elevated soil temperature	Root suppression	Shallow rooting	Poor anchorage	Cracked & heaved paving	Basic research	Planting site design	Drainage design	Soil amelioration	Soil design	Tree species selection
(a) Soil volume restriction: Natural composition	Stony soil			✓							✓		✓			×		×		
	Subsurface stone layer	✓									✓	✓	✓			×		×		
	Large boulder	✓	✓	✓							✓		✓			×				
	Shallow rocky base	✓		✓				✓			✓		✓			×				
	Excessively sandy soil			✓							✓		✓					×		×
	Excessively clayey soil			✓				✓	✓		✓		✓				×	×		×
(b) Soil volume restriction: Material organization	Dense or compacted soil	✓		✓	✓	✓		✓	✓		✓	✓	✓	✓	×			×		
	Textural discontinuity			✓		✓		✓			✓	✓	✓		×			×		
	High water table	✓						✓			✓	✓	✓		×		×			×
	Shallow solum	✓		✓							✓	✓	✓	✓				×		×
	Subsurface hardpan	✓		✓		✓		✓			✓	✓	✓					×		
(c) Soil volume restriction: Structure & porosity	Unstable aggregates			✓	✓	✓		✓	✓		✓		✓		×			×	×	
	Limited total porosity			✓	✓	✓		✓	✓		✓		✓		×			×	×	
	Lacking macropores (>60 µm)				✓	✓		✓			✓				×			×	×	
	Lacking mesopores (0.2– 60 µm)			✓							✓				×			×	×	
	Lacking micropores (<0.2 µm)										✓				×			×	×	
(d) Soil volume restriction: Artificial installation	Buried rubble layer	✓		✓		✓		✓			✓	✓	✓					×		
	Buried paving	✓		✓		✓		✓			✓	✓	✓					×		
	Buried utility line	✓	✓								✓		✓			×				
	Buried utility duct	✓	✓								✓	✓	✓			×				
	Buried utility box	✓	✓								✓		✓			×				
	Basement	✓	✓	✓				✓			✓	✓	✓			×	×			
	Building foundation	✓	✓	✓				✓			✓	✓	✓			×	×			
	Concrete root barrier	✓	✓								✓		✓		×					
(e) Soil volume restriction: Planting site design	Small tree pit	✓	✓	✓							✓	✓	✓	✓		×			×	×
	Small container	✓	✓	✓				✓			✓	✓	✓			×	×		×	×
	Narrow tree strip		✓								✓		✓			×			×	×
	Shallow tree strip	✓		✓							✓	✓	✓	✓		×			×	×
	Narrow planter		✓								✓		✓			×			×	×
	Shallow planter	✓		✓							✓	✓	✓			×	×		×	×
(f) Soil sealing: Paving	Impervious pour concrete	✓		✓	✓		✓		✓	✓	✓	✓	✓	✓	×	×				×
	Impervious asphalt	✓		✓	✓		✓		✓	✓	✓	✓	✓	✓	×	×				×
	Clogged porous material	✓		✓	✓		✓		✓	✓	✓		✓	✓	×	×				
	Clogged pervious material	✓		✓	✓		✓		✓	✓	✓		✓	✓	×	×				
(g) Soil sealing: Soil degradation	Compacted soil in open unit pavers			✓	✓				✓		✓		✓		×			×	×	
	Compacted surface soil			✓	✓				✓		✓		✓					×	×	
	Surface crusting			✓	✓		✓		✓		✓		✓		×			×	×	

from limited total porosity due to pore collapse resulting in higher packing density. Pores could be literally squeezed out by soil deformation and volume shrinkage to restrict root growth (Ley et al. 1995, p. 140–141). A healthy soil needs a balance distribution of three pore classes to fulfil key soil functions (Jim and Ng 2018, p. 368). They include macropores (> 60 µm), mesopores (0.2–60 µm) and micropores (< 0.2 µm). Compaction tends to reduce macropores which are essential for infiltration, drainage and aeration, as well as mesopores for storage and supply of plant available moisture (Jim and Peng 2012, p. 10).

Present understanding of the physics of porosity has remained limited at the practice front (Table 1c). Pertinent research findings are rarely noticed by practitioners and have hardly been converted to practices. Researcher can close the knowledge–practice gap by rendering the findings understandable and usable by practitioners. Appropriate segments of existing knowledge body can be extracted and applied to soil preparation and management to achieve optimal pore distribution. Deeper translational research can improve practice to ameliorate or prevent these problems (Jim 1998a, pp. 237–242, 1998b, pp. 241–242, Ampoorter et al. 2011, pp. 1741–1742).

Appropriate soil design can prevent their occurrence, and soil amelioration before tree planting can bring relief. Prescriptions for stable soil structure and porosity can be included in relevant professional standards and guidelines. Compost and other organic amendments (Oldfield et al. 2014, p. 270; Layman et al. 2016, pp. 29–30) and site naturalization (Jim 2003a, pp. 100–101; Millward et al. 2011, pp. 269–274) can be employed to rehabilitate degraded soil. The common use of prepared soil mix in landscape planting calls for research practice to enhance composition, property and preparatory method. As far as practicable, locally available materials should be used, and hence, the soil recommendations can be place specific. It is important to develop specifications for material and management to sustain long-term soil structure stability.

1.4 Artificial installation

Soil volume is often confined due to artificial causes imposed by soil disturbance during urban development, entailing truncation, burial, mixing, grading or improper planting site preparation (Scharenbroch et al. 2005, pp. 289–292) (Table 1d). Construction rubble or imported soil materials are often deposited to raise the grade of a development area. Many cities, especially the old ones, are literally built on multiple layers of debris laid down in different historical periods (Gunnerson 1973, pp. 233–235). Sometimes, rather intact old paving is covered by overburden materials. These relic wastes of civilization can render the soil materials unsuitable for landscape planting. Besides common stone-sized obstructions, lime and cementitious substances can raise soil reaction to alkaline pH to induce imbalance in available micronutrients (Jim 1998a, p. 242, 1998d, pp. 689–690, 1998e, pp. 176–177). The physical and chemical impacts of construction rubble on trees could be studied (Howard 2017, pp. 187–190) with reference to ameliorating brownfield sites for urban greening. Appropriate methods need to be developed to render such sites suitable for vegetation growth.

Some cities put utility lines underground, often in shallow depth under sidewalks or carriageways where they may conflict with tree roots (Randrup et al. 2001, pp. 212–214; Jim 2003b, pp. 89–91). The linear pipes and cables are accompanied by utility ducts, boxes and other subterranean installations. In dense urban areas, the underground space below the narrow sidewalk strip is often fully occupied by utilities to exclude trees (Table 1d). To install new lines or maintain old ones, trenches are frequently excavated to impose grave damages, especially to roots of roadside trees. Roots repeatedly cut and injured by trenching bring weak, unstable and hazardous trees. In compact urban areas, the basement of buildings may extend into the sidewalk strip to conflict with tree planting by restricting the soil volume. Building foundations bring similar usurpation of the subsurface space. Sometimes, concrete baffle root barriers are installed to prevent rooting in the utility belt to block root spread.

Most tree growth limitations due to subterranean utilities could be avoided by planting site design (Bieller 1992, pp. 77–78). Application of existing knowledge may resolve most problems (Table 1d). Deeper research practice could refine the preventive and mitigation materials and techniques. The underground utilities can be regimented by confining them to a well-defined utility corridor, preferably enclosed in a dedicated utility duct. Separation of utility and rooting zones can eliminate the common destructive impacts on roadside trees. In compact city areas with high-density buried utilities, a dedicated utility tunnel can be built under the carriageway to improve installation, maintenance and removal and eliminate conflicts with trees.

The long-term cost-effectiveness of innovative roadside infrastructure can be assessed by applied research vis-à-vis the full cost of the conventional approach to include negative impacts of frequent road opening (Table 1d). The inconvenience and compromised safety to road users, additional burden of maintaining and replacing unhealthy trees, and loss of ecosystem services that could otherwise be furnished by robust trees can be factored into the computations and deliberations. The logistics of roadside strip design and management, involving multiple parties with divergent concerns and priorities, can benefit from research practice on system science and public administration. Contributions of the urban green infrastructure should not continue to be overshadowed by transport needs of roads. The domination of the grey infrastructure and accompanied functions could be suitably diluted by environmental-ecological needs of the community (Svendsen et al. 2012, p. 6). To fulfil these objectives, a high-order, timely and sustainable coordination–cooperation regime cannot be more strongly emphasized.

1.5 Planting site design

Urban trees are sometimes planted in small tree pits, planters or containers (Table 1e). Some tree pits are tenaciously adhering to the anachronistic standard of about 1 m by 1 m in area and 1 m depth. Such a tiny amount of non-compacted soil, surrounded by heavily compacted soil prescribed by engineering specification, traps tree roots in a tiny soil volume described aptly as the teacup syndrome (Craul 1985, p. 337). The victim tree with stifled root system remains weak and unstable to demand lots of care, defying the very purpose of tree planting. Tree containers often suffer a similar fate, being tiny and suitable to shrubs rather than trees. Tree strips and planters are often too narrow and shallow to trap roots which are prone to entanglement, circling and girdling problems. The impermeable base of containers and planters incurs impeded drainage. In strong wind, the large trees planted in confined soil volume with limited root spread are prone to collapse (Figs. 1, 4, 5 and 6).

The design of tree planting installations should adopt out-of-the-box thinking (Table 1e). Planting practice can adopt measures to prevent blocking of root spread by unsuitable soils. General guidelines on the minimum amount of rootable soil volume need to be more assiduously applied to urban planting practice (Kopinga 1991, pp. 58–60). The rooting patterns of common urban tree species can be more extensively studied to provide a reliable basis to estimate rootable volume requirements. Tree pits can be enlarged in one direction at narrow planting sites and in two directions if space is available (Lindsey and Bassuk 1991, pp. 145–146; Watson et al. 1992, pp. 133–134). Relatively large planting sites can be equipped with super tree pits to bring superior tree performance (McConnaughay and Bazzaz 1991, p. 100; Bühler et al. 2007, p. 331). The temptation to insert a cluster of small tree pits instead of a few super ones should be resisted. Similarly, tree strips and planters can be widened and deepened as far as possible.

More importantly, tree pits and strips do not need to be consigned traditionally and invariably as completely isolated entities (Table 1e). The ample means to join and share soil volume can be earnestly explored. Different versions of subsurface soil connectors can be installed to allow roots to spread out of constricted soil volume and co-use contiguous and proximal soil volume (Jim 2017, pp. 276–278). The idea of *landscape altruism* can be expounded by three cardinal principles proposed to resolve the long-standing enigma of urban forestry in compact cities. (A full-scale articulation of the principles of landscape altruism is certainly beyond the scope of this essay and will be provided elsewhere.) The first principle is maximizing *creation of rootable soil volume* where they do not exist according to conventional thinking. The second is maximizing *connection of rootable soil volume* between nearby soil bodies. The third is maximizing *sharing of rootable soil volume* between neighbour trees. Collectively, they generate a subterranean network of closely knitted rootable soil to be co-used by trees. Such a scenario is reminiscent of trees in a forest where the soil is liberally shared. In this sense, the proposed methods are tantamount to emulation of nature, to trigger re-awakening to *re-naturalization in urban forestry*.

To translate the above principles into practice, soil corridors, subterranean soil conduits or root paths can be inserted between adjacent tree pits, between tree strips, between tree pits and tree strips, and between tree pits and nearby open soil areas (Table 1e). Some kerbside car parking space can be recruited to form planting peninsulas to accommodate trees and to allow linkage with adjacent planting areas through soil connectors (Jim 2017, pp. 278–281). Practice-oriented research can be extended to these alternative or pioneering planting designs to provide sustainable rooting volume so as to extricate trees trapped in confined sites (Day et al. 2010, pp. 150–152). The size, shape, alignment and lining of soil corridors offer ample fodders for research practice. The irrigation, drainage, aeration and amendment of soil inside soil corridors need to be studied to optimize their application. The rooting pattern and behaviour of different tree species can also be assessed. It is high time that the major bane of urban forestry, inflicting millions of trees worldwide for many decades and yet remaining steadfastly neglected, can be effectively resolved by research–practice synergy.

1.6 Soil sealing by paving

The land cover of compact cities is widely sealed by impermeable materials (Arnold and Gibbons 1996, pp. 245–247; Jim et al. 2018, pp. 3–6). Especially at roadsides, planting sites are commonly sealed by paving made of impermeable pour concrete or asphalt which are seldom reinforced (Table 1f). Soil sealing is commonly associated with soil compaction to present a double jeopardy. Paving aims at providing a firm, smooth and stable surface for pedestrians and vehicles. The underlying soil has to bear the load of the users. To achieve these targets, the soil invariably has to be well graded and heavily compacted before laying the impermeable cladding (Jim 1998e, pp. 175–176). The unfavourable soil properties and tree growth problems due to compaction, explained in Sect. 1, are aggravated and amplified by surface sealing. In addition, the pavement sub-base, usually composed of gravels with the interstices filled by fine-grained soil materials, is heavily compacted to achieve high bulk density and minimum porosity (Jim 1993, pp. 36–38). As such, it is not amenable to root growth. Cases of excessively soil sealing around large trees leading to tree collapse in strong wind are shown in Figs. 1, 4, 5 and 6.

The subpaving ambience suffers commonly from multiple deficiencies in water, air and internal soil volume (porosity) (Just et al. 2018, p. 143). Under the circumstances, tree roots tend to venture into the thin crevice lying between the paving bottom and the soil surface where relatively more sustenance is available (Randrup et al. 2001, pp. 210–212; D'Amato et al. 2002, p. 278). Secondary thickening of these shallow and aberrant roots often cracks and heaves the paving to bring hazards to pedestrians (Day 1991, pp. 200–203). Close to the trunk base, the notably thicker structural roots may cause

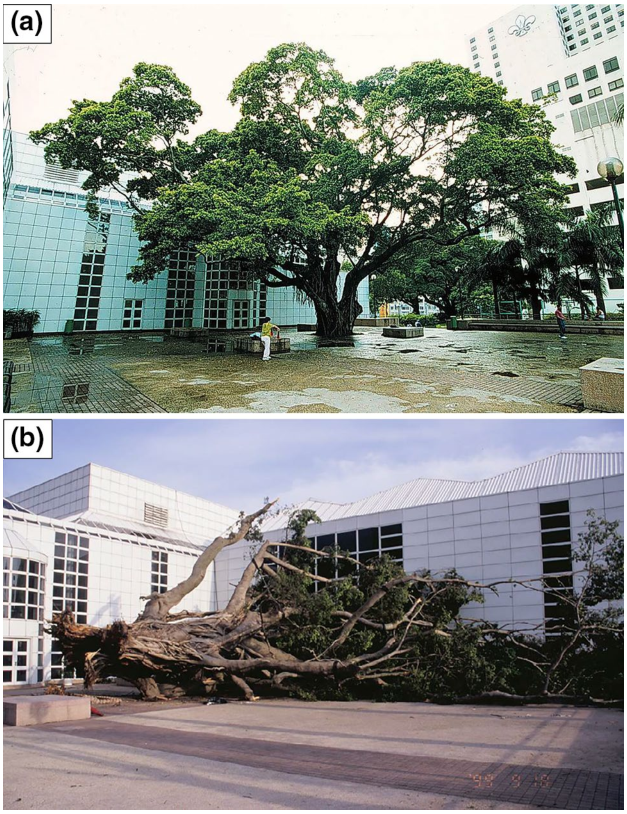

Fig. 1 **a** A valuable and rare heritage tree, a *Ficus microcarpa* (Chinese banyan) about 200 years of age, originally dwelled in an extensive site with open soil in a village area which subsequently became military barracks; in converting the site in the 1980s into an urban park, the original open soil was buried by a new 1 m thick of compacted soil layer and then sealed with impermeable pour concrete, trapping the giant tree in a tiny tree pit. **b** In 1999, a typhoon strike toppled the tree which exposed the badly decayed and degraded root system (Banyan Court, Kowloon Park, Hong Kong, C. Y. Jim photograph)

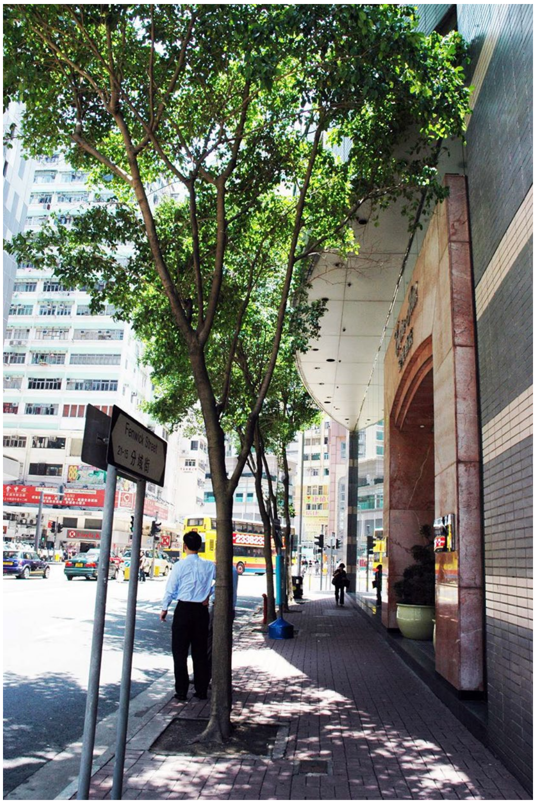

Fig. 2 These roadside trees (*Ficus benjamina*, weeping fig) planted in a compact urban area are trapped in tiny tree pits with soil volume restricted by the surrounding sealed and compacted soil (Johnston Road, Wanchai District, Hong Kong, C. Y. Jim photograph)

Fig. 3 This *Ficus microcarpa* (Chinese banyan) planting site is sealed by recently laid pour concrete up to the trunk base, even though the recreational open space has low pedestrian traffic (Homantin Estate, Kowloon, C. Y. Jim photograph)

more serious paving failure and deformation (Smiley 2008, p. 180). The common response of the road maintenance crew is replacing the defective paving with a new one, and in the process the culprit roots are cut away. The response of the victim tree is to generate new roots to compensate for the lost roots. Thus, the cracking–heaving problem would soon re-emerge to trigger another cycle of routine pavement repair. Evidently, the root of the problem should be tackled rather than tampering repeatedly with the symptoms.

Where a series of tree pits are installed along a paved roadside footpath, the soil between the pits is routinely compacted and sealed (Fig. 2). The planting strip at cramped roadside areas is often too narrow for trees, and it additionally suffers from sealed and compacted soil on both sides to confine root growth to a narrow soil belt (Fig. 6). In some ultra-compact cities such as Hong Kong or particularly crowded urban precincts in many cities, even areas designated for tree planting, including some parts of urban parks and other open grounds within development sites, are often sealed by hard paving (Figs. 1, 3, 4 and 5). Such extensive concreting of urban open spaces presumably aims at increasing the carrying capacity for park visitors and pedestrians

Fig. 4 A large *Ficus microcarpa* (Chinese banyan) collapsed when the old concrete paving of the recreational open space was undergoing repaving by new pour concrete; note the tiny tree pit and the limited development of lateral structural roots which are essential for tree anchorage (Homantin Estate, Kowloon, C. Y. Jim photograph)

Fig. 5 This huge *Ficus elastica* (Indian rubber tree) situated in a small local park is trapped in a tiny planter with shallow soil surrounded by hard paving; it was toppled by typhoon Mangkhut in September 2018 (Shekkipmei Estate, Kowloon, C. Y. Jim photograph)

and reducing the grounds maintenance burden. Usually, only small tree pits remain unpaved at such pervasively paved or intensively used areas (Fig. 4). In extreme cases, paving materials are laid all the way to the trunk base of trees (Fig. 3). Overall, to resolve such conflicts induced by the desire to co-use the limited land surface, pedestrian movement usually takes precedence over tree needs, resulting in restrictive soil surface sealing and confined soil volume.

The sealed soil, thus cut off effectively from the elements, can hardly perform satisfactory edaphic functions (Scalenghe and Marsan 2009; Just et al. 2018). Little rain and irrigation water can infiltrate into the covered soil. With meagre soil moisture replenishment, water-deficit stress to trees occurs frequently. Aeration is similarly restricted, which may elevate carbon dioxide concentration in the soil atmosphere to harm root functions (Gaertig et al. 2002; Viswanathan et al. 2011). Heat transmitted mainly by conduction from the warmed paving material can raise soil temperature to dampen root performance.

Fig. 6 A row of large *Ficus virens* (large-leaved banyan) are trapped in a narrow and shallow roadside planter; they were toppled by Typhoon Mangkhut in September 2018 (Wongtaisin Estate, Kowloon, C. Y. Jim photograph)

Moreover, the growth of most soil organisms under the pavement, including microbial decomposers, is hampered (Wei et al. 2014). Organic litter deposited on paved areas is usually swept away by street cleaners. As the subpavement soil material serves engineering load-bearing functions, it is deliberately prepared to have little or no organic matter, which implies meagre supply of nitrogen and phosphorus essential for tree growth. Nutrient supplies from dissolved and suspended materials in rainwater (wet deposition) and gravitational settlement of particulates (dry deposition) are severely limited. Decomposition, release of available nutrients and nutrient cycling cannot operate normally. A small amount of run-on water with some nutrient ingredients may enter the soil through the pavement cracks. Similarly, a small quantity of soil moisture may evaporate through the cracks (Timm et al. 2018, p. 84).

Sometimes, porous paving material is used to permit water and air passage through the small pores over its entire surface, or pervious material that allows movement through narrow seams between individual paving units (Volder et al. 2009, pp. 252–253) (Table 1f). A summary of recommended porous paving materials to enhance tree growth is given by London Tree Officers Association (2017). They include gravel with or without resin-binding, inorganic and organic mulch, rubber crumb, structural soil and permeable asphalt. Their differential effects on soil moisture infiltration, replenishment, storage and movement are subject to basic-cum-applied research with a view to optimizing planting site and soil design. These paving materials are designed to reduce soil sealing impacts by offering some connectivity between the atmosphere and the soil through the paver intermediary. However, the quantity and rate of fluid transmission through such sparingly permeable paving are limited (Indrawan et al. 2012, pp. 30–32). Inadequacies in design, material and workmanship in conjunction with site conditions and pavement use may clog the pores and seams. For instance, fine materials often migrate into the pores or interstices of the sand filling the seams to block the passages. Once they are effectively closed, for all intents and purposes, the consequence is tantamount to soil sealing. The sand bed of unit pavers can facilitate air and water movement, but their roles in water supply, aeration and root growth have remained relatively unknown. The long-term benefits of permeable paving to, respectively, newly planted and mature trees need to be ascertained by additional research (Volder et al. 2014, pp. 449–450).

1.7 Soil sealing by structural degradation

Soils not covered by paving could be degraded to become sealed (Table 1g). Some unit pavers have sizeable holes within and between individual members to supply more exposed soil in comparison with conventional ones. They can reduce the problems of soil sealing. However, the intervening soil could be compacted by trampling pressure, and the soil structure may fail due to rain splash and slaking processes to bring dense particle packing (Farres 1980, pp. 225–226). Similarly, a non-paved site could have its exposed soil damaged by trampling to cause surface soil compaction or aggregate breakdown to form a surface crust (Jim 1993, p. 43, 1998b, pp. 241–242). Soils with an inherently weak structure mainly due to inadequate organic matter and soils subject to drastic mechanical disturbance are prone to such degradation in material organization to induce a variant of soil sealing. Soils not well shielded by groundcover vegetation and organic litter are susceptible to aggregate damage by external forces.

The conventional paving materials, mainly concrete and asphalt, have been used extensively for decades. They could be improved by research practice to serve engineering functions as well as providing some permeability to facilitate tree growth (Volder et al. 2009, pp. 252–253; Fini et al. 2017, pp. 449–451; Table 1f). With looming climate change impacts, a design allowing water storage as well as infiltration can contribute to the cool pavement call (London Tree Officers Association 2017; Mota Daniel et al. 2018). A multidisciplinary research team with a practical inclination could develop a novel dual-purpose product. Unit pavers could be improved by increasing porosity or perviousness without compromising mechanical strength and stability. The materials for porous pavers or seams of pervious pavers could be enhanced to minimize clogging. The underlying sand bed of unit pavers could be modified to facilitate root growth. The amount of water that can infiltrate through the cracks in impermeable pavement, and the porosity and seams of unit pavers, could be ascertained by field experiments. The evaporation of water through these small openings could similarly be monitored in tandem with an assessment of their cooling effect on paving surfaces and the environs.

2 Strategies for closing the gap in resolving the constraints

Different disciplines and professions have endeavoured to connect research to practice, hoping that the two partners can interact intimately to bring mutual benefits and to advance in tandem (Van de Ven and Johnson 2006, p. 810). The massive environmental impacts imposed by humanity on the Earth system and the alarming consequences demand liberal application of ecological practical wisdom or ecophronesis (Xiang 2016, pp. 55–58) to bring effective and lasting solutions. The spirit of ecophronesis and ecopracticology advocated by Xiang (2010, 2018a and extended by Austin (2018) has inspired this analysis.

Nevertheless, in the specific realm of urban forestry, there is still a dearth of soil scientists who are interested in urban soil as a growth medium for urban trees. Moreover, there is a lack of soil science literature written specifically to cover the whole spectrum of socio-ecological practice, including planning, design, construction, restoration and management. Evidently, this status quo reflects a chronic shortage of soil scientists who are prepared to move to the research–practice interface of urban forestry, write practitioner-inspired, user-oriented and location-specific papers or books and establish dialogues with practitioners. Many soil scientists demonstrate only moderate interest in extending their research to the application domain.

On the part of the practitioners, they may find it difficult to understand soil science literature, especially topics that are theoretical and detached from real-world scenarios. The shortage of soil science education in urban forestry or arboriculture curricula may have contributed to the lack of the necessary knowledge to develop soil awareness and understand relevant references. As the acquisition of soil science knowledge requires field and laboratory training, it is difficult for practitioners to learn on their own. To bridge the knowledge–practice gap, the two parties need to and can move concurrently towards one another to meet at the midway position. Seven groups of issues leading to the lack of connection between researchers and practitioners have been identified (Table 2) together with proposed solutions to close the gap. They will be expounded in the ensuing paragraphs.

The above study of key urban soil constraints, besides identifying the critical knowledge gaps, has highlighted the common decoupling between research and practice. The wealth of soil science knowledge has only been sparingly translated into actual design and practice, and suboptimal soil condition is the norm rather than the exception. The infelicities account for inadequate understanding and lack of effective measures to resolve chronic soil volume and sealing constraints on urban trees.

2.1 Overhaul entrenched mindset and inertia

The conventional thinking and belief that research and practice are separate entities are still harboured in some quarters (Table 2a). Some researchers choose to stay on the theoretical high grounds and remain hesitant to descend to the practicality of the lowlands (Xiang 2017, pp. 2242). It should be clearly stated that such an anachronistic mentality is a hindrance to the attainment of a sustainable future. Professional practice that fails to advance with the knowledge frontier could fail to command due confidence and respect. Research often consumes plenty of resource, time and effort to accomplish. It is wasteful not to make good use of research findings to bring improvements in practice and hence in society at large. As both soil science and urban forestry have an inherent practical bent, the shortage of mutualistic convergence is all the more perplexing if not disappointing. It is necessary to raise awareness that research and practice are natural companions that should work jointly to advance science and applications in a united front. The useful synergies can be proactively promoted to cultivate the partnership mentality. Innovations in research can be fruitfully employed to bring associative innovations in practice. To boost the impetus of translational research, dedicated practice-based and practice-led research can be promoted (Candy 2006). The stakeholders can jointly realize continual improvement of the industry.

2.2 Foster the spirit and ethics of research practice

Basic and applied research could be accorded parity in terms of scholarly status so that researchers, including the young ones, can willingly and boldly espouse the latter (Table 2b). The translational activities can be supported, encouraged and incentivized by sufficient grants and other resources and by due recognition of outstanding achievements (FASEB 2012, p. 2). It is necessary to modify the compensation and promotion systems to reward both strands of excellence. Building a close linkage between industry and academia is conducive to generation of new ideas and funding. Dedicated guidelines on research–practice ethics should be promulgated, to be observed strictly by researchers. The multidisciplinary, interdisciplinary and transdisciplinary (MIT) approach could be realized in letter and in spirit by forming eclectic teams to tackle application topics from multiple perspectives.

2.3 Connect researchers and practitioners

Concrete measures can be instituted to bring researchers and practitioners closer together to share their aspirations and achievements (Table 2c). Collaborative efforts aiming at a common vision can raise the quantity and quality of socio-ecological practice. Two-way dialogues between the two germane groups could be encouraged, and sharing activities could be organized to nurture symbiosis, hybridization and generation of new ideas. Besides formal events, informal and serendipitous interactions are conducive to brilliant thoughts. Practitioners could be more actively drawn into the researchers' circuit, and vice versa, researchers could be pushed towards the practitioners' platform. The joint research strategy has to be geared towards the common practice target (McIntyre 2005, p. 359). To capitalize on the benefits of collaborative innovation, research teams could have members from both sides (De Silva et al. 2018, pp. 72–73). Funding bodies could play a pivotal role by encouraging or even requiring a joint research team for some projects with strong practice orientation.

2.4 Mine judiciously the useful research findings

Scholarly publications are a treasure trove of findings, some of which could be readily converted to practices (Table 2d). Professional journals or magazines often contain useful hints and stimulating insights of seasoned practitioners. Interesting ideas and inventions in patent documents could be explored for application potentials. Transferable and actionable knowledge with a practical bent could be targeted. It is necessary, however, to mine the right kind of materials. Some general guidelines could help the judicious selective exercise to separate wheat from chaff (Grimshaw et al. 2012, p. 4). Findings that have been rigorously verified by veracious scientific research and confirmed by multiple peer-reviewed studies are more credible. On the contrary, researches that are immature, using doubtful methods and drawing questionable conclusions should be excluded. Similarly, commercial purveyance of bad science and technology should be resolutely rejected. Thorough tests and trials should be conducted before new practices are adopted and promoted.

2.5 Update practices in proactive and timely manner

The research-to-practice stream is often beset by sluggish flow of information and inertia to change (Table 2e). Many

Table 2 Notable concerns and proposed research–practice agenda to facilitate transforming and transferring research findings to practice

Notable concern	Proposal to convert research to practice
(a) Overhaul entrenched mindset and inertia	Revamp deeply entrenched thinking and belief
	Raise awareness of common limitations and remedies
	Understand the synergy between research and practice
	Transform ingrained conservative inertia to change mentality
	Embrace the spirit of innovation and continual improvement
(b) Foster the spirit and ethics of research–practice	Foster and incentivize research–practice
	Accord parity to the status of basic and applied research
	Allocate more funding to research–practice
	Give due recognition to research–practice achievements
	Enhance research–industry partnership
	Ensure strict adherence to research–practice ethics
	Espouse multi-, inter- and transdisciplinary approaches
(c) Connect researchers and practitioners	Promote reciprocity between researchers and practitioners
	Draw practitioners into the research circuit
	Push researchers into the practitioner platform
	Organize joint activities to exchange ideas and concerns
	Offer opportunities for informal and serendipitous interactions
	Develop joint research teams for research–practice
	Funding bodies to encourage joint research team membership
(d) Mine judiciously the useful research findings	Mine research findings proactively for conversion to practices
	Scout for transferable-actionable knowledge with practical bent
	Accept findings verified by veracious scientific research
	Admit findings confirmed by multiple peer-reviewed research
	Refuse application of immature or questionable research
	Reject commercial purveyance of bad science or technology
	Conduct thorough tests and trials before adopting new practices
(e) Update practices in proactive and timely manner	Pump-prime the research-to-practice dynamics
	Identify hindrances in the research-to-practice stream
	Compress the research-to-practice time frame
	Establish task force in professional bodies to update practices
	Update professional standards on a regular basis
	Accelerate the pace of standard updating
(f) Disseminate methodically the modified and new practices	Identify progenitors to spearhead innovations
	Nurture pioneers to disseminate and demonstrate innovations
	Include research-to-practice skills in curriculum and training
	Organize workshops to pass on new skills and practices
	Require learning and using new practice in CPD[a]
	Publicize cases of successful and exemplary applications
(g) Communicate effectively to practitioners and stakeholders	Aim squarely at the expectations of the target audience
	Prepare and disseminate succinct practice guidelines
	Adopt popular science mode of communication
	Use plain language in communication
	Enlist simple charts, diagrams and tables to convey ideas
	Inform clients and consumers of the new practices
	Use the power of social media to reach stakeholders

[a] It denotes continuing professional development

organizations and individuals have worked with due diligence, yet the process has remained slow and limited in scope. The time lag and time duration to realize change are generally regarded as too lengthy. The latent or overt root causes leading to stalling, procrastination, protraction and resistance can be identified and bold steps taken to rationalize, streamline and resolve them methodically. The modus operandi could be overhauled to pump-prime the conversion processes and bring a faster turnover in the research-to-practice dynamics. The time frame to update professional standards could be compressed (e.g. City of New York Parks and Recreation 2009; British Standards Institution 2014). Professional bodies can establish a dedicated task force to shoulder the elaborate tasks and expedite the work flow and streamline the logistics. If necessary, cognate professional or trade bodies can form a joint task force to take care of cross-sector concerns.

2.6 Disseminate methodically the modified new practices

Once new practices have been thoroughly prepared and primed for adoption, they can be effectively and promptly disseminated to practitioners (Table 2f). A well-designed strategy could expedite diffusion and adoption of innovations by target recipients (Dearing and Kreuter 2010, pp. 3–4). The process could be spearheaded by progenitors. Some practitioners would expect to learn from leaders. Pioneers could be identified and nurtured to disseminate and demonstrate the new practices. New ideas could be promptly included in the educational curricula and training programmes. Professional bodies could demand members to learn new skills within a certain time period under their mandatory continuing professional development (CPD) schemes. A transitional period could be set during which old and new practices could co-exist, and after which only the new should be used.

2.7 Communicate effectively to practitioners and stakeholders

In transforming and transferring knowledge to applications, not just science is modified and metamorphosed to suit the recipients (Table 2g). The language could similarly be adjusted to suit the target audience. Step-by-step guidelines written in succinct structure and language would facilitate communication (e.g. Casey Trees 2008; LANDCOM 2008). The citizen science approach could convey complex or esoteric ideas in interesting and simple ways. Scientific terminology could be appropriately scaled down to follow the plain language mode as far as practicable. It is helpful to explain with simple and informative illustrations such as photographs, diagrams, charts and tables. The clients and consumers could be informed of new practices, as they could expedite the change to new skills by demanding them from practitioners. The power of social media could be proactively enlisted to transmit ideas quickly and extensively. The communicative power short video films could be more earnestly enlisted.

3 Conclusions

Greening cities are tantamount to bringing nature back to the laps of humans who have been detached from nature but have maintained the subliminal desire to connect with nature. The universal quest has been actively pursued in cities north and south, large and small, old and new, and dense and sparse. The achievements, varying greatly amongst urban entities, echo the broad spectrum of conditions and their permutations in the inter-related social, cultural, institutional, historical, economic and ecological realms. Extensive research findings in different geographical regions indicate that both the enabling and the stress factors share remarkable commonality across different lands. Urban forestry, as a relatively young discipline and profession, has relentlessly explored the materials and methods to facilitate tree growth in cities and to avoid and ameliorate the plethora of constraints. Researchers and practitioners have worked severally and jointly to find solutions to vexing problems.

Some common tree growth limitations, however, have remained tenaciously chronic if not entrenched. For decades, they have escaped the attention of managers and continued to suppress tree performance. They account for many cases of poor tree performance, premature decline, tree hazards and wasteful use of resources. The ill effects of soil volume constraint and soil sealing are quite pervasive and well known, yet they continue to be neglected, to the extent that they have become the bane of urban forestry. Following the present rather fixated thinking and operation, effective solutions do not seem to be forthcoming. The more departure from nature, the more effort is needed to maintain trees, and the less effective is the tree care input. Urban forestry could shed the yokes of this vicious circle by replacing ineffectual yet ingrained practices, and insouciance and indifference, with bold new practices that embody the fruits of research practice. Following nature's ways as far as practicable in the urban stress context would allow rejuvenation of naturalistic arboriculture, which could be defined as tree care practice that adopts and emulates natural environmental conditions to foster tree growth.

A survey of the literature indicates existing knowledge mainly in soil physics that could be converted without much difficulty to practice to relieve the ingrained problems. The study also identifies knowledge gaps that could be filled by the joint efforts of researchers and practitioners adopting the collaborative research–practice mode of inquiry. The synergies to be derived from the mutualistic partnership can be cultivated, with all members aiming at the common vision of healthier and safer trees. The intimate team can be well equipped to move blissfully from practice and for practice to beyond practice (Xiang 2018b).

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