

Allergenic tree pollen in Johannesburg and Cape Town as a public health risk: Towards a sustainable implementation framework for South African cities

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Abstract

South Africa's urban population is increasing, and in parallel, urban green infrastructure has shown an increase in alien tree species, e.g., mulberry (*Morus* sp.), oak (*Quercus* spp.) and plane trees (*Platanus* spp.) to name a few. This causes ecological problems since alien trees are often more water-demanding and competitive than indigenous trees, but they also increase the abundance of respiratory diseases often triggered by an allergic reaction towards the pollen of those alien taxa. In the current study, utilizing 7-day volumetric spore traps, we illustrate that the most abundant tree pollen in the two largest cities of South Africa, Cape Town and Johannesburg, is produced by alien trees with a high risk of allergenicity. This adds another aspect related to public health when evaluating plant species composition in urban forestry and urban ecology, which underlines the urgency of more intense monitoring. More importantly, this - for South Africa - newly emphasized risk for public health underlines the applicability of current directives (i.e., Spatial Development Frameworks (SDFs), localized Precinct Plans, Land Use Schemes (LUSs)) and implementation options in urban planning. Here, we present ideas that may be implemented in such a framework. From both a public health and an ecological perspective, it is recommended to plant indigenous trees like *Combretum erythrophyllum*, *Vachellia* and *Senegalia* spp. that have fewer ecosystem disservices, like a lower impact on public health due to lower allergenicity/lower pollen occurrence and providing more ecosystem services such as lower water needs.

1 Introduction

A substantial increase in urban population is forecasted for developing countries in the Global South, with the fastest predicted rate in Africa, by tripling the current population of 1.26 billion by 2050 [1]. This will lead to the development of unsustainable trajectories in urban areas and the large-scale transformation of valuable natural areas, putting development pressure on the green spaces in and around urban areas [2]. Different concepts are used in sub-Saharan Africa to describe these urban green spaces [3]. The concept of urban forest is often used for tree-dominated (woodland) communities in cities [3]. According to Escobedo et al. [4] the urban forest includes individuals and groups of planted and remnant natural trees in public (e.g., streets and parks) and private (e.g., gardens) urban areas (Fig. 1). The discipline of Urban Forestry was developed in North America and Europe and involves the management of urban trees and their resources for their 'physiological, sociological, economic, aesthetic, and ecological benefits' [5, 6]. Although Shackleton [7] described a paucity of urban forestry research in South Africa, recent advances include, e.g., the importance of planning and management frameworks [8], role of plant nurseries [9] and phenological studies of urban forests [10]. Another concept used for urban green spaces, more recently for South Africa, is urban green infrastructure (UGI) (Fig. 1). UGI includes the urban forest but also non-woodland habitats such as natural grasslands and wetlands, as well as man-made habitats such as lawns, green roofs, green walls, bioswales and rain gardens [3]. UGI definitions focus on the interconnectedness of the different green spaces and the various benefits (ecosystem services) they provide [3, 11]. The rationale behind the inclusion of the concept of 'infrastructure', according to Pauleit et al. [12] is to align planning for UGI with the grey infrastructure (transport, communication, water supply and wastewater systems) in terms of their specific benefits. The definition of UGI includes two core principles needed for its planning and development, namely multifunctionality and connectivity [3]. These two principals have a wide application in terms of social, economic, and ecological aspects, and UGI should be regarded as a complex social-ecological system [13]. Other UGI principles include the integration between the green and the grey infrastructure, relevance on multiple scales over the long-term and social inclusion of all stakeholders, also addressing environmental injustice [3, 12, 14]. Globally, several disciplines are studying UGI, with Urban ecology as the most prominent.

It is challenging to give one comprehensive definition for Urban ecology due to various and still evolving perspectives. Most definitions describe it as an inter- and transdisciplinary science involving several disciplines from the natural and social sciences and other relevant urban stakeholders such as planners, managers, policymakers and the general public (citizen science) [15, 16, 17]. For Wu [18], Urban ecology has become synonymous with Urban landscape ecology and is an important part of Sustainability science, therefore, he defines Urban ecology broadly as 'the study of spatiotemporal patterns, environmental impacts, and sustainability of urbanisation with emphasis on biodiversity, ecosystem processes and ecosystem services'. Although Urban ecology has mainly developed with a focus on Global North realities, principles and frameworks, an immense body of urban ecological knowledge has been developed for the Global South over recent years [19]. These studies have shown the uniqueness of urban areas and approaches in studying the Global South and identify specific research needs for advancing Urban ecology for the Global South. These needs include aspects such as addressing and integrating inequality and informality, disparities in terms of UGI provision, and specific links between UGI and human health [20]. Whether we use the concepts of urban forests or UGI, Urban forestry or Urban ecology, the provision and management of ecosystem services (ES) to make cities and human settlements inclusive, safe, resilient, and sustainable (see Sustainable Development Goal number 11) [21] is key.

Although ES is not a new concept, it gained prominence with the publication of the Millenium Ecosystem Assessment and refers to the direct and indirect benefits humans derive from ecosystem functions [22]. Urban ES are generally divided into four classes, namely supporting (e.g., biodiversity), provisioning (e.g., food, medicine, water), regulating (e.g., climate and flood regulation, carbon sequestration, water purification) and cultural/socio-economic aspects (e.g., tourism, recreation, mental and physical health, spiritual experience, and sense of place) [23, 24]. Research on urban ES is much further developed in the Global North but see Shackleton [25] (provisioning ES), Escobedo [26] (urban regulating ES), and Dobbs et al. [27] (cultural urban ES) for summaries of the state of urban ES research in the Global South. Research on urban ES in sub-Saharan Africa focuses more on provisioning and regulating ES, and there is a significant prominence in South African studies [11]. Although UGI and urban ES are included in some policy-relevant frameworks in Global South cities, the same cannot be said for the various negative effects that humans experience from the UGI/urban forest, known as ecosystem disservices (EDS) [28, 29]. Davoren & Shackleton [30] grouped the urban EDS experienced in the Global South into six classes, namely aesthetic, ecological, economic, health, psychological and cultural impacts. Although there is a paucity of research on all these EDS in South Africa, the lack of information on health impacts and specifically pollen-related allergies associated with the UGI/urban forest is significant (Fig. 1). Determining the effect of this and other EDS on human health and well-being is 'essential for environmental-decision making since it indicates

where management interventions are needed, by defining high-priority areas for control and determining the scale at which the UED should be managed' [30]. In UGI planning the management of EDS and improvement of ES would contribute to the development of healthy urban green spaces.

From an analytical point of view, even though tree planting might contribute to better respiratory health through the improvement of air quality and thermal comfort, certain studies list EDS produced by urban trees with respect to the suitability of planting specific tree species in cities [31], in which some tree species may also emit pollen aeroallergens [32] (Fig. 1). Pollen aeroallergens trigger symptoms of allergic diseases such as hay fever, conjunctivitis, itchy nose, wheezing, and asthma [33]. According to the World Allergy Organisation, between 10 and 30% of the global population shows allergic sensitisation to pollen and prevalence rates are increasing worldwide [34]. Studies on the effect of land cover on allergic and respiratory health are increasing. A study in England found that the presence of more tree cover, gardens, and green space in residential areas was associated with fewer asthma hospitalizations [35]. Another study, in Northern Belgium, documented that when exposure to airborne pollen or allergenic trees cannot be avoided during the pollen season, sensitized individuals may experience psychological stress [36]. Other studies find that children living with more green space near their homes suffer more from wheezing and have an increased risk of allergic rhinitis [37] and asthma [38].

Therefore, because allergic rhinitis has become a major respiratory disease, continuous aerobiological monitoring of airborne pollen was conducted to highlight the major contribution of plants growing in UGI to the development of allergy symptoms in the local populations [39, 40]. Analysis of airborne pollen provides valuable information on biological air quality, different plant taxa and the distribution of local vegetation [41]. In addition, categorising pollen sources and quantifying their contribution to the overall pollen spectrum can enable a more efficient design of urban parks and gardens in terms of the choice of species and avoid allergy risk [42]. New methods for 3D simulation, mapping, and urban planning are now being used in urban aerobiological research to assess pollen exposure [43, 44, 45].

Allergenic tree species are a new challenge for urban planners, designers and managers. The impact of allergic pollen on human health must be considered while choosing land cover vegetation, and non-allergenic pollen plants are the optimal options. Today, several studies focus on the potentially allergenic tree species in urban parks in the context of public health and allergenicity [46]. An index of urban green spaces to quantify the risk of tree pollen allergy has been developed in the Global North [45, 47]. This index is used for an assessment of the environmental health risk and an improvement in the planning and design of urban green spaces [48, 49, 50]. However, a large gap in our knowledge still exists regarding the state of the interactions between human exposure and the UGI for trends of high biodiversity across different biogeographical regions within the Global South, and more specifically for South Africa which is a major economic hub on the continent with a large degree of urbanization.

Numerous studies illustrate the high floristic diversity of UGI in South Africa, which stems from the introduction of ornamental species, both indigenous and alien [51, 52]. Species composition is determined based on local investigation of airborne allergenic pollen and baseline survey on vegetation. Furthermore, UGI are characterized by the abundance of allergenic alien species introduced from the northern hemisphere as ornamental trees, including cypresses (*Cupressus* spp.), plane trees (*Platanus* spp.), pines (*Pinus* spp.), olive trees (*Olea europaea* subsp. *europaea*), and oaks (*Quercus* spp.). The abundance of specific alien trees confirms the cause of pollinosis symptoms and their marked allergenicity, illustrating an important issue in the South African environment [53, 54]. Many allergenic pollen plants are centralized in urban areas, threatening human health, and the negative impact of allergenic pollen plants has not been considered during the species selection and collocation process of UGI. During the pollen season in spring (August-October for most taxa), the blooming of the alien tree species often simultaneously releases large amounts of often allergenic pollen into the atmosphere; considered among the most prevalent in the pollen spectrum in South African cities according to Berman [55]. An overview of the indigenous and alien allergen in South Africa documented that Johannesburg is the most heavily tree-planted city in South Africa, with alien trees (such as pines, oaks, planes, eucalyptus trees), but also acacias (*Senegalia/Vachellia* spp.) and other African trees including Combretaceae, consequently allergic reactions to tree pollen is common in Johannesburg, especially in spring [56]. Furthermore, plane and oak trees are the most common cause of short-lived allergy symptoms in the Western Cape, which occur each year in August and early September [57]. Also, in 2000 it was found that 15% of South African Olympic athletes were sensitive to plane tree pollen [54].

Pollen grain concentrations can be spatially and temporally highly heterogeneous depending on the proximity of sources but also on the urban topography of the environment. In recent research, which considered five northern hemisphere cities (Barcelona, Montreal, New York City, Paris, and Vancouver) with different urban forests and population densities, Sousa-Silva et al. [58] presented evidence on how tree pollen allergenicity datasets can shape the risk for pollen-allergy sufferers. However, the literature lacks studies from Global South cities, especially in Africa that focus on plant taxa and combine aerobiological datasets to explicitly explore the pattern of allergenic tree distribution in UGI.

As a response to this apparent research gap, this paper builds an argument that the two study areas, Johannesburg, and Cape Town, need to consider, integral to their urban planning and design, the abundance and distribution of allergenic tree species in their UGI (Fig. 1). This consideration should essentially consider the applicability of current directives in the form of SDFs, Precinct Plans, LUSs and practical implementation options; all in attempting a sustainable implementation framework.

2 Materials And Methods

For the purpose of this research, a multiple case study methodology [59], was employed as this enabled the researchers to "investigate a phenomenon in a specific setting" (allergenic pollen-producing trees within the context of the cities of Johannesburg and Cape Town), to "inform a wider inquiry" [59, 60] regarding the health risk for the South African population, as well as the management thereof in a sustainable implementation framework.

2.1 Study areas

The study was undertaken in the cities of Johannesburg and Cape Town, the two largest cities which are also centres for trade, industry, tourism, culture, and education, to allow comparisons between the representativeness of the vegetation in the UGI (Fig. 2). Located in the southwestern Cape of South Africa with a distinct winter rain climate, Cape Town (CPT) lies within a globally recognized biodiversity hotspot of the enigmatic Fynbos biome with the characteristic plant families Proteaceae, Ericaceae and Restionaceae; the biome covers an area of 2460 km² [61, 62]. The topography is complex as Table Mountain rises steeply to a height of 1086 meters from its position close to the port of Cape Town in Table Bay and there are two coastlines around the Cape Peninsula. These features give rise to different climatic conditions within a small area. The climate is Mediterranean with winter rainfall and warm, dry summers but rainfall varies from 350 mm on the western coast to > 2000 mm per year on the highest mountain summits [62, 63]. The city's history of European colonization reaches back to 1652 when first alien plant species like e.g., oaks were introduced [64]. The natural vegetation is degraded and reduced due to urban development, with neophytes like *Platanus* spp., *Pinus* spp., *Quercus* spp. and Australian *Acacia* spp. being common [63, 65].

The second study site, the city of Johannesburg (JHB), is regarded as one of the most extensive man-made urban forests globally [66, 67]. The regional climate is warm-temperate and features a typical summer rainfall pattern with warm, wet summers and dry, cool winters. It is located within the temperate Grassland biome with patches of savanna in the summer rainfall region of South Africa but is also affected by anthropogenic impact due to urbanization processes [62]. Johannesburg's urban forest/UGI is regarded as an extraordinary urban ecological asset with 6.1% covered by trees, both remnant and planted indigenous and planted and naturalised alien species. Many North American and Eurasian taxa, e.g., *Platanus* spp., *Morus* spp., *Betula* spp., *Fraxinus* spp., *Cupressus* spp. and *Quercus* spp. are also widely distributed as are southern hemisphere taxa like *Jacaranda mimosifolia* or *Eucalyptus* spp. [68].

2.2 Pollen data

Airborne pollen sampling was performed during 2019–2022, using a 7-day Hirst-type volumetric trap manufactured by Burkhard. The Cape Town sampler is situated 8m above ground on a rooftop at the South African Astronomical Observatory. The Johannesburg spore trap is located on the roof of the Richard Ward Building at 12m above ground, School of Chemical and Metallurgical Engineering, Braamfontein Campus East, University of the Witwatersrand (Fig. 2). Both samplers are calibrated to continuously suck air at a rate of 10 l/min. Pollen grains were trapped on a Melinex tape fixed on a rotating drum coated with Vaseline jelly, which was then cut into seven daily segments and mounted on the slides with a glycerol jelly media. The daily mean concentration of the number of pollen grains was examined using an optical light microscope (CX 23) with ×400 magnification along three full lengthwise traverses. Pollen counts were expressed as daily pollen concentrations (p.g/m³). The annual sum of daily pollen concentrations (annual pollen index - API) for each aerobiological station is used in the inventory development process. The pollen types considered in this study were pollen of trees such as species of *Cupressus*, *Platanus*, *Quercus*, *Pinus*, *Morus*, *Betula*, and the families Oleaceae, and Myrtaceae, which are allergenic pollen producers according to the South African Pollen Network [69]. Other trees which do not produce large amounts of allergenic pollen recorded in the atmosphere of sampling stations were included in the analysis.

3 Results

3.1 Total and seasonal distribution of pollen trees

The continuous aerobiological monitoring of the air recorded at the two sites was compared to demonstrate a possible difference in the airborne pollen of the particular trees. The pollen of relevant tree species and families recorded during the period 2019–2022 was considered, e.g., *Cupressus* (cypress), *Platanus* (plane), *Pinus* (pine), *Olea* (olive), *Morus* (mulberry), *Betula* (birch), *Quercus* (oak), Myrtaceae (gum), *Fraxinus* (ash), *Podocarpus* (yellow wood), *Searsia* (karree), *Populus* (poplar), Combretaceae (bushwillow), *Ulmus* (elm), *Casuarina* (she-oak), *Acacia* type (australian acacias), and Tiliaceae (linden family) (compare Fig. 3, Table 1). Most dominant species were of Northern Hemisphere origin (*Cupressus*, *Platanus*, *Pinus*, *Olea*, *Morus*, *Betula*, *Quercus*, *Populus*, *Ulmus*) or Australian (most Myrtaceae (*Eucalyptus*), *Casuarina*, some *Acacia*-type pollen). Those taxa are well represented in both cities. Only Combretaceae are exclusively indigenous trees (typical savanna-woodland trees, namely *Combretum* spp. (bush willows). The diversity of taxa found at the two sites was similar. Comparisons of the API of the trees in both study sites are shown in Table 1. Differences in the annual pollen content in the cities studied are obvious. Both cities have high annual pollen amounts, with mean values of 5059 p.g/m³ (CPT) and 6847 p.g/m³ (JHB). A total of eight tree taxa largely exceeded an average of 100 p.g/m³ in JHB, as well as *Morus*, *Betula*, *Quercus*, *Pinus*, and *Fraxinus*, in comparison to six taxa that occurred in CPT where *Olea* and Myrtaceae have distinctly higher values. The main dominant pollen type in JHB was *Platanus* with a mean value of 3353 p.g/m³. However, a considerable API of 2777 p.g/m³ of *Cupressus* was identified in CPT. The pollen types with the lowest concentrations in JHB were *Casuarina*, Tiliaceae, and *Acacia*-type (including indigenous *Vachellia* spp. and *Senegalia* spp. as well as Australian *Acacia* spp., respectively), *Fraxinus*, *Populus*, and Combretaceae in CPT.

The general trend of the average daily mean concentrations of dominant tree pollen types for both localities is presented in (Fig. 3). A pronounced difference in seasonality is evident. There were apparent differences in the pollen season dynamics between the stations of CPT and JHB. The average of pollen concentrations for each site evidenced that higher levels were registered in CPT, except *Platanus*, *Morus*, *Quercus*, and *Betula* pollen which reached higher concentrations in JHB.

Table 1

Tree pollen types, annual pollen index (API), max API, and average API recorded in the cities studied (2019–2022). *Alien trees **Indigenous trees.

Pollen types	Common name of trees	Cape Town						Johannesburg						Average API 2019–2022	
		2019–2020		2020–2021		2021–2022		2019–2020		2020–2021		2021–2022		CPT	JHB
		API	Max	API	Max	API	Max	API	Max	API	Max	API	Max		
<i>Cupressus</i> *	Cypress	2692	483	1269	148	4370	383	752	49	874	49	865	48	2777	830
<i>Platanus</i> *	Plane	397	65	618	56	21	4	3220	371	3594	207	3245	276	345	3353
<i>Pinus</i> *	Pine	1084	287	66	12	523	51	134	17	245	16	255	12	558	211
<i>Olea</i> */**	Olive	264	56	47	6	1408	209	58	10	61	12	32	9	573	51
<i>Morus</i> *	Mulberry	101	14	22	3	0	0	144	36	1380	140	835	75	41	786
<i>Betula</i> *	Birch	26	6	8	1	28	1	166	22	734	54	554	36	21	485
<i>Quercus</i> *	Oak	195	14	132	12	62	7	46	8	708	84	284	14	130	346
Myrtaceae*/**	Gum trees and other members of the myrtle family	250	21	683	26	384	47	215	14	247	12	128	9	439	197
<i>Fraxinus</i> *	Ash	6	4	1	1	5	1	12	1	176	30	411	23	4	200
<i>Podocarpus</i> **	Yellowwood	0	0	11	6	21	4	50	10	148	24	45	6	11	81
<i>Searsia</i> **	Karree	14	3	127	7	1	1	46	5	148	50	39	6	47	78
<i>Populus</i> *	Poplar	0	1	18	25	6	4	3	1	171	12	44	5	8	73
Combretaceae**	Bushwillow	0	0	0	0	0	0	17	6	94	5	59	6	0	56
<i>Ulmus</i> *	Elm tree	55	9	85	13	31	4	2	1	20	4	114	12	57	45
<i>Casuarina</i> *	She-oak	8	1	24	5	19	4	10	2	47	9	37	7	17	31
<i>Acacia</i> */**	Australian acacias, indigenous acacias	4	1	1	1	6	1	7	4	21	2	12	1	4	13
Tiliaceae**	Linden family	5	1	2	1	73	15	7	3	18	4	9	2	27	11
Total	-	5101	984	3114	334	6958	1041	4889	569	8686	714	6968	547	5059	6847

4 Discussion

4.1 Tree pollen aeroallergens in South African cities.

Aerobiological research aims to identify sources of airborne pollen concentrations and quantify their contribution to overall pollen levels. This enables specific recommendations to be made regarding the most suitable ornamental species and is thus an essential step in ensuring a more efficient design of urban parks and gardens [70]. This study shows important information about the abundant allergenic pollen types and their respective aerobiological patterns in the studied cities. In relation to pollen index and peaks, cypress, plane, pine, olive, mulberry, birch, oak, and ash tree pollen types are most abundant which is reflected in the spore traps revealing the urban landscape composition within JHB and CPT (Fig. 3). Thus, the most frequent pollen types detected in the spore traps include species native to Europe and, secondarily, North America. This group included some of the main causative agents of pollen allergy in the Mediterranean area, such as *Cupressus* (*C. sempervirens*, *C. arizonica* [71], *Platanus* [72, 73], and *Olea* [74] with values of potential allergenicity and others with a lower degree of allergenicity such as *Pinus* [75] and *Quercus* [76]. Other species such as *Betula* [77] and *Fraxinus* [78] are a cause of pollen allergy in Europe. All of them share an anemophilous character, high pollen production, an extensive flowering period (Fig. 3), and very high allergenic pollen grains, which led us to consider them as major allergens in the UGI of South African cities.

4.2 Towards an implementation framework

UGI in South Africa may, from an urban planning perspective, be implemented by considering a three-tier approach (strategic planning, land use control and implementation), especially as Retief *et al.* [79] underscore megatrends evolving from a single predictable solution towards open and multi-purpose approaches.

4.2.1 Strategic Planning

As is often the stance, spatial planning directives (policy, law, and guidelines) in South Africa are not necessarily prone to purposefully advocate UGI, resulting in urban planners treating it too generally, as an all-embracing archetype within the diverse disciplines of urban planning [80]. In contrast, Brundtland [81] qualifies the coexistence of development (urban) and the environment, feasible once the responsibility of making the “ecosystem the first priority”, is accepted. Failing in contemplating UGI from the onset, and also on a strategic level, will ceaselessly impede upon finding its way into urban planning.

Recent planning directives e.g., the Spatial Planning and Land Use Management Act (SPLUMA), [82] have, nonetheless, seen references to the exceedingly diverse concepts of the “sustainable development of land” and the principle of “spatial sustainability” in its norms and standards (although neglecting to offer their implementation in practical ways). The lamentations of Farthing [83] oscillate that planning research ever so often fails in meeting the needs of practitioners and should provide evidence, directives, and practice. The SPLUMA, encouragingly, permits the inclusion of environmental opportunities, typically UGI, in forward planning instruments i.e., the municipal SDFs or in more detailed “local plans” (SPLUMA, [82]), also known as Precinct Plans [84]. While mostly leaving the incorporation of spatial sustainability in these documents open to the interpretation of urban planners, strategic planning is perceived as the first necessary advent in designing healthy urban green spaces in South Africa. The latter goal of healthy urban areas is also emphasised by the Sustainable Development Goals’ (Goal 11.6) focus on improved air quality in cities [85]. The potential allergenicity of the tree species commonly used as ornamentals in these urban spaces may further be captured and managed, more specifically, through land use control measures.

4.2.2 Land Use Control

Departing from strategic planning, the SPLUMA, similarly provides for the preparation of new and integrated Land Use Schemes (LUS) by municipalities in, inter alia diverting from spatially distorted settlement patterns, by also taking cognisance of “environmental management instruments” [82]. As the SPLUMA resorts under national authority, municipalities had to prepare inimitable By-Laws, inter alia facilitating the preparation of LUS, within the context of the SPLUMA. Through this vehicle, municipalities are provided with the opportunity to prepare land use controls for improving the incorporation of UGI in the development and management of their jurisdictional areas; either through their “land use management” by-law or any other appropriate/ newly prepared by-law. The facilitation of UGI and the design of healthy urban green spaces in South Africa are, therefore, duly established by this arrangement. However, since directives do not necessarily guide or enforce the practical implementation of sustainability on an urban scale, other than its mere mentioning, municipalities are left with a predicament, evidently seeing UGI low on the development agenda and impeding implementation options as meaningful disciplinary logic in the applied [86] and real-world [87].

4.2.3 Implementation

While the attainment of UGI, and subsequently the design of healthy urban green spaces in South Africa are to be incepted into strategic planning and land use control, its practical implementation seemingly leaves urban planners despondent. Although the South African Council for Scientific and Industrial Research (CSIR) [88] accentuates healthy ecosystems and climate-safe facilities when designing urban open spaces, it falls short in addressing the design of healthy urban green spaces in a practical and achievable way. Research in this article is perceived as a pertinent keel in the chopping sea of UGI as it attempts to offer implementable and scientifically sound solutions within the built environment, towards the design of healthy urban green spaces in South Africa. The built environment already presents functional and practical building blocks, offering opportunities for UGI, culminating in the design of healthy urban green spaces. In this instance, and originating from the work of Girling and Kellet [89], these building blocks are represented in the form of “fabrics” and “networks” in shades of green and grey (Table 2), where (i) networks refer to spatial corridors through which people and organisms flow, (ii) fabrics to spaces distributed between and served by networks, while both fabrics and networks are (iii) grey, if serving the built and urban environment and (iv) green, if serving ES, (v) all in a complex and interwoven relationship. It is a construct illustrating the practical building blocks, all within which introducing non-allergenic, indigenous species to urban landscapes may well be conducive to designing healthy urban green spaces in South Africa. The building block approach relates well to specific UGI principles such as connectivity, multifunctionality in terms of the provision of various ES, the integration of green and grey infrastructure and relevance on multiple scales [3, 12, 14].

Table 2
A framework for the practical introduction of non or low-allergenicity trees in cities.

Green networks	Protecting, restoring, and interconnecting the urban ecological structure
Grey networks	Accessible, connective, and walkable, tree-lined street networks
Grey fabrics	Mixed land uses within walking distance
Green fabrics	Preserved remnant forests, tree-lined streets, and tree-covered spaces

A fifth component, not captured in the building blocks of Girling and Kellett, but traversing all four components, is the social component or community that daily utilises urban networks and fabrics. Social inclusion is also an important principle of UGI planning and is often neglected in urban areas of the Global South [3]. In this regard, implementing community-based participatory planning is admittedly inevitable to obtain meaningful solutions and insight from the residents, informing decision-making in designing healthy urban green spaces in South Africa [89, 90]. Cilliers and Cilliers [91], nonetheless, caution urban planners that the benefits of ecosystems are often subservient to socio-economic pressures in South African communities, thereby accentuating the need for participatory planning. Involving residents in the decision-making processes and the co-production of solutions [92], especially in addressing the allergenicity of the tree species commonly used as ornamentals in South African cities, may contribute to the sustainability of the proposed solutions [93]. Efforts to attain green urbanism in this manner will, in all probability, be accepted and maintained by a well-informed, continuously involved and concerned community.

4.3 Sustainable Urban Forestry

For cultural and historical reasons, the presence of these species with allergenic pollen cannot be readily reduced. An exception is the management of declared invader species according to legislation, for example, *Acacia*, *Morus*, *Eucalyptus* and *Populus* [94]. Wind-pollinated *Morus* (Mulberry tree) was planted to provide multiple ES (shade, hedge, windbreak, fruit tree) in South Africa, but easily escaped from cultivation, now spreading into woodlands, within cities and along rivers often out-competing native species due to its fast growth and tolerance for droughts, different climatic conditions, and infertile soils in comparison with indigenous taxa (category 3 invader) [94, 95]. *Morus* is much more widespread in Johannesburg than in Cape Town (Fig. 3), in both cities, it can be seen along streets and streams or as a ruderal plant. Since it is both used as a fruit tree and releases a massive amount of pollen, it is of special importance that the tree can cause both food and pollen allergies [94, 96]. Some genera, like *Eucalyptus* and *Pinus*, include species which are both invasive and have a high-water demand and are therefore actively removed from the landscape [97, 98]. *Pinus* pollen has moderate allergenicity [99] but is a common pollen grain detected in Cape Town due to the fact that especially Mediterranean pines are well-adapted to seasonal droughts and poor soil conditions and are often successful competitors of the indigenous vegetation (Fig. 3). Myrtaceae pollen comprises *Eucalyptus*, a declared invader [94], and was recognized as an important allergen for children with asthma in Australia [100]. *Eucalyptus* deserves attention since the pollen counts for Cape Town are -for short durations- alarmingly high (Fig. 3). *Acacia*-type pollen, both representing indigenous *Vachellia* and *Senegalia* species but also declared invaders such as the Australian acacias [96], are underrepresented both in Cape Town and Johannesburg and of lesser concern for public health as is e.g., neophytic *Populus* (Fig. 3). *Casuarina* pollen, with low allergy potential, including *Casuarina cunninghamiana* and *C. equisetifolia*, are also declared invasive species from Australia and are listed as invasive aliens in the Western Cape, similar to *Searsia succedanea* which is indigenous to eastern Asia [96]. *Platanus* pollen represents much higher concentrations in the city of Johannesburg than in Cape Town. Plane trees are widespread as alley trees in Johannesburg because they are tolerant towards high levels of air pollution which is common in the city [101]. Abutaleb et al. [102] underline the abundance of London plane (*Platanus × acerifolia*) trees in Johannesburg using remote sensing data, and its pollen is one of the main causes of pollen-related diseases in South Africa [103]. According to several atmospheric pollen studies, plane trees have intense and short blooming periods [104, 105, 106, 107]. The allergenic importance of *Platanus* is caused by the abundance of pollen grains released by many individual trees along streets and in parks [42]. Pollen appears abruptly in the air, and peak counts are usually recorded only a week after the start of the pollen season with an average of 36 days, a pattern reported in Madrid, Barcelona and Córdoba [108, 109]. For this reason, special attention must be given when considering the planting of plane trees in the future design and management of South African UGI.

For the family Cupressaceae, the API reflects significant differences between the sampling sites, being higher in CPT. *Cupressus* species are popular alien, ornamental trees frequently grown in South African parks and gardens as ornamentals, shade trees, windbreaks and hedges, and shelter belts [110]. The dominant species are native to the Mediterranean basin (*Cupressus sempervirens*), California (*C. macrocarpa*), Arizona (*C. arizonica*), Mexico (*C. lusitanica*), and Himalaya-South China (*C. torulosa*). Only three Cupressaceae species are indigenous to South Africa, as part of the venerable African cedar genus *Widdringtonia* (*W. cedarbergensis*, *W. schwartzii*, and *W. nodiflora*). The previous two species only naturally exist in a relatively small number of locations, but *W. nodiflora* has a distribution that stretches from the southwest of the Western Cape Province northward into Malawi [111], but none of these species are commonly planted in CPT. In practical allergenicity terms, a study by Ordman [112] showed that fourteen cases of winter-spring hay fever and allergic conjunctivitis have been investigated and found to be associated with cypress-pollen sensitivity. On the other hand, the allergenicity of cypress pollen extracts may depend on where they have been collected. Bar-Dayana et al. [113] described a cross-reactivity between cypress allergens and allergens from *Podocarpus gracilior* and *Callitris verrucosa* and, both species, have been put forward as surrogates for controlling cypress allergy. Among other common northern hemisphere trees with the greatest allergenic potential, *Betula*, *Quercus*, and *Fraxinus* are associated with an abundance of pollen concentrations and make a significant contribution to the city of JHB where they are more common than in CPT. Different stakeholder views on the ES (especially recreation and aesthetics) and EDS provided by trees could lead to conflict if certain invasive species are removed. To address these conflicts in CPT, a management framework was developed based on stakeholder perceptions that distinguished between invasive species that can be tolerated, actively managed, or totally removed [114]. This framework could be expanded to include tree species with specific EDS such as those producing allergenic pollen. It is essential to not only manage but also to avoid the increase of the numbers of these species in newly developed UGI, in order not to aggravate their impact on allergy sufferers. The main reason why a greater effort should be made to limit the presence of alien species is that they are known to trigger symptoms in sensitive residents [48] and others have also other EDS like high water demands [115].

In a future framework which can be used to guide city actors (Fig. 4), it is recommended to point out those taxa which are of public health concern in the major cities of South Africa, CPT and JHB. Pollen grains of the predominantly Mediterranean genera *Cupressus*, *Pinus* and *Olea* are abundant in CPT within the Mediterranean Fynbos biome whereas pollen grains of temperate broad-leaved forest tree taxa *Platanus*, *Morus*, and *Betula* are the three most prominent pollen types in JHB which lies within the temperate Grassland biome. In contrast to the widespread alien trees, most of the indigenous tree species are animal pollinated and have colourful, large flowers with sticky, ornamented and relatively heavy pollen which are not widely dispersed and are produced in much lower quantities. Since those trees provide many ES, have a low water demand and are less risky in terms of allergenicity, they are better suited for an urban environment than their alien counterparts. The indigenous coral tree (*Erythrina* spp.) is recommended as is the River bushwillow (*Combretum erythrophyllum*), which is widespread in Johannesburg and with its pollen also reflected in relatively low quantities in the spore trap findings. *Combretum erythrophyllum* grows well in urban environments, provides shade, adds ornamental value, has no negative impact on water balance and does not release allergenic pollen. Other recommended indigenous tree species often planted in Johannesburg include *Searsia lancea*, *S. pendulina*, *Celtis africana*, *Olea europaea* subsp. *africana*, *Harpephyllum caffrum*, *Kiggelaria africana* and *Schotia brachypetala* [116]. Indigenous acacias (e.g., *Vachellia karroo*, *V. sieberiana* var. *woodii* and *Senegalia galpinii*) also have a high ornamental value, are water-wise, and have attractive flowers which are insect pollinated and release only few pollens into the atmosphere. All these indigenous tree species can be easily identified except for *Celtis africana* that could be confused with the alien species, *Celtis sinensis* which is often naturalised in urban areas and is recently flagged as a potential invasive species [117].

5 Conclusions

Pollen grains emitted in urban areas constitute a source of allergy. This study revealed the abundance of allergenic wind-pollinated alien trees throughout the UGI in two large South African cities. An urgent need exists to screen ornamental trees for allergenicity in South Africa before introducing them into urban green spaces, to improve the quality of the urban environment and protect pollen-allergy sufferers. Aerobiological criteria should be considered when planning urban green spaces for aesthetics and recreation. Valid strategies (Fig. 4) include using insect-pollinated, preferably indigenous (also often less water-demanding), species, which tend to produce less pollen and less aerodynamic pollen, than wind-pollinated species and ensuring the predominance of female plants in the case of dioecious species. It is also important to promote greater species diversity by focusing on indigenous species when designing new gardens, parks, and alleys. This measurement will prevent the excessive use of monospecific profiles, which can prompt a sharp increase in airborne pollen counts, but also increase ecological diversity and available ecological niches.

Current directives discussed in this article, such as implementing UGI principles (e.g., multifunctionality, connectivity, integration of grey and green infrastructure, multiple scale relevance and social inclusion) and the suggested framework (Fig. 4), are deemed largely sufficient to serve as a sustainable implementation framework for UGI. It is also questioned whether it is necessary to formulate additional directives for attaining healthy urban green spaces. Rather, the challenge seems to be how knowledge regarding allergenicity could be conveyed to city actors and to enhance their willingness in establishing healthy urban green spaces in SA cities. SPLUMA requires each municipality to include an Implementation Plan (Section 21) in the compilation or revision of an SDF, which is the appropriate vehicle to include a *localised interpretation* of the abovementioned framework. The application of current directives (SDFs, LUSs and precinct plans, and SPLUMA) in collaboration with practical implementation options, are already steps in the right direction to ensure that healthy urban green spaces are developed in SA cities.

Declarations

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Figures

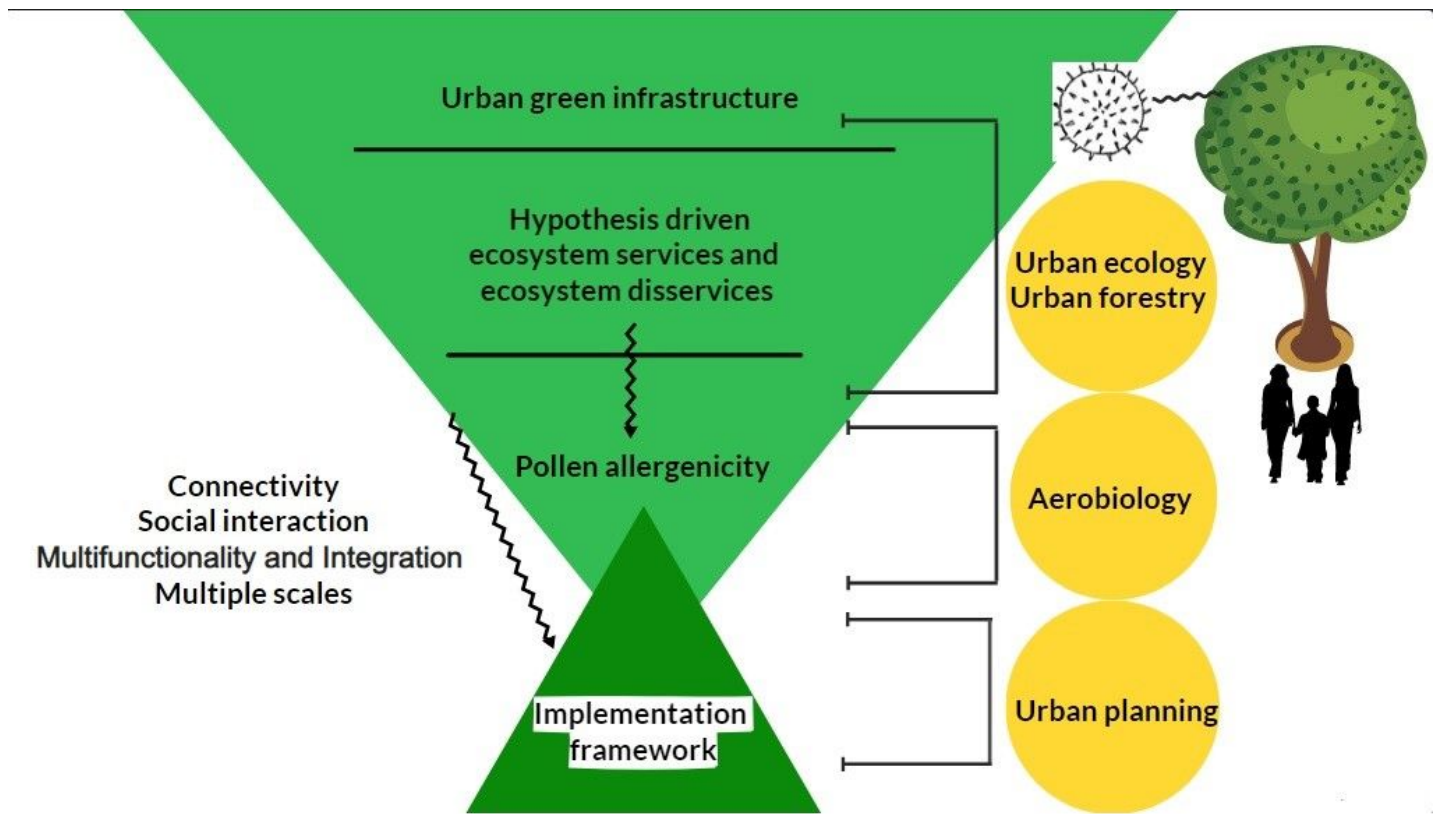


Figure 1

Implementation of a sustainable urban framework for South African cities.

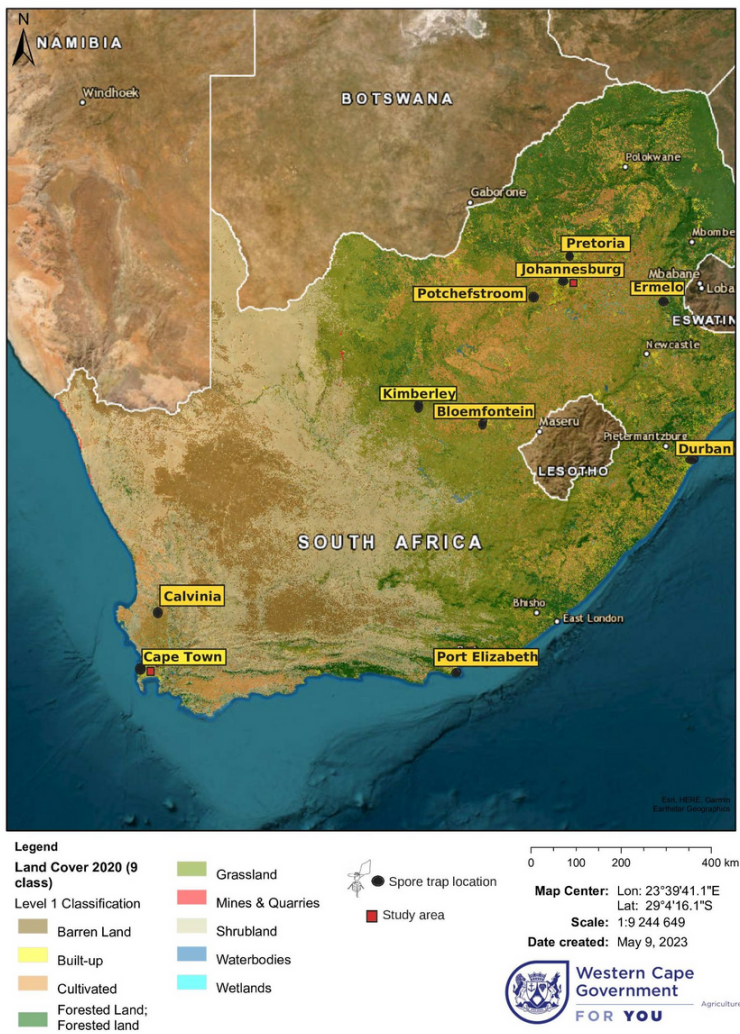


Figure 2

A map of the ten aerobiological sampling stations which are run by SAPNET (South African Pollen Monitoring Network). Also shown are land use patterns in South Africa (<https://gis.elsenburg.com/>) (created date May 06, 2023).

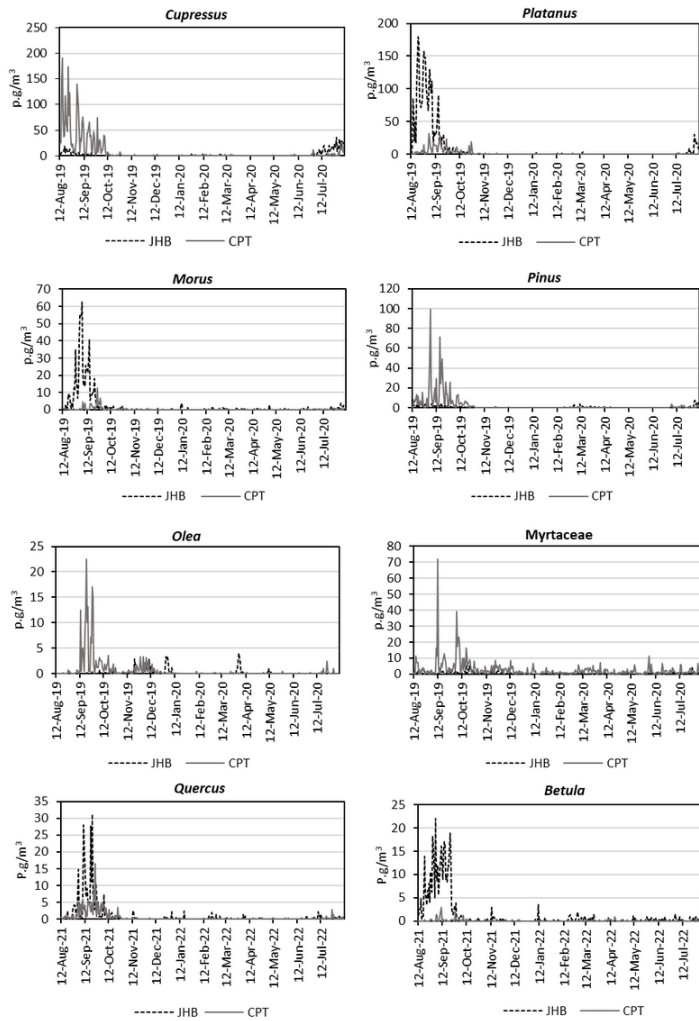


Figure 3

Average seasonal dynamics of dominant pollen trees detected in the cities of Cape Town (CPT) and Johannesburg (JHB) (2019-2022).