Breathe: Implementation of green barriers to mitigate air pollution in school playgrounds – case studies from UK and Argentina

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Except where otherwise indicated, this thesis is my own original work.

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Abstract

Globally, more than 90% of children live in areas that exceed the World Health Organization air pollution limits. Simultaneously, evidence has shown that children are especially susceptible to suffer detrimental health effects caused by air pollution. Some of these health conditions include asthma exacerbation, bronchitis, or cognitive impairment. Innovative solutions that mitigate the risks to children's health from air pollution are urgently needed.

This thesis examined green (vegetated) barriers as a nature-based solution to air pollution in school playgrounds, where children spend a large part of their day. It intends to close the technical and application gaps for green barrier implementation. For this purpose, real-life green barriers were installed in two school playgrounds, in Sheffield, UK and in Buenos Aires, Argentina, and are the focus (case studies) of this research. Through the UK case study, the research aimed to 1) assess the air pollution mitigation potential of green barriers in school playgrounds considering the air pollution-vegetation interaction, 2) identify the co-benefits, trade-offs and disbenefits of green barrier implementation for school communities, and 3) understand the implementation process and practicalities of green barriers in school playgrounds. Additionally, through the Argentine case study, this research aimed to 4) identify barriers and solutions to green barrier implementation in school playgrounds in a Latin American context. Action research was carried out throughout the implementation process at both schools, and was complemented by quantitative (air pollution monitoring and leaf microscopy) and qualitative (interviews, surveys, and narratives) methods to achieve the various research aims.

Air quality was only monitored at the Sheffield school, which showed that 'thin' green barriers (1.00-2.20 m) have the potential to reduce air pollution when properly designed and implemented. Air quality improvements were significant for the pollutant nitrogen dioxide (13%), but rather low for particulate matter (2%). Despite such small reductions, this research found that particulate matter is captured by the green barrier plants, and that this pollution reduction mechanism is maximised by plant biodiversity. Additionally, the Sheffield case study showed that a diligent green barrier design can provide other social (e.g., safety, wellbeing, and increased place quality), environmental (e.g., habitat provisioning for wildlife), and economic (increased subscription/interest in the school) benefits, which are highly valued by the school community. Finally, this research showed that the implementation of green barriers is largely influenced by its global context. Specifically, the Buenos Aires case study showed that green barrier implementation in a country without robust green intervention frameworks faces multiple obstacles, more than previously reported in the predominantly Euro-American literature. However, commitment, collaboration, and experimentation (as an urban living lab) can help overcome those hurdles.

Overall, green barriers showed to be a valid complementary tool to the efforts of reducing and mitigating air pollution, with the relevant addition of creating safe and healthy environments for children and the broader school community.

Chapter 1
Introduction

"Two girls, two stories.
Two different endings.

The haze hides the mountains
that surround Mexico City's Valley.
Again, the landscape beauty is gone.
But should I go out or stay home,
which one will make me worse?
When I was young,
I didn't even have a choice.
Forced behind the bars of a smog prison,
shielding from the outside in our classroom.
Playing hide and seek with death in disguise,
winning by a whisker.

When she was young,
Her pirouettes couldn't stop
London's bittersweet dance
squashing her throat so hard
she could forget where she was.
Struggling for every breath,
heavy as a thousand cars on her chest.
An evanescent nine-year-old body.
Her swing expired prematurely.
Her death certificate: air pollution.

Deep breaths extend lives Yogis say,
but deep breaths are taking ours,
with toxic gases like creeping vines,
with tiny particles, yet not innocent,
begrime our throats, our lungs, our blood.
They burn our insides without fire,
most of the time oblivious to our eyes.
They oxidise us from the inside out,
and we rust as the city's going about,
turning copper, then blue, then pale.
A concrete jungle noxious affair.

And there's no secret to tell.
It just seems like clean air
is basic human right
we were denied."

María del Carmen Redondo Bermúdez, 2022.

Problem statement

In Mexico City in the '90s, there was a mandate to minimise being outside during high air pollution days. I was the little girl trapped inside the classroom, banned from playing in the playground. But despite all the bad memories of that time, I survived. Ella Kissi-Debrah did not in London in the early 2010's. Her asthma was so acute that she visited the hospital 28 times in 28 months. She was the first person in the UK to have air pollution as a cause of death in her certificate (BBC News, 2020). Her story is a powerful and painful reminder of the seriousness of the problem, especially for children. Just like Ella, millions of children are exposed to air pollution globally. In fact, 300 million children live in highly polluted areas, where outdoor air pollution is at least six times higher than the World Health Organisation's (WHO) guidance. This number escalates to 2 billion children exposed to air pollution above the recommended maximum in the guidance when considering only particulate matter (PM) pollution (UNICEF, 2016), a seriously harmful pollutant.

But why are children more at risk of developing health problems caused by air pollution? The answer relies on their bodies' development state, which is not mature and is growing. For instance, children are born with only 20% of the alveoli (the lungs' gas exchange structure) they will produce into adulthood. In order to achieve a 100% capacity, they need a clean and supportive environment, and air pollution hinders this process. Moreover, due to their small size, children breathe more air per unit of body weight than adults, resulting in higher toxic pollutants intake (Schraufnagel et al., 2019). As expected, exposure to air pollution causes lung damage and is linked with childhood asthma (Khreis et al., 2017; Thurston and Rice, 2019). Yet, less apparent physiological and mental health and developmental issues are also linked with the impacts of air pollution on children. For example, slow brain maturity (Pujol et al., 2016), cognitive impairment leading to lower verbal ability (Midouhas et al., 2018), association with attention-deficit hyperactivity disorder (ADHD) (Thygesen et al., 2020), and with feelings of depression and anxiety (Roberts et al., 2019; Yolton et al., 2019).

Air pollution is a global problem, with serious repercussions at the local scale. In the UK, this health and environmental problem only started to be taken seriously in 2016, after the law firm ClientEarth sued and won its case against the UK government over failing to secure good air quality for its citizens (ClientEarth Communications, 2016), leading to the creation of the Clean Air Act 2018. Other NGOs and community groups are working on the issue, for instance, 'Mums for Lungs' have campaigned since 2017 for cleaner air around schools (Mums for Lungs, n.d.) and Sustrans' poll results reveals that children across the UK are concerned about air pollution and want to take action to help reduce its impact (Sustrans, n.d.).

On the other hand, air pollution is dominant in low- and middle-income countries, which tend to have less accountable and environmentally aware governments. In fact, 91% of global premature deaths related to poor air quality occurred in those countries (WHO, 2018). The burden of disease in children is, therefore, higher, and prevention is critical. In Argentina, a middle-income country in Latin America, air quality policy is incipient and, despite air pollutant concentrations being poorly measured, they show exceedances through the year (Pineda Rojas et al., 2020). In recent years, NGO Greenpeace has been campaigning to raise awareness of the problem, highlighting that air pollution exists around schools in Buenos Aires, the capital city (Greenpeace, 2018).

Whether it is in high-, middle- or low-income countries, children around the globe are breathing dirty air and paying the cost with their health. Solutions that promote clean air environments for children are urgently needed.

Air quality toolbox

In response to the growing evidence of air pollution's detrimental effects on human health, the WHO (2021) has reassessed their suggested exposure limits for two air pollutants: nitrogen dioxide (NO_2) and particulate matter of 2.5 microns or less in size ($PM_{2.5}$). From 2021, annual limits of NO_2 were reduced three times, from 40 to 10 µg m^{-3}. This gas pollutant is primarily related to burning, for instance of combustion engines, i.e. vehicle traffic. On the other hand, annual limits on $PM_{2.5}$ were halved, from 10 to 5 µg m^{-3}. $PM_{2.5}$ is made of liquid or solid tiny particles that are generated by various sources, such as vehicles' brake and tyre wear, dust from construction sites, or use of woodstove burners. It is important to acknowledge that no air pollution levels are safe; notwithstanding, these major changes to WHO exposure limits exhort for immediate actions to reduce and mitigate pollution.

A large array of indirect and directed actions already exist to improve air quality. On one hand, international cooperation intends to address transcontinental pollution, which travels across the globe moved by the wind, such as PM from desert dust or from fire smoke (Task Force on Hemispheric Transport of Air Pollution, 2010). Nevertheless, at a local scale, efforts to reduce air pollution vary and include all sectors of the socio-economic system. These efforts include changes in citizens' practices, such as car sharing and active travel; mandatory and voluntary industry certifications or guidelines, such as LEED certification (US Green Building Council, 2021); or policy creation and enforcement, such as the European Union Directive for Air Quality (European Commission, 2015). UK and Argentine governments have implemented different measures to prevent exposure to bad quality air, some of which have significantly reduced air pollution in the UK. In fact, from 2010 to 2019 NO_x decreased by 32% and $PM_{2.5}$ by 11% (DEFRA, 2022). Some of these measures include establishing Air Quality Management Areas, expanding Clean Air Zones from London to other cities, or developing awareness campaigns (DEFRA, 2019). However, such efforts have not been enough to ensure compliance with WHO and UK's air quality (AQ) standards. On the other hand, Argentina has few directed actions to reduce air pollution. One of them included a ban on domestic waste burners in 1978 (Buenos Aires Ciudad, n.d.), but contemporary policy is primarily targeted at greenhouse gases emission reduction. Still, periodic air pollution exceedances occur in the country.

The role of green barriers – a nature-based solution

All of the above-mentioned measures have an impact on air quality but also limitations and constraints, and, taken together, do not seem to lower air pollution to 'safe' levels. Alternatively, using plants to mitigate air pollution could complement the existing air quality toolbox.

The phytoremediation capacity of plants (pollution removal or amelioration) is well established for soil and water (Willey, 2007). Less was known for air pollution, until some early studies from the 1980s and 1990s started to understand the link between plants and air pollution reduction. These studies focused on toxic gas absorption by plants, either intended to clean VOCs (volatile organic compounds) from indoor environments (Wolverton et al., 1989; Wolverton and McDonald, 1982), or NO_2 from road transport (Morikawa et al., 1998, 1992). Research on air pollution removal using plants is growing, especially in the last 10 years. Recent evidence shows that plants can be used outdoors not only to absorb, but also to capture (deposition) and block air pollutants (Hagler et al., 2012; Tong et al., 2016). These mechanisms are in play when plants are used as barriers. Each mechanism is explained in detail in Chapter 2.

Landscape architecture has used plants as barriers for centuries and for multiple purposes. For instance, hedgerows have served as agricultural field boundaries since the mid-15th century in European landscapes, also providing wild food and retaining valuable nutrients in the soil (Collier, 2021). In recent times, hedgerows and tree barriers are planted along highways for transport noise reduction and as windbreaks (Fang and Ling, 2005; Van Renterghem et al., 2012), and evidence suggests that they also act as soil purifiers (Sarah et al., 2019). Moreover, hedges planted in cities can help to solve urban challenges such as flooding or high temperatures, and provide habitats for wildlife (Blanusa et al., 2019). Regarding air quality, 'green barriers' or 'green fences' are being strategically designed by landscape architects to reduce air pollution. They are part of an emergent type of green infrastructure (GI), coined green infrastructure for air quality (GI4AQ) by Hewitt et al. (2019). Green barriers entail linear vegetation that adapts to the urban layout and serves as a physical and biological obstacle to air pollutants. Green barriers are intended to protect places located behind the vegetation by reducing air pollutant concentrations. Evidence of their effectiveness is varied; modelling studies have shown air pollution reductions from 2-54% (Li et al., 2016; Pearce et al., 2021), whilst limited real-life case studies demonstrate reductions up to 37% (Al-Dabbous and Kumar, 2014; Kumar et al., 2022; Temper and Green, 2018).

This type of GI lies under the nature-based solutions (NbS) umbrella, which refers to solutions inspired and supported by nature that intend to create environmental, social and economic benefits (Cohen-Shacham et al., 2019). Moreover, extensive evidence suggests that NbS provide benefits beyond their main intended role. For instance, NbS in cities can provide habitats for biodiversity, local-climate regulation, water regulation, opportunities for pollination, or waste treatment (Hanson et al., 2017). They also have an impact on communities, facilitating spaces for recreation and social interaction, enhancing people's well-being, improving place quality, or creating livelihoods (Maia da Rocha et al., 2017). It is through this multifunctionality perspective that this research considers exploring green barriers as a green infrastructure for air quality 'plus' (GI4AQ+); a nature-based solution intended to mitigate air pollution and that delivers co-benefits (the 'plus') beyond its primary aim.

Global perspectives

The studies in this thesis aim to examine green barriers' role in schools, encompassing their air quality impacts, their further co-benefits, trade-offs and disservices, the processes needed to achieve their implementation, and the practicalities of doing so in different global contexts: the UK and Argentina.

Although common elements are part of the implementation process of NbS in different global cities (e.g., monitoring methods or construction/planting techniques), regional differences may appear due to the local ecological, cultural, and political context. On the other hand, NbS research coverage is uneven across the world. For instance, the number of NbS studies from Latin America is three times smaller than from Europe (Dobbs et al., 2019). As NbS implementation is based on collaborative approaches (Frantzeskaki, 2019), understanding these processes for different global contexts is key to their success. Moreover, NbS from one region cannot easily build on outcomes from other regions, they need to be shared but adapted and tested in the localities. For this research, the UK (a high-income country in Europe) and Argentina (a middle-income country in Latin America) greatly differ and there is room for understanding the processes and validity of multifunctional GI4AQ+ in schools from each country.

Gaps in knowledge

GI4AQ+ is in its infancy regarding evidence-based knowledge and application, even more in the less economically favoured parts of the world. Based on the knowledge gaps identified by Kabisch et al. (2016) for each NbS dimension: effectiveness, design, implementation, and their relationship with society (Figure In1), the following section reflects on five knowledge gaps intrinsic to GI4AQ+.

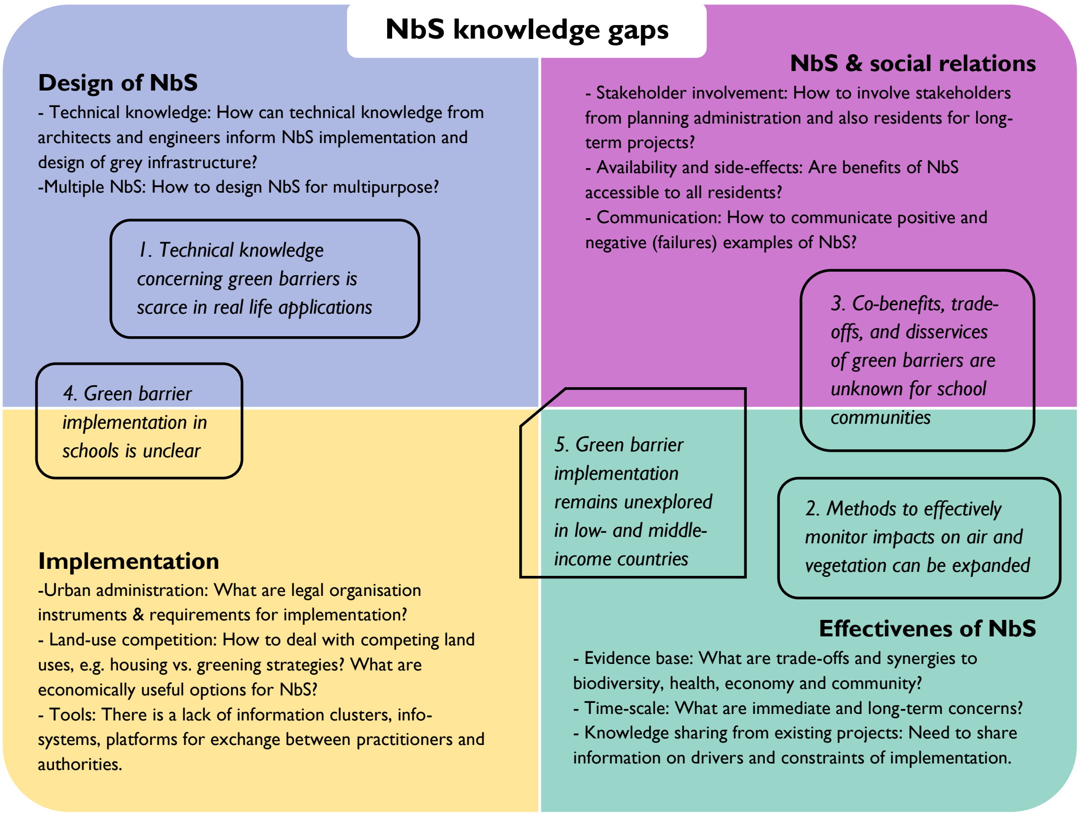


Figure In1. Knowledge gaps for study in this thesis (encircled) within the knowledge gap framework of nature-based solutions (modified from Kabisch et al., 2016).

1. *Technical knowledge concerning green barriers is scarce in real life applications – design gap*

Kabisch et al. (2016) highlighted the need to develop technical knowledge to inform multifunctional NbS design. The lack of that knowledge puts NbS at disadvantage to well established grey infrastructure. In the case of green barriers, substantial evidence indicates that GI can help to mitigate air pollution, yet little is known about its effectiveness and application in real-life scenarios. Only a handful of studies have focused on installing green barriers and monitoring their impacts; most research is conducted in sites where different types of vegetation already exist (e.g., Al-Dabbous and Kumar, 2014; Chen et al., 2015; Deshmukh et al., 2019; Kumar et al., 2022), or are based on modelling air pollution behaviour in various GI scenarios (e.g. Chang, 2006; Currie and Bass, 2008; Jeanjean et al., 2017; Tong et al., 2016; Xing and Brimblecombe, 2019). Therefore, developing technical knowledge on GI4AQ+ design, plant selection, and implementation is lacking and hindering green barriers uptake.

2. *Methods to effectively monitor impacts on air and vegetation can be expanded – design gap*

Assessment of NbS impacts remains a major challenge as is often neglected due to the lack of expertise or resources (Cardinali et al., 2021). For GI4AQ, establishing monitoring methods to effectively assess the impact of greenery on air quality is important for both the air and the vegetation components. However, the air pollution-vegetation interaction is rarely studied. Most research is conducted on either quantifying pollution on the plants (e.g., PM captured by leaves in Castanheiro et al., 2020; Sgrigna et al., 2020; Wang et al., 2019) or quantifying pollutant concentration changes in the air (e.g., Fuller et al., 2017; Ottosen and Kumar, 2020), but not both. Studies integrating the air pollution and vegetation components and expanding knowledge on effective monitoring methods are needed to unlock GI4AQ's potential.

3. *Co-benefits, trade-offs, and disservices of green barriers are unknown for school communities - effectiveness and social relations gaps*

The NbS field requires expanding its research on benefits synergies and trade-offs, as currently only a handful of studies document such positive and negative interactions for different user groups (Dumitru et al., 2020). Moreover, acknowledging the co-benefits of NbS could foster their mainstream (Giordano et al., 2020) and failure to do so may hold back their implementation (Sarabi et al., 2019). For GI4AQ+, co-benefits, trade-offs, and disservices may be extrapolated from evidence concerning other GI, but they have not been specifically explored in the school context. Understanding these synergies and trade-offs is critical to prevent undesired outcomes derived from green barrier implementation in schools and to support sensible designs that effectively work for the school communities.

4. *Green barrier implementation in schools is unclear – design and implementation gaps*

Knowledge shortfalls on NbS implementation processes hinder their wider adoption (van der Jagt et al., 2020). Kabisch et al. (2016) reinforce that and call for knowledge-building on the instruments and tools needed to successfully implement NbS. In the case of green barriers, the lack of comprehensive guidance on their co-creation and implementation, from technical to governance aspects, poses a hurdle to their development. Furthermore, green barriers in schools may have specific requirements to satisfy their special embedded communities and, as Onori et al., (2018) highlight, it is important to consider the particular needs and wants of schools to prevent and overcome barriers to GI implementation. Therefore, exploration of the specific implementation processes of green barriers in schools is needed and could help practitioners and school communities to create multifunctional GI4AQ+.

5. *Green barrier implementation remains unexplored in low- and middle-income countries – implementation, effectiveness, and social relations gaps*

In the NbS literature, there are multiple established hurdles that hinder NbS uptake including issues with partner and stakeholder integration, mismatch between short- and long-term engagement, lack of understanding of maintenance and monitoring, and lack of political will or of financial resources (Sarabi et al., 2019; van der Jagt et al., 2020). These hurdles are derived from studies in high-income countries (such as Frantzeskaki, 2019), almost exclusively in the European context (Hanson et al., 2020). On the other hand, barriers and solutions to GI implementation remain unclear in low and middle-income countries which, unlike Europe, are less likely to contemplate and promote NbS in their policy. Therefore, it is critical to develop an understanding of the barriers and solutions to GI4AQ+ in those parts of the world, where poor air quality remains an even larger challenge than in high-income countries.

Disciplinary orientation

The nature-based solutions field is multidisciplinary, as this research is. Experts in NbS constantly advocate for the study and understanding of these interventions from an integrated perspective, which can only be achieved by the conjunction and collaborative work of professionals, academics, and communities knowledgeable in different topics, and working towards a common goal. For example, Nesshöver et al., (2017) recognise that NbS provides an opportunity to carry out multidisciplinary research through an integrative and systemic approach, which requires the input of all relevant stakeholders.

That said, several disciplines converged to carry out this study. The supervisory team is comprised of six researchers. Five of them are based in Sheffield, UK, and possess expertise in landscape architecture, social science, horticulture and ecology, human geography, atmospheric science, and materials engineering. The remaining researcher is based in Buenos Aires, Argentina, and is an agronomy engineer, specialising in vegetation for landscape architecture. The principal researcher and author of this thesis is an environmental engineer with post-graduate studies in applied ecology. Moreover, collaboration with different sectors of society was needed to carry out this research, such as with school communities, landscape architectural practices, engineering companies, local authorities or education and environmental protection ministries, among others. It is important to acknowledge that this is a truly multidisciplinary (additive), interdisciplinary (interactive), and to some extent transdisciplinary (holistic) research study that needed the support of other fields and collaborators outside academia to achieve its aims.

This thesis was submitted to the Department of Landscape Architecture at the University of Sheffield; a department that is diverse by nature. Landscape Architecture is a research form but also a practice of built-up and natural environments. It encompasses elements of engineering, ecology, environmental science, and sociological studies. Therefore, Landscape Architecture is a discipline that can effectively move with the dynamics needed to execute and assess NbS in the real world. Although this study is multi-, inter-, and transdisciplinary, Landscape Architecture holds it together and its disciplinary approach was key to achieving this study's completion.

Research design

To address the aims and gaps in knowledge established above, this thesis proposes four research aims and their respective research questions (Table In1).

Table In1. Research aims and questions of the thesis.

Research aims	Research questions
1. Assess the air pollution mitigation potential of green barriers in school playgrounds, considering the air pollution-vegetation interaction.	Air component • Can a multi-species thin green barrier provide enough protection against NO_2 and PM air pollution for a school in Sheffield, UK? • What is ambient PM around such UK inner-city school made of? • What has a larger influence on school air quality: a multi-species thin green barrier implementation or low-vehicle traffic (due to covid-19 lockdown) in Sheffield, UK? Vegetation component • Do the micromorphological mechanisms of PM capture differ within the plants of a green barrier in Sheffield, UK? • Under similar exposure conditions, does PM density differ within those green barrier plants? • Does leaf surface roughness correspond to higher particle capture for those green barrier plants?
2. Identify the co-benefits, trade-offs and disbenefits of green barrier implementation for school communities.	What are the perceived co-benefits of implementing GI4AQ+ in a Sheffield, UK school according to its school community?
3. Understand the implementation process and practicalities of green barriers in school playgrounds.	Which critical dimensions need to be considered to implement GI4AQ+ in UK schools?

4. Identify barriers and solutions to green barrier implementation in school playgrounds in a Latin American context.	What are the barriers and solutions to GI4AQ+ implementation in a Buenos Aires, Argentina school?

In turn, to fulfil the research aims and answer the research questions, this research comprises two collaborative case studies to implement green barriers in school playgrounds. The case studies are located in Sheffield, UK and in Buenos Aires, Argentina (see Figure In2). The research included planning, designing, constructing, and maintaining green barriers in two school playgrounds that previously had little vegetation. The collaboration took place between researchers, school communities, city governments, the private sector, and volunteers. Green barrier development ran parallel for both case studies, culminating in planting the vegetation in October 2019 in Sheffield and in November 2019 in Buenos Aires. After planting, research activities continued to monitor and assess the specific factors that would answer the research questions.

Figure In2. World map with case study locations in Sheffield and Buenos Aires, and illustrative pictures of the school playgrounds before and after the green barrier implementation.

Action research was the overarching primary research approach used throughout the collaborative implementation of green barriers in the two case study schools. However, the specific research design – and research methods – differ between the case studies, as each was intended to achieve different research aims. The Buenos Aires case study used exclusively social science methods: stakeholder interviews, researcher narratives, and content analysis; whilst the Sheffield case study included scientific and social science methods: air quality monitoring, meteorological conditions monitoring, scanning electron microscopy (SEM), 3D optical profilometry, elemental composition analysis with energy dispersive X-rays (EDX), modelling and statistical analysis, stakeholder interviews, and a questionnaire survey. Figure In3 shows the relationship between the case studies, methods used, and research aims. Each method is further explained in its corresponding chapter (see Figure In4).

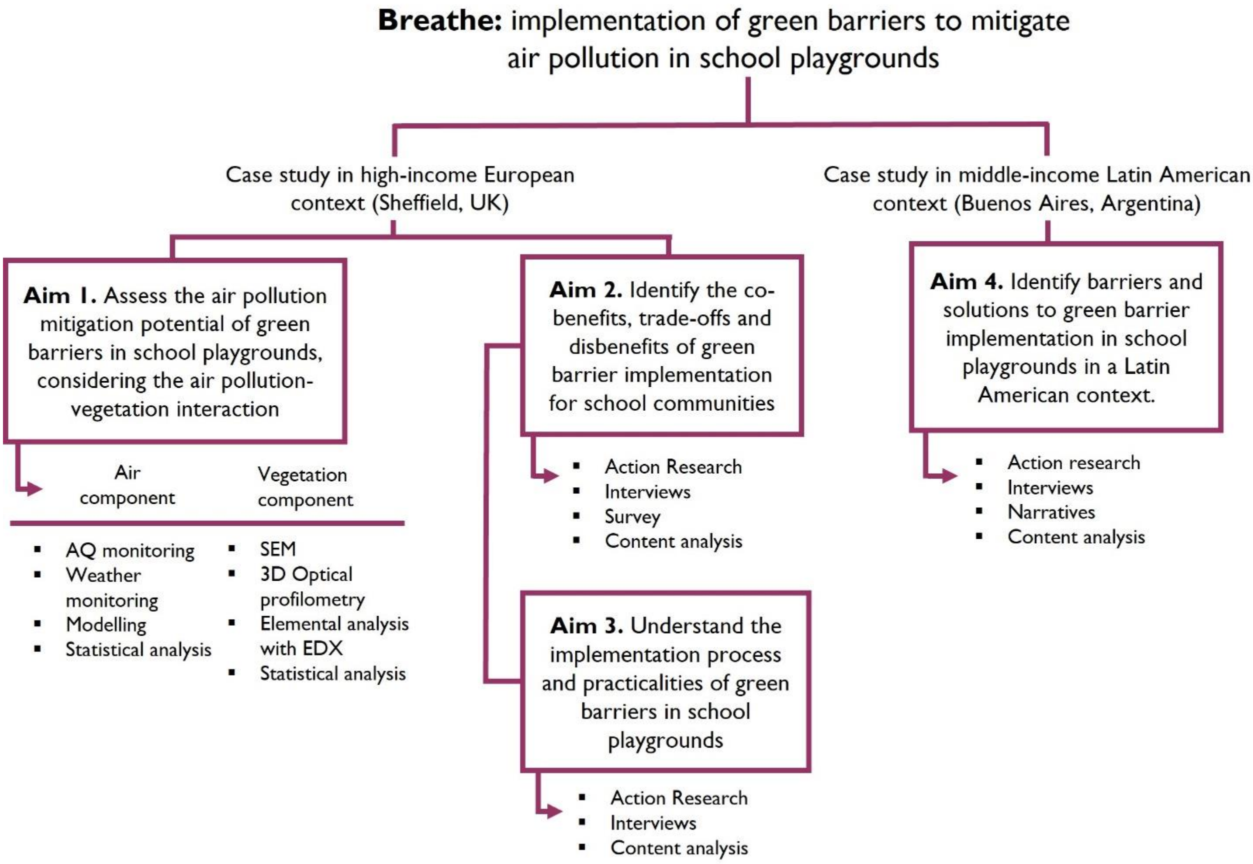


Figure In3. Methods used in this study to address the research aims.
AQ = air quality; SEM = scanning electron microscopy; EDX = energy dispersive X-rays.

Thesis structure

This study is presented as a thesis including published work. In accordance with the Code of Practice of The University of Sheffield, this thesis format includes published work or unpublished work formatted with the intention or possibility of publication. Here, five publications (one in peer-review process) are included, which are presented across the four following chapters. A sixth chapter presents an integrated discussion of the findings, followed by a conclusion that highlights the overall contribution to knowledge. Figure 4 illustrates the structure of this thesis.

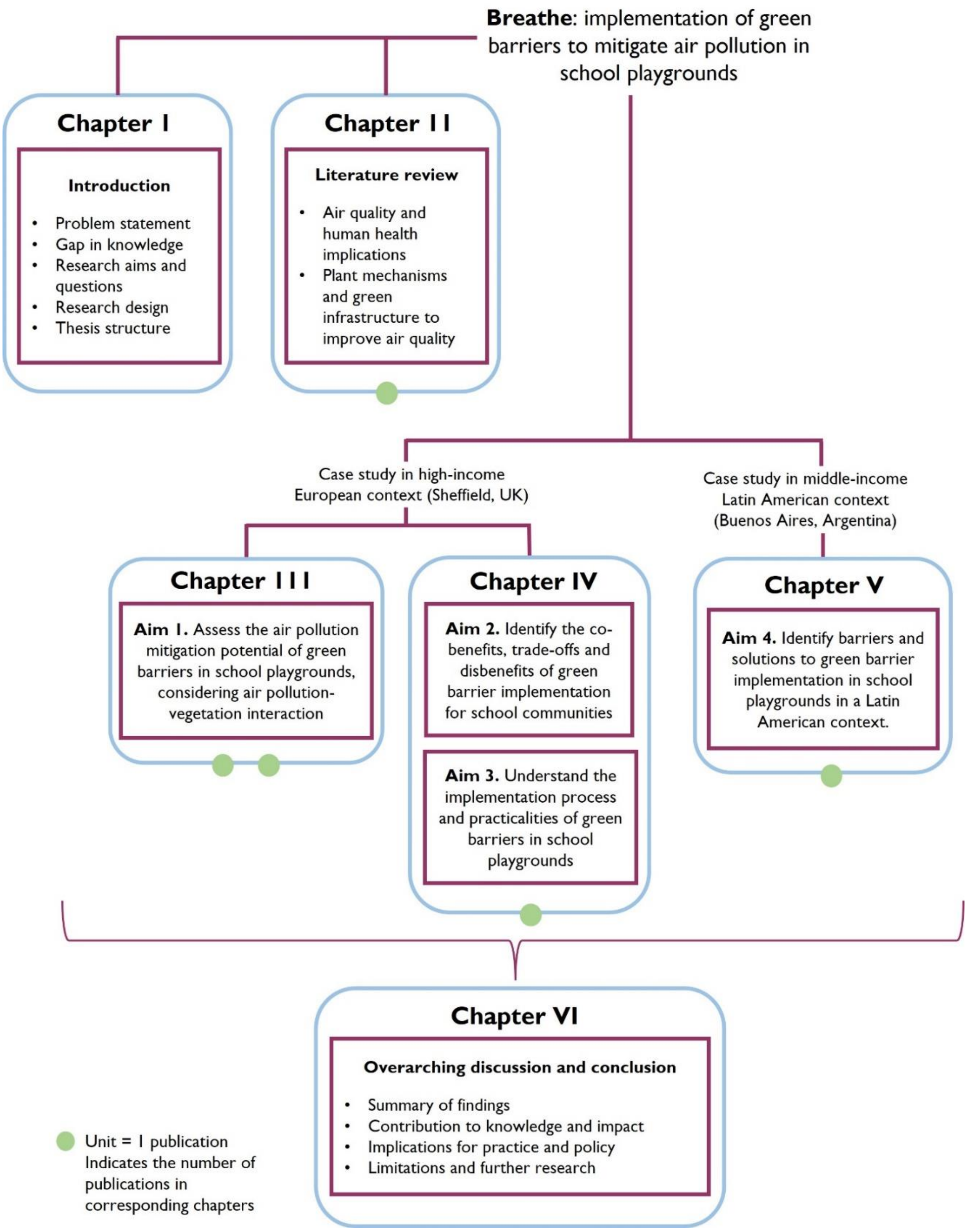
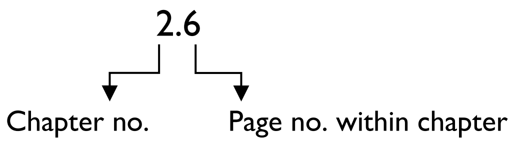


Figure In4. Diagram showing thesis structure, its relationship with the research aims, and number of publications.

Pagination

Due to the nature of this thesis, an innovative pagination structure has been used and is reflected in the table of contents. It consists of the chapter number followed by a period and the page number within that chapter. It can be found at the bottom right of each page, including in published materials. For example:



Chapter I – Introduction

This chapter introduces the context and gaps in knowledge that shaped this research. It states the research aims and questions, and explains the methods followed to answer them. It also defines the structure that this publication format thesis follows.

Chapter II – Plants, air quality and human health

The second chapter introduces key concepts relevant to the field of air quality and green infrastructure via a literature review that summarises the types of pollutants, their health implications, and evidence of the role of vegetation in mitigating air pollution.

Box 1. Details of publication in Chapter II

Redondo Bermúdez, M.C., 2020. Plants, Ambient Air Quality, and Human Health, in: Leal Filho, W., Wall, T., Azul, A.M., Brandli, L., Özuyar, P.G. (Eds.), Good Health and Well-Being. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham, pp. 1–12. https://doi.org/10.1007/978-3-319-69627-0_125-2

Status: Published in the Encyclopedia of the UN Sustainable Development Goals. Available under paid subscription to the Encyclopaedia.

Acknowledgement of contribution: MCRB is the sole author of this publication, and led the conceptualisation, methods, investigation, and full manuscript writing and editing.

Chapter III – Air pollution mitigation potential of green barriers in school playgrounds

The third chapter explores the technical side of green barriers via two publications, focusing on the vegetation-air pollution interaction. It investigates each one of these components to understand the air pollution mitigation potential of green barriers in school playgrounds. It fulfils aim one, which is explored through the Sheffield case study.

Box 2. Details of publications in Chapter III

Redondo-Bermúdez, M.C., Chakraborty, R., Val Martin, M., Inkson, B.J., and Cameron R.W. A practical green infrastructure intervention to reduce air pollution in a UK school playground.

Status: Manuscript intended for open access publication.

Acknowledgement of contribution: MCRB is the first author of this publication, and led the conceptualisation, methods, data curation and analysis, manuscript writing and editing. RH conducted the fixed monitor data analysis/modelling and supported manuscript writing of methods. MVM, BJI, and RWC provided supervision and manuscript editing.

Redondo-Bermúdez, M.C., Gulenc, I.T., Cameron, R.W., Inkson, B.J., 2021. 'Green barriers' for air pollutant capture: Leaf micromorphology as a mechanism to explain plants capacity to capture particulate matter. Environ. Pollut. 288, 1–12. https://doi.org/10.1016/j.envpol.2021.117809

Status: Published in Environmental Pollution. Access with subscription until November 2023, when the green access embargo period ends.

Acknowledgement of contribution: MCRB is the first author of this publication, and led the conceptualisation, methods, data curation and analysis, manuscript writing and editing. ITG conducted optical profilometry and supported manuscript writing of methods. BJI and RWC provided supervision and manuscript editing.

Chapter IV – Critical dimension for green barrier implementation in school playgrounds and perceived co-benefits

The fourth chapter comprises one publication that introduces the GI4AQ+ concept in more detail. Using the Sheffield case study, this chapter focuses on aims 2 and 3. It elaborates on the co-benefits of such GI perceived by the school community, as well as on the implementation process of green barriers in schools.

Box 3. Details of publication in Chapter IV

Redondo-Bermúdez, M. del C., Jorgensen, A., Cameron, R.W., Val Martin, M., 2022. Green Infrastructure for Air Quality plus (GI4AQ+): defining critical dimensions for implementation in schools and the meaning of 'plus' in a UK context. Nature-Based Solut. 2, 2–13. https://doi.org/10.1016/j.nbsj.2022.100017

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Chapter V – Green barriers outside the European context, implementation in Buenos Aires, Argentina

The fifth chapter focuses on aim 4 and uses the Buenos Aires case study. It comprises one publication that explores the barriers facing the implementation of green barriers in Argentine schools. It also delves into the process of GI implementation and the attributes that our case study had to foster green barrier implementation.

Box 4. Details of publication in Chapter V

Redondo Bermúdez, M. del C., Kanai, J.M., Astbury, J., Fabio, V., Jorgensen, A., 2022. Green Fences for Buenos Aires: Implementing Green Infrastructure for (More than) Air Quality. Sustain. 14, 1–25. https://doi.org/10.3390/su14074129

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Chapter VI – Discussion and conclusion

This chapter integrates the research findings and provides an overarching discussion of their meaning. It also elaborates on the contribution to knowledge and significance of the research, the implications for practice and policy, the limitations faced during the research development, and offers suggestions for future research.

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Chapter 11

Plants, air quality and human health

Publication included in this chapter:

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P

Plants, Ambient Air Quality, and Human Health

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Synonyms

Green infrastructure; Nature-based solutions; Outdoors air pollution; Phytoremediation

Definitions

AOT40: The sum of the differences between 40 ppb (parts per billion) and hourly ozone concentrations greater than 40 ppb during an accumulation period. For crops, the accumulation period is defined as 1st May to 31st July (growth period until harvest). For forest, the accumulation is defined as 1st April to 30th September (vegetation/growth period).

Nature-Based Solutions: The European Commission describes them as actions which are inspired by, supported by, or copied from nature; they are used to protect, sustainably manage, and restore natural and modified ecosystems and have multiple cobenefits for health, the economy, society, and the environment.

Green Infrastructure: The European Environmental Agency defines it as a strategically planned network of natural and seminatural areas with other environmental features designed and managed to deliver a wide range of ecosystem services in both rural and urban settings.

Background

Air pollution is most of the time invisible to the naked eye; however, not seeing it does not take away the harmful impacts that it causes to human and ecosystem health. Air pollution is defined as a mix of gases and particles that can cause harm to living beings or materials (Kampa and Castanas 2008).

According to the Sustainable Development Goals (SDG) Report, in 2016 the world's population faced 4.2 million premature deaths from ambient air pollution (outdoor) in urban and rural areas (United Nations 2019), with about 90% of these deaths occurring in low- and middle-income countries (World Health Organization 2018). The situation could worsen in cities as the urban population increases. By 2050, urban areas are expected to accommodate 68% of the world's population, an increase of 2.5 billion compared to 2018 (UN 2018).

The use of plants in Nature-Based Solutions (NBS) can contribute to solving the air quality challenge that urban dwellers suffer. Plants can help to mitigate air pollution through physical and phytoremediation mechanisms. To achieve the incorporation of plants into the intricate urban

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landscape, we can make use of green infrastructure (GI), which aids to add vegetation in diverse forms. However, to maximize air quality gains through GI, it is important to understand the air pollution context of a place including it sources, its geospatial and meteorological conditions, and the existing vegetation.

The following sections intend to give a more in-depth insight into the toxicity and health implications of air pollutants, the mechanisms of plants to mitigate them, and the incorporation of plants into cities for this purpose through GI.

Air Pollution and Health Impacts

Anthropogenic activities are the principal contributor to ambient air pollution. The sources range from fossil fuel burning in industrial facilities, power-generation plants, or motorized vehicles, to waste incineration sites and agricultural field burning practices (WHO 2019; EPA 2014). This type of air pollution is produced by incomplete combustion, and the outcomes are influenced by the type of fuel used. Other sources of air pollution entail fertilizer application, civil engineering construction activities, road dust, vehicle brakes, mining, and other industrial processes such as cement or chemicals manufacturing (Liati et al. 2019; EPA 2014).

On the other hand, natural processes can also generate air pollution, such as volcanic emissions, wildfires, wind-blown mineral dust, soil processes in wetlands, or foliar emissions by plants. Some of these natural processes are sensitive to changes in land cover and soil moisture, which could be of anthropogenic origin (Task Force on Hemispheric Transport of Air Pollution 2010). Moreover, air pollution is transboundary: the pollutants generated in one area can travel to other regions and spread across countries (Vallack and Rypdal 2019) if the meteorological conditions, quantity generated, and pollutants transformation processes permit it (Task Force on Hemispheric Transport of Air Pollution 2010).

Air pollutants can be classified in two categories: trace gases and particulate matter. Trace gases include nitrogen oxides (NO_x), sulfur dioxide (SO_2), ground-level ozone (O_3), volatile organic compounds (VOCs), and carbon monoxide (CO), among others. Three of these gases, NO_2, SO_2, and O_3, are the most common outdoor gases found in cities. Particulate matter and these three trace gases are highly detrimental to human health and the World Health Organization (WHO) has established concentration guidelines to reduce their impacts. Therefore, they are the focus of study in the following sections.

Trace Gases

Trace gases are categorized by their formation in the atmosphere as primary or secondary pollutants. The traffic-related gases NO_2 and SO_2 are considered primary pollutants, that is to say, that they are emitted directly by the source of pollution. In contrast, O_3 is a secondary pollutant generated by the interaction of NO_2 and other precursor gases in the atmosphere in the presence of sunlight (Task Force on Hemispheric Transport of Air Pollution 2010).

The harmful effects of these gases to human health depend primarily on their concentration and their water solubility. Higher solubility gas pollutants (e.g., SO_2) tend to remain in the outer layers of the body, such as the skin and the most external airways, whereas lower solubility gas pollutants (e.g., NO_2 and O_3) can travel further into the respiratory system. The chemical properties of the latter contribute to a more profound irritation of the respiratory tract, including the lungs (Schraufnagel et al. 2019a).

Particulate Matter

Particulate matter (PM) is an aerosol pollutant – i.e., solid or liquid particles suspended in the air (Gawronski et al. 2017) – that can be formed by many different chemicals attaching to the surface of the particle including sulfur and calcium (Qian et al. 2019; Yang et al. 2019); metals such as copper, iron, chromium, aluminum, and manganese, among others (Leonard et al. 2016; Maher et al. 2013); or organic compounds like polycyclic aromatic hydrocarbons (Gong et al. 2019).

Particulate matter is too small to be detected by the human eye, except under certain meteorological conditions and concentrations that create hazy days. It is classified by its size in PM_{10}, $PM_{2.5}$, PM_1, and ultrafine particles (UFP), with a diameter of 10 μm, 2.5 μm, 1 μm, and < 0.1 μm, respectively. The largest fraction (PM_{10}) tends to be found in agglomerates and is more likely to stay in the upper airways and the head. On the other hand, the smaller fractions are found as both, agglomerates and individual particles (Liati et al. 2019). Their small size allows them to enter finer cavities of the respiratory system (Guarnieri and Balmes 2014) and even to translocate across the lung tissues into the blood circulation, reaching almost every organ of the body (Schraufnagel et al. 2019a).

Particulate matter of 2.5 μm is the most extensively studied fraction due to its detrimental health effects and the feasibility to measure its concentration in the air. PM_1 and UFP are less considered in scientific studies and haven't been regulated by the WHO. However, their small size entails increased reactivity and high surface area compared to mass, which make them especially toxic and mobile. Consequently, fine PM can effectively reach many regions of the body, such as the brain and the alveolar region in the lungs (Chen et al. 2016).

Health Impacts

Since all types of pollutants can be present at the same time in the air, it is difficult to allocate the effect of a contaminant to a specific disease. Moreover, the consequences of continually breathing polluted air are not exclusive of the respiratory system and manifest in almost every part of the body.

There is a well-known association between air pollution and asthma, mainly caused by gases' oxidative stress on the respiratory tract and by inflammation of the airways due to the action of PM (Guarnieri and Balmes 2014). This association is not limited to the exacerbation of asthmatic symptoms but related to the potential development of the disease, for instance, during childhood (Khreis et al. 2017). Other respiratory diseases linked to air pollution include bronchitis, chronic obstructive pulmonary disease, and general lung function reduction (WHO 2013); as well as the association to increased emphysema, typically caused by smoking (Wang et al. 2019).

Air pollution effects extend beyond the respiratory system to many other parts of the human body. Typically, air pollutants have been associated with cardiovascular damage, such as arrhythmia, heart failure, vascular inflammation, and thrombosis (Argacha et al. 2018). For instance, a study conducted in Mexico City revealed that children and young adults that experienced sudden death had magnetic nanoparticles in their hearts, possibly the cause of cardiac damage due to the potential of disturbance to the heart's electrical impulse (Calderón-Garcidueñas et al. 2019).

Most recently, the comprehensive review of air pollution and noncommunicable diseases by the International Respiratory Societies' Environmental Committee (Schraufnagel et al. 2019b) has shown evidence of damage to almost every organ of the body. They have listed 42 diseases associated with air pollution that affect the following organ systems: lungs, brain, eyes, heart, liver, blood, fat, pancreas, intestines, genitals, kidneys, joints, bones, and skin. Moreover, other pathobiological processes mentioned include impaired hemoglobin formation, increased sleep apnea symptoms, increased eye tearing, cognitive dysfunction, poor sperm quality, and immune and oxidative stress response leading to cancer, among others.

Exposure to poor air quality by pregnant women is associated with detrimental repercussions to newborn children, causing, for instance, wheezing and asthma in their early years (Schraufnagel et al. 2019b) and delays in cognitive and motor development (Lertxundi et al. 2015; Kim et al. 2014). Air pollution even plays a part in mental health as it has been considered as a risk factor to develop depression and been related to increased unhappiness (Roberts et al. 2019; Vert et al. 2017; Zhang et al. 2017).

To better communicate the health implications caused by air pollution, van der Zee et al. (2016) have expressed its effects in terms of equivalent number of daily passively smoked cigarettes. They took into account four health dimensions with strong scientific evidence that link them to air pollution: low birth weight, lung function, lung cancer, and cardiovascular mortality. The overall estimate health risk of living in a polluted environment varies depending on the air pollutants present: NO_2, $PM_{2.5}$, and black carbon. The effects of each pollutant were converted to an average of daily passively smoked cigarette equivalents; where 10 μg m^{-3} of NO_2 = 2.5 cigarettes, 10 μg m^{-3} of $PM_{2.5}$ = 5.5 cigarettes, and 1 μg m^{-3} of black carbon = 4.0 cigarettes. For instance, they estimated that living next to a freeway in Amsterdam causes a health risk equivalent to an average of 10.1 (+/−1.8 of standard error) passively smoked cigarettes a day. In contrast, reducing traffic by 50% in a busy street lowered the effects of pollution to an estimate of 4.3 (+/−0.9) passively smoked cigarettes.

To reduce the health impacts of air pollution, the WHO offers evidence-based guidance through its *Air Quality Guidelines*, where it presents suggested concentration limits and their rationale. Moreover, many institutions and governments in different countries have their own guidelines and targets (see Table 1). In 2016, nine out of ten urban dwellers were breathing air with $PM_{2.5}$ above the WHO recommended levels. In the same year, it was estimated that 97% of the cities in low- and middle-income countries, and 49% in high-income countries exceeded the WHO air quality guidelines (UN 2019).

In summary, air pollution in cities is primarily caused by anthropogenic activities. It is associated with multiple diseases, encompassing damage to almost all the organs in the human body, and even causing disturbance to our well-being. Gas pollutants affect mainly the respiratory system, while PM can travel deeper and damage other regions of the body, being its chemical composition the determinant of harm. It is urgent to improve air quality and ameliorate human health, for which the use of plants through NBS is a mitigation tool that can address the problem.

Plants' Mechanisms to Reduce Air Pollution

Plants can contribute to purifying the air that surrounds them. This capacity is called phytoremediation, which, in a broader sense, comprises the use of plants to remove pollutants from the environment (i.e., air, soil, and water). The phytoremediation capacity of plants is one of the mechanisms of action of NBS, which mimic the actions of nature to address environmental, social, and economic challenges. The effective use of plants for air pollution mitigation requires the understanding of the processes and mechanisms that occur in and outside the plants' structure and can be categorized based on the nature of the air pollutants.

Trace Gases

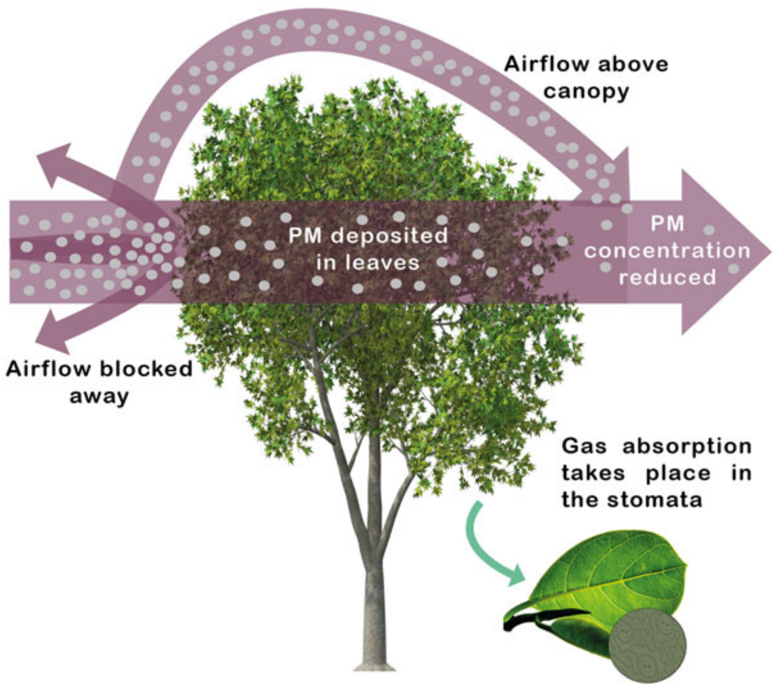
Plant respiration involves a gas exchange between carbon dioxide and oxygen. It takes place in the stomata, which are pores located in the leaves and other plant structures that open and close to let gases diffuse in and out of the plant. Since NO_2, SO_2, and O_3 exist in the atmosphere as gases, they can be uptaken by plants' stomata during the respiration process, which is considered the principal route to enter the plant (see Fig. 1). Additionally, cuticular adsorption is responsible for a minor proportion of NO_2 uptake by the leaves (Geßler et al. 2019). The absorption of high concentrations of these air pollutants can cause adverse effects to the plants; therefore, the European Directive has set concentration limits for the protection of vegetation and ecosystems (see Table 2). Nevertheless, some species are more tolerant to air pollution and can aid in its mitigation.

Small doses of sulfur dioxide can be a source of sulfur to the plants, which is needed to create the amino acids required for a correct system functioning. However, high levels of SO_2 can be toxic, cause injury,and lead to plant death (Weyens et al. 2015); therefore, plants cannot phytoremediate this air pollutant. The European Directive annual limit for the protection of vegetation and ecosystems is 20 μg m^{-3} for SO_2.

In the case of NO_2, the response and tolerance of plants have been more researched due to the need to find species that can act as sinks of this air pollutant. The first serious discussions and experiments emerged during the 1990s when scientists were trying to find a "nitrogen dioxide-philic plant" (Morikawa et al. 1998). The premise is

Plants, Ambient Air Quality, and Human Health, Table 1 Air quality guidelines by international organisms and countries

Air pollutant	WHO	US EPA	European Commission	China	Mexico
Nitrogen dioxide	40 μg/m³ Annual mean	53 ppb Annual mean	40 μg/m³ Annual mean	40 μg/m³ Annual mean	210 ppb 1-h mean
Sulfur dioxide	20 μg/m³ 24-h mean	75 ppb 1-h mean	350 μg/m³ 1-h mean	150 μg/m³ 24-h mean	110 ppb 24-h mean
Ozone	100 μg/m³ Maximum daily 8-h mean	70 ppb Maximum daily 8-h mean	120 μg/m³ Maximum daily 8-h mean	160 μg/m³ Maximum daily 8-h mean	70 ppb Maximum daily 8-h mean
PM_{10}	20 μg/m³ Annual mean	150 μg/m³ 24-h mean	40 μg/m³ Annual mean	70 μg/m³ Annual mean	40 μg/m³ Annual mean
$PM_{2.5}$	10 μg/m³ Annual mean	12 or 15 μg/m³ Annual mean	25 μg/m³ Annual mean	35 μg/m³ Annual mean	12 μg/m³ Annual mean
Reference	WHO (2006)	EPA (2016)	European Commission (2019a)	Ministry of Environmental Protection (2016)	Gobierno de la Ciudad de México (2018)



Plants, Ambient Air Quality, and Human Health, Fig. 1 Diagram of plant's mechanisms to mitigate particulate matter and gas air pollution

based on the capacity of plants to transform NO_2 into innocuous organic nitrous compounds when incorporated into the plant through the nitrate assimilation pathway (Weyens et al. 2015), and on the outcomes of experiments suggesting that NO_2 can stimulate plant growth (Takahashi and Morikawa 2019). Nevertheless, at acute levels, NO_2 causes oxidative stress and decreases the chlorophyll content levels of the plants, although they can recover after experiencing this environmental stress (Sheng and Zhu 2019). Moreover,

Plants, Ambient Air Quality, and Human Health, Table 2 European Directive limit concentration of gas air pollutants for the protection of vegetation and ecosystems

Air pollutant	Concentration limit	Averaging time
Sulfur dioxide	20 μg/m^3	Annual mean
Nitrogen oxides	30 μg/m^3	Annual mean
Ozone	Target value of 18,000 μg/m^3 based on AOT40	Average over 5 years

AOT40 = Accumulated ozone exposure over a threshold of 40 parts per billion
For further information, see "Definitions."
Reference: European Commission (2019b)

the European Directive annual limit for NO_x is 30 μg m^{-3} for the protection of vegetation.

Taking into account the damage that NO_2 can cause, plants can be clustered by their assimilation capacity and sensitivity, where a "high assimilation, low sensitivity" type of plant would be the best suited for air pollution mitigation. Some species identified to fit in this category are *Robinia pseudo-acacia, Sophora japonica, Populus nigra, Gardenia jasminoides, Prunus lannesiana, Acacia dealbata, Hydrangea macrophylla, Eucalyptus viminalis, Hibiscus cannabinus,* and *Nicotiana tabacum* (Takahashi et al. 2003; Morikawa et al. 1998).

Despite these findings, the NO_2 phytoremediation capacity of plants is not entirely understood and is highly variable, even among species with a common taxonomic level. Takahashi et al. (2005) tested 70 different plants and found a 122-fold difference between the highest and the lowest NO_2 assimilation, as well as significant differences in the assimilation capacity of different species from the same family, such as in the Rosaceae family. They also reported greater NO_2 assimilation by deciduous woody plants compared to evergreen species; which is possibly related to deciduous plants' higher leaf nitrogen content, higher net photosynthesis, and higher growth rate. However, keeping their leaves during winter is an asset of evergreen species for air pollution mitigation in cities, where plants' action is needed all year round. Other determining factors of NO_2 assimilation are stomatal conductance/resistance and epicuticular absorption (Geßler et al. 2019).

Simultaneously, some plants can release gases that add to the NOx balance in the atmosphere when they are subjected to an excess of nitrogen deposition, which could come from air pollution. For instance, some conifers and certain herbs with the C3 photosynthetic pathway have been identified as NO emitters (Chen et al. 2012), and care must be taken when considering to introduce them in the urban environment.

Lastly, O_3 is not considered an air pollutant that can be cleaned from the atmosphere through the use of vegetation; rather, it is a highly harmful gas that causes oxidative damage to the plants. Foliar damage from acute O_3 concentrations is displayed as spots and decoloration of leaves, while chronic exposure hinders growth and photosynthesis (Castagna and Ranieri 2009). As O_3 is a precursor of NO_2, the assimilation of the latter by vegetation could decrease its atmospheric concentration and influence the reduction of O_3.

Particulate Matter

Particulate matter is influenced by the wind, as its direction and speed move the particles. When PM flows within a wind current and collides with a plant, the particles face the consequences of this encounter in two ways. First, when the plant is vigorous, like trees with dense canopies, part of the wind gets blocked away as the plant acts as a physical barrier; therefore, the cleaning effect is attributed to the dispersion of PM. Secondly, part of the airflow carrying the remaining PM passes through the plant, which acts as a biological filter that captures the particles on its leaves and other external structures (see Fig. 1). The mechanism of action is deposition of PM on the extensive surface area of the plants (Gawronski et al. 2017). Wind currents can lead particles towards vegetation or plants can attract PM through their electromagnetic charge. Additionally, small size, PM, such as UFP, might be uptaken by the plant through the stomata (Xiong et al. 2014).

Since PM deposition occurs on the surface of the plants, leaf micromorphology and other external traits influence their ability to capture particles. The most influential traits are leaf shape, leaf surface roughness, hairs or trichomes presence, and wax presence.

Broadleaved and conifer plants differ in their PM removal ability. There is a clear difference in the leaf shape between both types: conifers have acicular (needle- and scale-like) shapes, and broadleaved plants fall in all the other categories. Several studies have demonstrated that the particular leaf shapes of conifers are conducive of their high PM retention (Weerakkody et al. 2018a; Song et al. 2015; Beckett et al. 2000). One argument for it is that conifers possess a large "Stoke's number" compared to other plant types, which is positively related to particle capture and influenced by the diameter of the leaf (Beckett et al. 2000). The Stoke's number is defined as the ratio of the stopping distance of a particle to a characteristic dimension of the obstacle, in this case the leaf. Moreover, the small leaf area and acicular shape of conifer leaves cause a more turbulent flow around them which reduces their boundary layer, causing PM to impact and adhere more effectively (Chen et al. 2017). Some examples of conifer species tested and proved efficient in the literature are *Juniperus formosana, Cupressocyparis leylandii, Pinus nigra, Pinus tabulaeformis, Pinus bungeana, Pinus armandii, Platycladus orientalis, Taxus baccata*, and *Thuja plicata* (Przybysz et al. 2019*;* Chen et al. 2017; Song et al. 2015; Beckett et al. 2000).

In terms of broadleaved plants, there is an ongoing discussion about the influence of shape and size in PM capture. Some authors suggest that lobed and lanceolate shapes and small leaf sizes seem better at retaining PM, while contrary arguments of no influence lay on the fact that canopy density is a factor of wind turbulence (i.e., a factor of PM deposition) that cannot be represented by individual leaf shapes. On the other hand, leaf traits that expand the surface area, such as micro-grooves, crease, and ridges, favour PM capture, in comparison to smooth leaf surfaces. Moreover, the presence of hairs or trichomes on the leaves has been positively correlated with PM capture. This highly significant characteristic adds to the complexity of the leaf surface and increases its area, simultaneously preventing PM resuspension (Weerakkody et al. 2018b; Chen et al. 2017; Leonard et al. 2016). An example of the latter is the higher fine particle capture efficiency of pubescent birch (*Betula pubescens*) than of silver birch (*Betula pendula*), attributable to the hairiness of pubescent birch being more than ten times bigger than the other birch species (Räsänen et al. 2013).

Some examples of researched and effective broadleaves species are the following: *Heuchera villosa*, *Geranium macrorrhizum* L., *Sophora japonica, Eucommia ulmoides, Euonymus japonicus, Buddleja davidii, Viburnum opulus, Carpinus betulus, Quercus ilex, Acer campestre, Ulmus glabra,* and *Rosa rugosa,* among others (Muhammad et al. 2019; Weerakkody et al. 2018b; Chen et al. 2017; Song et al. 2015).

Particulate matter can also be trapped by the sticky surface of plant wax. PM can either stay on the surface or get embedded in the wax coating and, in some cases, it can penetrate the plant by diffusion, reaching internal organelles such as the cell wall or vacuoles. Embedded PM is associated with waxy leaves more than with other waxy structures (Gawronski et al. 2017; Song et al. 2015). *Hedera helix* L. is an example of a plant effective at PM capture due to its epicuticular wax (Zanoletti et al. 2018).

Plants' Microbiota

2.7 The interaction of the plants with their microbiota as an influential element of air pollution reduction is a field largely unexplored. Despite that fact, it is known that foliar-associated microorganism can biodegrade or biotransform air pollutants, which is known as phylloremediation. Microorganisms present in the leaves can degrade the air pollutants and aid in the detoxification of the plant. Furthermore, the pollutants that run off to the soil due to rainfall or leaf fall interact with the bacteria and fungi present in the roots of the plant. Current research shows that certain microorganisms in plants have the capacity to degrade organic compounds, and scientists hypothesize that NO_2 and SO_2 could also be processed based on the knowledge of their nitrogen and sulfur cycles. Further research should be carried out to understand better the microbiota-plant interaction and its impact on air pollution (Wei et al. 2017; Weyens et al. 2015).

Although thousands of plants have not been studied to look for their phytoremediation properties, evidence directs us to find suitable plants for specific geospatial and climatic contexts based on leaf shape, leaf micromorphology, and gas assimilation capacity. For instance, conifer species known to be effective at PM capture cannot be used in lowland tropical territories. Nevertheless, there are plenty of species with other characteristics that enhance PM capture, such as rough leaf surfaces and hair presence, that better suit the climate and that might reach a similar effect. Understanding the plants' mechanisms to reduce air pollution can guide the selection of species in a local urban context and safeguard the health of its residents.

Planting in Cities to Reduce Air Pollution

The incorporation of vegetation into the urban landscape can contribute to air pollution mitigation and improve human health. However, to maximize the benefits and prevent any adverse effects of plating in cities, it is important to take into account the suitability and adaptability of the plants to the urban environment. In specific, the meteorological conditions and the built-up environment of cities play an essential role in the effectiveness of vegetation to air pollution mitigation.

Meteorological Parameters and the Built-up Environment

Firstly, the dispersion of air pollutants and the capacity of plants to reduce their concentration depend on meteorological variables. Rainfall and strong winds are two events that not only reduce the pollutants concentration in the atmosphere but also clean the leaves from PM and restore their capacity to capture particles (Chen et al. 2017). On the contrary, rainfall can also add PM to leaves through wet deposition (Vallack and Rypdal 2019) and change the relative humidity of the air affecting the dry deposition speed of the particles (Chen et al. 2017).

Wind speed also influences particle capture efficiency. Beckett et al. (2000) found higher PM capture at faster velocities (8 and 10 m s^{-1}) with a small increment between them; possibly related to a bounce-off effect from the leaves. Moreover, the urban built-up environment alters the wind speed and wind direction. Namely, the presence or absence of buildings creates two built-up environments that affect the airflow conditions: (1) street canyons – streets with buildings along both sides of the pavement, and (2) open roads – streets with buildings only on one side of the road, with buildings widely spaced and far away from the road, or open spaces. The wind conditions of each environment influence air pollution flow and, therefore, determine the selection of the most feasible type of GI to clean the air of a particular area.

Green Infrastructure

Plants can be introduced to the urban landscape through the incorporation of green infrastructure (GI). There are multiple types of GI, including parks, street trees, green barriers, green walls, and green roofs, among others. The different types of GI allow adapting the vegetation to the characteristics of the urban landscape, including the two built-up environments mentioned above: street canyons and the open roads.

In the case of street canyons, it is known that the incorporation of street trees can change the airflow patterns and reduce the dispersion of air pollutants, creating higher concentrations below the canopy at urban dwellers level. However, the potential accumulation of air pollutants under street trees can be diminished by increasing the spacing between the trees and the overlapping of their canopies. Moreover, the use of hedges (low-level dense vegetation) of an average height of 2 m can improve the air quality in street canyons, and the highest reduction reported is 61% considering a single hedge line in the center of the street (Abhijith et al. 2017).

For open road conditions, green barriers (rows of trees, shrubs, or other vegetation types that create a physical and biological obstacle for air pollutants to reach an area of interest) can mitigate air pollution by reducing the concentrations downwind. Studies have shown a reduction in air pollutant concentrations between 15% and 60% behind the barrier; being porosity, thickness, and orientation to wind direction the parameters that contribute the most to its effectiveness (Abhijith et al. 2017).

Green barriers should be oriented based on the prevailing wind condition, where the clean air area is located behind the barrier, i.e., downwind. They should be placed at a distance where the peak level of air pollution occurs in front of the barrier, and be thick enough to deal with the pollution coming from the source (Morakinyo and Lam 2016). According to Baldauf (2017), the optimal vegetation porosity lays between 10% and 50% to create a balance between the air that is blocked away and the air that passes through the vegetation. Additionally, he suggests the use of voluminous barriers to foster air pollution mitigation, and, in the case of large open roads like highways, 5–10 m of thickness is recommended. However, most inner-city streets have limited space for planting; hence, only thinner green barriers can be planted. Inner-city green barriers should have full coverage (from the ground to desired top height) to have a positive effect on local air quality, and a minimum height of 1.5 m (Kumar et al. 2019).

Green fences, a type of green barrier made up of only climber species (specially *Hedera helix* L.), exemplify GI that responds to these particular city conditions. Even though *Hedera helix* L. is not ranked at the top of the air phytoremediation spectrum, neither for NO_2 absorption (Takahashi et al. 2003) nor for PM accumulation (Muhammad et al. 2019), it just needs a narrow space for planting and can achieve full coverage all year long when the plants are mature. These characteristics make green fences highly suitable for air pollution mitigation of specific areas in the urban environment. For instance, a study by Kings College London demonstrated an average reduction of 22% in NO_2 behind a green fence installed in a schoolyard (Tremper and Green 2018).

Lastly, green walls and green roofs are GI that has been created to fit the intricate geometry and lack of space in cities. They consist of small vegetation arranged and attached along vertical (walls, bridges) or horizontal but elevated (roofs) urban infrastructure. They are primarily built for building temperature regulation and can provide air cleaning to an extent. Limited studies have focused on the latter and have shown a maximum improvement in air quality of 95% for UFP and 35% for NO_2 by green walls and a range of improvement between 2% and 52% by green roofs (Abhijith et al. 2017).

Conclusion and Further Directions

The quality of the air we breathe is a crucial human health and well-being factor. Through the human respiration process, air pollutants get into the body, reaching almost every organ and affecting pathobiological processes. Trace gases (NO_2, SO_2 and O_3) and PM are the most detrimental air pollutants to human health and have been regulated by international bodies such as the WHO. Trace gases mainly harm the airways, while PM toxicity is related to the nature of the particle and to its small size, which allows it to get deep into the lungs, penetrate the blood circulation, and reach many other organs of the body.

Since anthropogenic activities are the largest cause of air pollution in cities, the situation can be managed and changed. While tackling the source of pollution should be the main objective, other indirect actions such as the use of GI and particular plant species can help to improve local air quality and bring other cobenefits typical of NBS.

Plants mitigate air pollution through different mechanisms based on the type of pollutant. They help to disperse PM or capture it through deposition on their large surface area, and absorb gas pollutants through the stomata of the leaves. Even though only a few plant species have been studied for their phytoremediation properties, the evidence gives guidance to find suitable plants for specific geospatial and climatic contexts. For PM, the most important characteristics are leaf micromorphology and shape, where traits that enlarge the surface area such as grooves or crease and traits that add texture such as hair presence, enhance PM capture. For gases, the pollutant assimilation is more variable and specific to the species; however, there is not enough scientific evidence to give clear guidance of plants characteristics suitable for gases reduction. Further studies should take this into consideration to close the gap of knowledge, especially to find species with high assimilation and low sensitivity to NO_2, a traffic-related air pollutant. Additionally, the study of phylloremediation would also add to the understanding and application of air pollution reduction by plants and their entangled microbiota and should be further studied.

Not only the plant selection is important to achieve urban air pollution reduction, but also the meteorological parameters and built-up environment of the place should be taken into consideration. These parameters define the most suitable GI to specific city configurations. The use of place-adequate GI serves as a strategy to improve air quality and deal with detrimental health impacts of air pollution.

Cross-References

- ▶ Anthropologically Disrupted Biogeochemical Cycles and the Effect on Sustainable Human Health and Well-Being
- ▶ Assessment of Exposures in Vulnerable Populations: Exposure and Response Modelling for Environmental Contaminants Through a Lifetime
- ▶ Climate Change and Health
- ▶ Environmental Determinants of Health
- ▶ Environmental Health and Sustainability

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Chapter III

Air pollution mitigation potential of green barriers in school playgrounds

Publications included in this chapter:

Redondo-Bermúdez, M.C., Chakraborty, R., Val Martin, M., Inkson, B.J., and Cameron R.W. A practical green infrastructure intervention to reduce air pollution in a UK school playground (intended for open access publication).

Redondo-Bermúdez, M.C., Gulenc, I.T., Cameron, R.W., Inkson, B.J., 2021. 'Green barriers' for air pollutant capture: Leaf micromorphology as a mechanism to explain plants capacity to capture particulate matter. Environ. Pollut. 288, 1–12. https://doi.org/10.1016/j.envpol.2021.117809

Green infrastructure for air pollution mitigation in school playgrounds – a UK case study

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Abstract

Air pollution severely compromises children's health and development, causing physical and mental implications. We have explored the use of site-specific green infrastructure in schools as an air pollution mitigation measure to improve children's environment. By constructing a green barrier (linear vegetation that creates a physical and biological obstacle for polluted air) in a case study school playground in Sheffield, UK, we were able to assess air quality pre-post intervention and compare it with two control sites. Nitrogen dioxide (NO_2) and particulate matter <2.5 μm in size ($PM_{2.5}$) concentration change was evaluated after data collection via three methods: continuous monitoring with fixed devices, 2) monthly monitoring with diffusion tubes, and 3) intermittent monitoring with a mobile device. Data from the former was de-seasonalised to remove the influence of weather and annual variations, and solely observe the impact of the green barrier. Data collected with the remaining methods were used for qualitative spatial analysis. De-seasonalised results indicate a concentration reduction of 13% for NO_2 and of 2% for $PM_{2.5}$ in the school playground after two years of plant establishment. Further reductions in NO_2 levels (25%) were observed during an exceptional low mobility period caused by covid-19 lockdown measures, evidencing the importance of reducing air pollution at the source. Such was not the case for $PM_{2.5}$ levels, which increased during lockdown. Additionally, particles captured by a green barrier plant, *Hedera helix* 'Woerner', were observed and analysed using SEM/EDX techniques. Elemental analysis of these particles indicated natural and potential anthropogenic pollution sources, especially from vehicle traffic. Overall, green barriers are a valid complementary tool to improve school air quality, with quantifiable and significant air pollution changes even in our space-constrained site.

Keywords — air quality, air pollution, green infrastructure, green barrier, nature-based solutions, covid-19 lockdown

1. Introduction

Air pollution continues to be one of the most pressing challenges of the urban landscape, causing environmental quality decline and human health implications. In particular, children's exposure to air pollution has severe repercussions to their health. At the same time, a shocking 93% of children under 15 years old breathe polluted air worldwide (WHO, 2018). These children might have experienced a range of illnesses, from adverse neurodevelopment (Calderón-Garcidueñas et al., 2011; Freire et al., 2010) and mental health problems (Roberts et al., 2019), to decreased respiratory and cardiovascular functions (An et al., 2021; Brugha and Grigg, 2014). Whilst tackling the sources of pollution remains the most recommended way to cut down toxic emissions and protect children's health (Payne-Sturges et al., 2019; Sofia et al., 2020), the current implemented measures worldwide do not seem sufficient for the urgency of solving a mostly anthropogenic problem (Amann et al., 2020). In that sense, additional mitigation measures to protect vulnerable populations have been explored, including the use of green infrastructure (GI) to reduce air pollution at a local level.

Under the nature-based solutions umbrella, GI encompasses any type of natural and semi-natural areas managed to deliver ecosystem services (European Commission, 2013). In the urban landscape, this translates into street trees, parks, green roofs, green walls, hedges, green barriers or fences, among others. GI has the potential to reduce ambient air pollution via multiple mechanisms: gases absorption such as nitrogen dioxide (NO_2), gases and particulate matter (PM) deflection and dispersion, and PM deposition on plants' structures (Redondo Bermúdez, 2020). Simultaneously, various factors affect GI's performance to improve air quality (AQ), such as the urban layout and the local wind direction (Baldauf, 2020), or the plants' composition and their AQ functional traits (Deshmukh et al., 2019; Grote et al., 2016).

The use of GI in school facilities to reduce pupils' exposure to air pollutants has been suggested by the (US EPA, 2015). Some schools have put the GI proposal into practice in the UK – specifically installing green barriers or fences. For instance, schools in Dorset and London have installed ivy panels around the school facilities' perimeter (Groundwork, n.d.; Landscape & Urban Design, 2019); four schools in Manchester are part of a trial run by Lancaster University where evergreen hedges were planted between school premises and passing traffic (Barrett, 2019; BBC Newsround, 2021); and the Mayor of London's Green Fund awarded a grant to twenty-nine primary schools to plant vegetation and boost air quality (Mayor of London Press Office, 2019). Although purposely implemented green barriers exist in these UK schools, there is little/weak scientific evidence on actual air pollution concentration changes. Moreover, most research to date comprises AQ assessments in places with pre-existing GI onsite which do not offer understanding of air pollution pre-post intervention, or are based on modelling studies that present ideal situations for air quality improvement (Al-dabbous and Kumar, 2014; Chang, 2006; Deshmukh et al., 2019; Jayasooriya et al., 2017; Jeanjean et al., 2017; Morakinyo and Lam, 2016; Pugh et al., 2012; Xing and Brimblecombe, 2019). Current research fails to capture real-life constraints to green barriers implementation and their AQ implications based, especially when adapted to school environments.

To fill the gap in research, this study assesses AQ impacts of GI in a real case scenario: a school playground where a green barrier was purposely built. Therefore, pre- and post-intervention conditions can be fully acknowledged. The green barrier was developed for a case study school in Sheffield, UK, and its design responds to real challenges in the school environment and with the school community. Here, we focus on evaluating the GI intervention in terms of NO_2 and PM concentration changes, and on identifying the sources of the latter. The following sections elaborate on the methods followed (Section 2), the AQ outcomes due to the green barrier implementation and a discussion based on three research questions (Section 3): i) can site-specific thin green barriers provide enough protection against NO_2 and $PM_{2.5}$ air pollution in school facilities? ii) what is ambient PM around inner-city schools made of? and iii) what has a larger influence on school air quality: thin green barrier implementation or low-vehicle traffic (due to covid-19 lockdown)? Concluding remarks are presented in Section 4.

2. Methods

2.1 Study design

A green barrier was installed in a case study school in Sheffield, UK. Air quality was monitored pre and post such GI intervention at the case study school (Sch-GB site) and at two other sites serving as control for data comparison and contrast (Figure 1). The control sites are located within a 2 km radius from Sch-GB, and comprise a site in the city centre (City site) – providing an urban background – and another school playground without a green barrier (Sch-NoGB site). Air quality was monitored at those three sites from April 2019 to October 2021 (Figure 2). Sources of air pollution at the study sites include motorised transport and residential/commercial forms of burning, such as woodburning stoves. In Sheffield, 81% of road transport accounts for cars and taxis, while the remaining 19% includes buses, light vans, heavy goods vehicles, and motorcycles (UK Department for Transport, 2020).

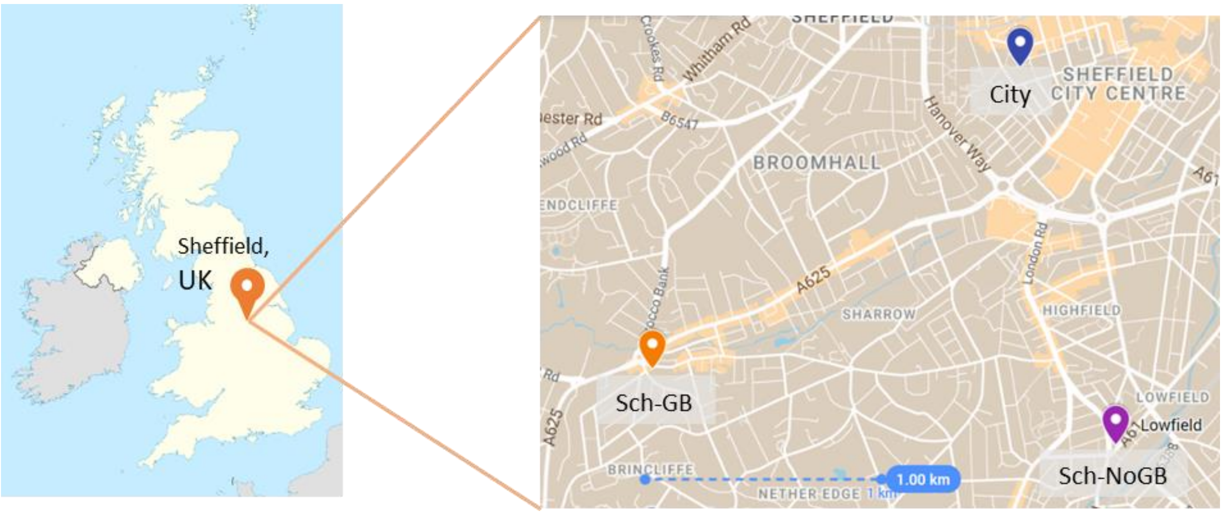

Figure 1. Location of the study sites for air quality monitoring in Sheffield, UK. 'Sch-GB' refers to case study school with a green barrier; 'City' refers to a city centre site (control); 'Sch-NoGB' refers to an urban school site without a green barrier (control).

In light of the study happening during covid-19 pandemic times, which caused citizen's mobility and 'normal' activities disruptions due to UK governmental restrictions and lockdowns to contain the spread (Institute for Government, 2022), only three periods from the AQ campaign were adequate for analysis and comparison (Table 1). These periods were most similar in vehicle traffic flow and comprised the same months for each year of the study. Vehicle traffic flow (vehicle h^{-1}) data are reported for each period and site in Table 2. These data were collected at a 1-hour resolution from the Urban Flows Observatory portal (Ortiz, n.d.), which compiled data recorded by Sheffield City Council. Additionally, a period of low-vehicle traffic and low-citizens' mobility (first lockdown April-

June 2020) was selected for contrast and comparison with the three other periods Table 1. Figure 2 shows the study's timeline with the data collection periods.

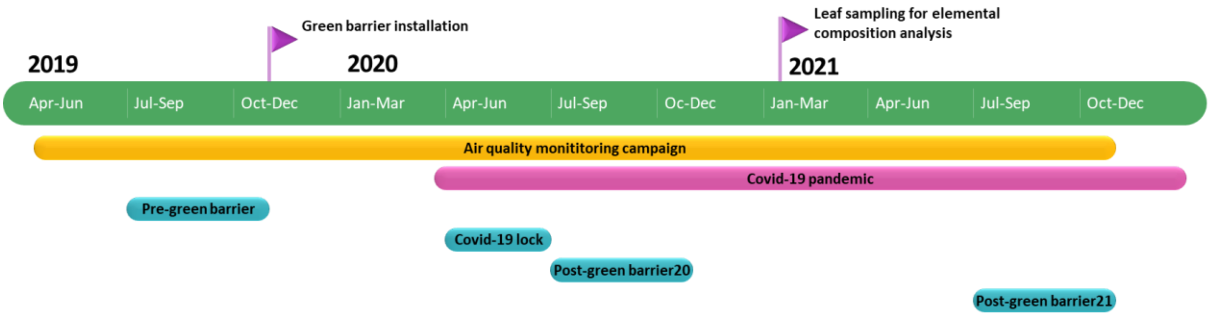

Figure 2. Air quality data collection periods. Blue colour represents periods selected for data analysis. *Figure in colour

Table 1. Periods selected for air quality assessment from the study's data collection campaign.

Data collection period	Abbreviation	Date	Description
Pre-green barrier	pre-gb	July - October 2019	Baseline period: before the green barrier was implemented in Sch-GB site's playground.
Covid-19 lockdown	lock	April – June 2020	Period after the green barrier implementation with first national lockdown measures to contain the covid-19 pandemic. Vehicle traffic and citizens' mobility were highly restricted.
Post-green barrier20	post-gb20	July - October 2020	Period one year after the green barrier implementation. Covid-19 restrictions were eased from 23rd of June to 31st of October 2020. Second national lockdown came in force on 5th of November 2020.
Post-green barrier21	post-gb21	July - October 2021	Period two years after the green barrier implementation. Last phase of covid-19 pandemic restrictions ease, and full reopening of all economic activities on 19th of July 2021.

Table 2. Mean traffic flow (vehicle h^{-1}) at closest sensors to the study sites, per selected periods.

Period	Site		
	Sch-GB Mean ± SE	**City** Mean ± SE	**Sch-NoGB** Mean ± SE
pre-gb	331.2 ± 4.2	231 ± 3.6	NA
lock	197.4 ± 3.6	83.4 ± 1.8	268.2 ± 3.6
post-gb20	303.0 ± 4.2	160.2 ± 2.4	386.4 ± 3.6
post-gb21	342.0 ± 9.0	200.4 ± 3.0	463.2 ± 4.8

2.2 Green infrastructure intervention

A purposely designed multi-species green barrier – the GI intervention – was installed at the case study school (Sch-GB site). Such a green barrier was co-produced with the school community and many other contributors participating in six project stages from October 2018 to January 2020 (so called GF-Sheff project). The project stages included introduction and goal setting, green barrier design, construction, planting, project debriefing, and maintenance (Redondo-Bermúdez et al., 2022).

The case study school has one- and two-story buildings of late-Victorian character, and an active and highly used playground that accommodates 270 pupils in the infant stage (5-7 years old) throughout the day. During pupils' drop-off (8:50h) and pick-up times (15:10h), parents and children walk through the playground and socialise. From 10:30h to 15:00h, the playground is used on and off for play and lunch activities. Additionally, one day a week the playground is used for sports all-day-long, and extra-curricular sports club take place twice a week up to 16:15h.

Before the green barrier was installed, the playground had only a low stone-wall (0.60-0.75 m high) and spaced metal railings (which allowed air flow) as a separation from the adjacent streets (Figure 3). These streets are in close proximity to the school, between 1.90-2.20 m away from the playground's perimeter. Motorised vehicle traffic continuously circulates around the school, and car parking is available on one street adjacent to the playground (Figure 4). Moreover, residential and commercial facilities dominate the area. Therefore, local air pollution sources include vehicle traffic, and domestic and commercial activities.

The green barrier construction started in July 2019 with groundworks preparations and culminated in late October 2019 with local community's supported planting (Figure 2). The multi-species green barrier comprises a mix of 31 different taxa planted along the playground's border (Figure 4), which extends for 60 m. Its height ranges from 2.2-2.4 m. Its width is 0.9 m continuously, except on the northwest corner of the playground, where it extends up to 1.30 m. Five taxa act as the green barrier's structural plants and are the key components of air pollution deposition, deflection, and dilution. The remaining taxa are complementary plants that add sensory interest and an aesthetic design. All the plants were incorporated in an almost-mature stage that created a low-porosity green barrier, providing an immediate screening effect. Further information on the characteristics of the green barrier and the species used can be found in previous studies (Redondo-Bermúdez et al., 2022; Redondo-Bermúdez et al., 2021). Pictures of the Sch-GB site before and after the green barrier implementation are depicted in Figure 3, and Figure 4 provides detailed information on the taxa used for the green barrier and its planting design.

	View from inside the playground	View from street
Before green barrier imp.		
After green barrier imp.		

Figure 3. Pictures of the case study's school playground before and after the green barrier implementation (Sch-GB site). *Figure in colour

Plant name	Planting plan code	Plant name	Planting plan code
Structural plants		**Herbaceous plants**	
Hedera helix 'Woerner'	Hed Woerner	*Alchemilla mollis*	Alc mol
Juniperus scopulorum 'Blue Arrow'	Jun Blu	*Anemanthele lessoniana*	Ane les
Thuja occidentalis 'Smaragd'	Thu SMA	*Asplenium scolopendrium*	Asp sco
Chaemacyparisus lawsonia 'Ivonne'	Cha Ivo	*Bergenia cordifolia* 'Purpurea'	Ber Pur
Phyllostachys nigra	Phy nig	*Calamagrostis x acutiflora* 'Karl Foerster'	Cal KF
Shrubs		*Deschampsia caespitosa* 'Goldtau'	Des Gol
Choisya ternate	Cho ter	*Geranium endressii* 'Wargrave Pink'	Ger War
Cornus alba 'Sibirica'	Cor Sib	*Heuchera micrantha* 'Palace Purple'	Heu PP
Cornus sanguinea 'Midwinter Fire'	Cor MF	*Liriope muscari* 'Big Blue'	Lir Big
Erica carnea 'Springwood Pink'	Eri SP	*Nepeta* 'Six Hills Giant'	Nep SHG
Erica carnea 'Springwood White'	Eri SW	*Polystichum setiferum*	Pol set
Euonymus fortuneii 'Emerald Gaiety'	Euo Eme	*Salvia officinalis* 'Purpurescens'	Sal Pur
Fatsia japonica	Fat jap	*Sedum spectabile* 'Brilliant'	Sed Bri
Hypericum 'Hidcote'	Hyp Hid	*Stachys byzantina* 'Big Ears'	Sta Big
Lavandula angustifolia 'Hidcote'	Lav Hid	*Verbena bonariensis*	Ver bon
Rosmarinus officinalis 'Miss Jessopp's Upright'	Ros MJU	*Sarcococca confusa*	Sar con

Figure 4. Planting plan of the green barrier at the Sch-GB site. Blue arrows depict prevailing wind directions, size represents frequency. Modified from Urban Wilderness.

2.3 Air quality data collection

To assess the air pollutants concentration change due to the installation of the green barrier, collection and assessment of AQ data was carried out at the three monitoring sites (Sch-GB as site with GI intervention; and City and Sch-NoGB as control sites), and during the different sampling periods (pre-gb, lock, post-gb20, postgf-21). Concentrations were measured for NO_2 and $PM_{2.5}$ via three methods: 1) NO_2 and $PM_{2.5}$ continuous monitoring with fixed devices, 2) NO_2 monthly monitoring with diffusion tubes, and 3) $PM_{2.5}$ intermittent monitoring with a mobile device. Additionally, meteorological conditions were recorded using a weather station (OTT MetSystems) installed at Sch-GB. The weather station measured air temperature, relative humidity, air pressure, wind speed and direction, precipitation intensity, and global radiation in 15-min intervals. Details of each AQ data collection method are described in the following sections.

2.3.1 Continuous monitoring with fixed devices - NO_2 and $PM_{2.5}$

Each study site had a fixed AQ monitor measuring air pollutant concentrations continuously through the day. Therefore, NO_2 and $PM_{2.5}$ data were extracted from each monitor's data portal at a 1-hour resolution. Consequently, 24 measurements (in $\mu g\ m^{-3}$) were collected per air pollutant for each day of the data collection periods. Data were available for all sites and all periods, except for NO_2 during lock and post-gb20 periods at Sch-GB site.

The use of fixed monitors for AQ assessment is a common practice by governments and researchers alike. Following extensive AQ research in Sheffield using reference monitors and low-cost sensors and considering the cost feasibility (Chakraborty et al., 2020; Munir et al., 2019), the research team opted for collecting data via both types of monitors. Details of each monitoring device corresponding to the study sites are shown in Table 3. City and Sch-NoGB sites have reference sensors managed by UK Department for Environment, Food and Rural Affairs (DEFRA), and Sheffield City Council, correspondingly. For the Sch-GB site, a low-cost monitor (AQ Mesh, V5.0) with medium accuracy was installed in the school facilities (Figure 5). This monitor's performance is reliable (Environmental Instruments Ltd, n.d.) and has been used in several studies (Breathe London, 2021; Merico et al., 2019; Wong et al., 2019; Zauli-Sajani et al., 2021), including school facilities (Castell et al., 2018; Mohammed et al., 2022). It has an internal weather sensor that corrects data for weather effects using proprietary software, and data is also O_3-filtered to correct for cross-gas effects (eliminating O_3 sensitivities and providing accurate NO_2 concentrations). Moreover, to refine data quality, correlation between the low-cost monitor with reference sensors from the control sites was carried out, and concentrations were scaled.

Table 3. Fixed air quality monitors specifications for each study site.

Study site	Air quality monitor type	Air quality monitor specifications	Monitoring technique	References
Sch-GB (green barrier intervention)	Low-cost (medium data accuracy) Data quality: • Proprietary software for air pollutant concentration correction from cross-gas effect and from cross-interference with environmental conditions, developed by the manufacturer. • Data correlation and scaling with reference sensors.	AQ Mesh V5.0 Developed by Environmental Instruments Ltd. Monitor at 1.7 m above ground level, 3 m away from closest road	NO_2: Electrochemical $PM_{2.5}$: Optical particle counter	(Environmental Instruments Ltd., n.d.; Environmental Instruments Ltd, n.d.; Munir et al., 2019)
City (control site – city centre)	Reference (high data accuracy)	Monitoring station from DEFRA's AURN Station from ground level to 3 m high, 15 m away from closest road	NO_2: Chemiluminescence $PM_{2.5}$: Tapered Element Oscillating Microbalance	(Munir et al., 2019; UK Air Information Resource, n.d.)
Sch-NoGB (control site – school)	Reference (high data accuracy)	Monitoring station from Sheffield City Council Station from ground level to 2.5 m high, 3.5 m away from closest road	NO_2: Chemiluminescence $PM_{2.5}$: Tapered Element Oscillating Microbalance	(Munir et al., 2019; Sheffield City Council, n.d.)

DEFRA: UK Department for Environment, Food and Rural Affairs
AURN: Automatic Urban and Rural Network

2.3.2 Monthly monitoring with diffusion tubes – NO_2

Diffusion tubes provided by Sheffield City Council were installed inside Sch-GB's playground in three different locations (Figure 5) to measure NO_2 concentrations. This AQ monitoring technique is part of the UK government tools utilised to review and assess mean annual NO_2 concentrations (DEFRA, n.d.). Diffusion tubes are passive samplers of atmospheric NO_2 and provide monthly indicative measurements. Atmospheric NO_2 reacts with the tubes' coated triethanolamine (TEA) cap and, after chemical analysis (colorimetry) by the correspondent laboratory, NO_2 monthly concentrations are calculated and provided (Loader, 2006).

Sheffield City Council manages a network of diffusion tubes in the city, which includes monitoring at Sch-NoGB and City study sites (Sheffield City Council, 2021). Therefore, Sch-GB NO_2 concentrations were compared within the playground and also with the control sites for the four data collection periods (pre-gb, lock, post-gb20, and post-gb21). Local and national co-location studies of diffusion tubes with reference monitors take place every year to adjust NO_2 results. Bias adjustment is already reflected here and included correcting the data with bias adjustment factors from Sheffield City Council studies. These factors are 0.98, 0.93, and 0.93 for 2019, 2020, and 2021, correspondingly. It is worth noting that there are NO_2 measurements for each month of the data collection periods, except for the lock period at Sch-GB, which only has data from June 2020 due to covid-19 disruptions; and the post-gb20 period at Sch-NoGB, which is missing data from July 2020.

2.3.3 Intermittent monitoring with a mobile device – $PM_{2.5}$

To complement the fixed AQ monitoring at Sch-GB, a low-cost mobile device (Aeroqual series 500) was used to measure $PM_{2.5}$ (via optical particle counter), temperature, and relative humidity at eight different locations. Five sampling locations are inside the school playground and three are located on the adjacent streets (Figure 5). Air sampling includes high-pollution times during the school day (pupil's drop-off and pick-up times), which were previously identified via the fixed monitor data. Data collection took place from May-July and September-October 2019 (pre-gb), and from September-October 2020 (post-gb20). During the data collection periods, $PM_{2.5}$ and meteorological conditions (humidity and temperature) were collected with 1-min resolution at each sampling point, for 5 consecutive minutes at a time. A total of 2,074 observations were collected and used for analysis. Due to the mismatch of pre and post green barrier collection periods, caused by covid-19 disruptions, data was clustered by its meteorology. This meant that pre and post GI intervention data with the same mean humidity and temperature were compared. Data clusters included 1) high humidity (81%) and low temperature (14ºC) days, and 2) low humidity (52%) and high temperature (20ºC) days. These thresholds were selected to have similar number of observations pre-post intervention. The mobile monitoring device has been successfully used in other studies (Abbass et al., 2020; Apparicio et al., 2018; Embiale et al., 2019; Oguntoke et al., 2019). Moreover, to improve data quality we conducted a field co-location with the MOBIUS (MOBIle Urban Sensing vehicle) reference sensor from the Urban Flows Observatory, The University of Sheffield (Urban Flows Observatory, n.d.) (Figure S2 in Supplementary Material).

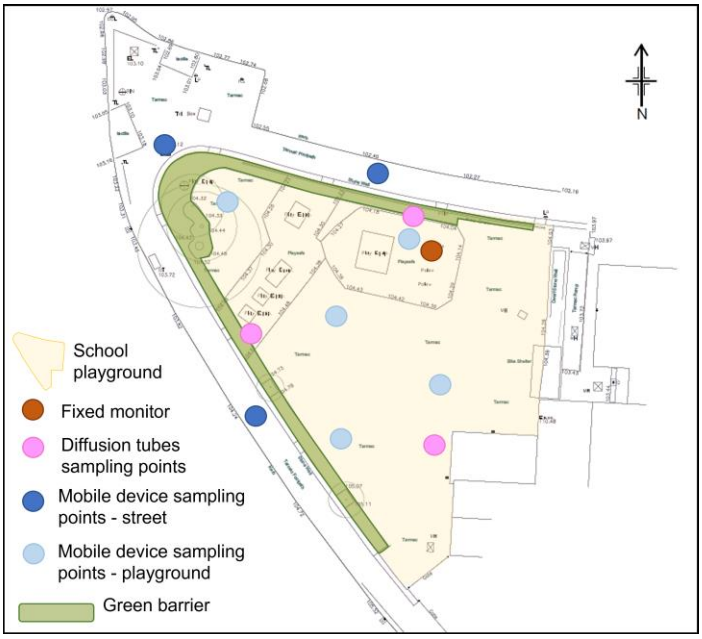

Figure 5. Air quality sampling locations in the case study school (Sch-GB) for diffusion tubes (NO_2), mobile low-cost device ($PM_{2.5}$), and fixed low-cost monitor (NO_2 and $PM_{2.5}$). *Figure in colour

2.4 Air quality assessment

To assess the impact of the GI intervention on school air quality, we carried out a comparison of air pollutant concentration changes from the baseline period (pre-gb) to the three post green barrier periods, for Sch-GB within itself, and with the control sites. Air quality data were processed in a combination of Excel, R software, and Python programming languages, and general statistics were evaluated to calculate air pollutants concentration difference (in %), according to Equation 1:

$$(1) \qquad [NO_2 \; or \; PM_{2.5}] \; difference \; (\%) = \left(\frac{[P_x]*100}{[P_0]}\right) - 100$$

Where P_x represents either NO_2 or $PM_{2.5}$ mean concentrations at each study period (one at a time), and P_0 represents the mean concentration of the same air pollutant during the pre-gb period. Due to different baseline concentrations at each study site, air pollutant concentration differences (in %) were comparable across the city, unlike raw concentrations.

Prior this computation, fixed monitor data was subjected to de-seasonalisation (Section 2.4.1) to reflect the sole effect of the green barrier more accurately. On the other hand, diffusion tubes and mobile device data maintained the influence of the weather, therefore, their results reflect it and were primarily used for qualitative spatial analysis (Section 2.4.2)

2.4.1 Data de-seasonalisation

The global covid-19 pandemic resulted in significant heterogeneity in recorded trends of anthropogenic emissions across the time under study. Variations in air quality as measured are also strongly impacted by meteorological conditions. As in previous studies that investigated the effect of covid-19 restrictions on air quality (Bao and Zhang, 2020; Menut et al., 2020; Mohajeri et al., 2021; Ropkins and Tate, 2021), we eliminated these uncertainties using a de-seasonalising approach. After treating missing data and removing outliers, we used a two-step approach – using the R package 'deweather' (Carslaw, 2021) – to exclude the effect of trend and weather on the air quality data and to normalise it, as detailed below.

- Step 1 – Deweather:

We used the 'gbm' package to investigate and adjust for non-linear relationships between meteorological variables, air quality measurements, and temporal variables, to forecast the variability associated with the hour of the day, day of the week, and week of the year. The latter factored in seasonal weather factors that were not considered by the other components. Additionally, we included a trend term to account for covid-19 related changes in emission patterns during the three-year study period via a Machine Learning (ML) technique based on the Generalized Boosted Regression Tree Model (BRT) (Ridgeway, 2017). The model is formed, as shown in Equation 2:

$$(2) \qquad [PM_{2.5}] = RH + \bar{u} + trend + \emptyset + T\theta + t_{hour} + t_{weekday} + t_{JD}$$

Where *RH* is relative humidity, $\bar{u}$ is the mean hourly wind speed, *trend* represents annual variations, $\emptyset$ is the mean hourly wind direction (degrees, clockwise from the north), and $T\vartheta$ is the mean hourly temperature (^{0}C). Variables representing hour of the day, t_{hour}, day of the week, $t_{weekday}$, and day of the year, t_{JD}, were also considered for the model development.

For each site, 80% of the hourly meteorological and pollutant measurements were used for training the BRT model, with the remaining 20% split for testing and validation, with the goal of developing the most suitable model. This determination is achieved automatically using commonly used metrics such as Pearson's correlation coefficient (r), root mean square error (RMSE) and mean bias (MB). Individual models were developed for $PM_{2.5}$ and NO_2 for the time of the study.

- Step 2 – Meteorological normalisation:

We used the 'metSim' function to create meteorological simulations in order to validate the model and make predictions. After developing the model, the meteorological averaging process was used to predict weather conditions numerous times using random sampling (Carslaw, 2020). The 'metSim' function was used to perform this sampling. The final model was developed to forecast concentrations while accounting for the change in trends caused by covid-19 restrictions and meteorological variability. This method predicts concentrations that are representative of typical meteorology accounting for the covariates (temperature, humidity, wind speed, wind direction, week of the year, weekday, hour of the day, and trend). The model's performance was evaluated using tenfold cross-validation. The model fitting results and the relation between $PM_{2.5}$, NO_2, and the covariates are shown in Figure S1 (Supplementary Material).

2.4.2 Air quality pattern trends

To characterise overall air quality trends of each study site, air pollutant concentrations were analysed using the 'Theil-Sen' tool built-in 'Openair' R package (Carslaw and Ropkins, 2012). The approach provided a non-parametric measurement of trends based on 'the median of the slopes of pairs of points with varied x-values', slope estimation, and bootstrap uncertainty estimate (Ropkins and Tate, 2021). Because these trends during lockdown vary from prior years and may obscure the results, leading to incorrect conclusions, they were removed using a process similar to weather normalisation. De-seasonalised modelled data (15 min resolution) filled the vacant periods and a trend between 2019 and 2020 was stablished. 'Theil-Sen' calculated the monthly mean concentrations and the slopes between all pairs of the data. The final 'Theil-Sen' estimate of the slope (Figure 6) is the median of all these slopes. Air quality pattern trends aid to understand pollution over time at Sch-GB and the control sites, and to observe the green barrier's effect on AQ. Statistical significance to the *p-value*<0.001 was determined from the trends' overlaid slope at the 95% confidence intervals.

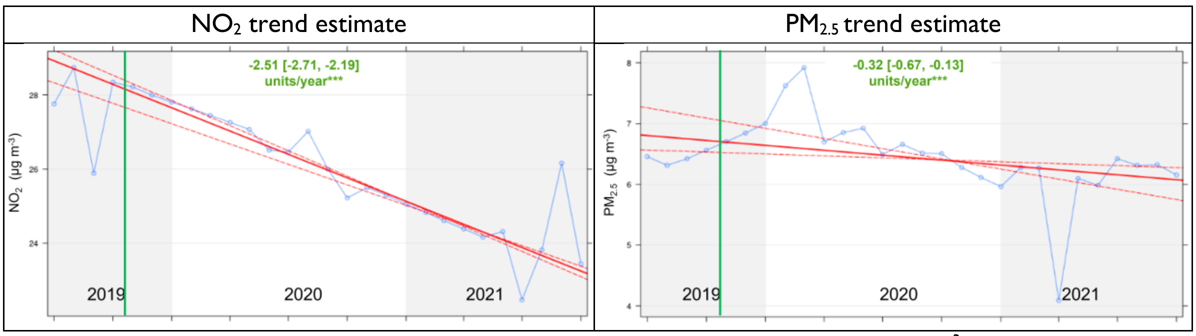

Figure 6. De-seasonalised mean NO_2 and $PM_{2.5}$ concentration trends (blue line, in µg m^{-3}) at Sch-GB site across time using de-seasonalised modelled data. The green vertical line represents the green barrier installation in the playground. The solid red line represents the overall trend estimate, and the dashed red lines represent 95% confidence intervals for the trend based on resampling methods. *** Shows that the trend is statistically significant at $p<0.001$. *Figure in colour

2.4.3 Qualitative spatial analysis

Diffusion tubes (NO_2) and mobile low-cost device ($PM_{2.5}$) data were primarily used for spatial analysis. The lower accuracy of these methods compared to 24/7 hourly data collection from fixed air quality monitors, combined with the ease of monitoring across space, make them more suitable for qualitative analysis in geographical visualisations. Therefore, data was mapped at playground and city scale. This analysis provides a valuable visualisation tool to extract detailed information on pollutants concentration change across the playground and city.

2.5 Qualitative PM elemental composition identification

A green barriers' mechanism of action to reduce air pollution is PM deposition on the plants' surface. In order to identify the sources of ambient PM in the case study school, we carried out an elemental composition analysis of the particles deposited on the leaves' surface of *Hedera helix* 'Woerner', the plants that cover the full length of the green barrier (Figure 4). Six leaf samples were collected in January 2021 at 1.25 m height from the school ground (Figure 2). They were stored in plastic containers, attaching the stem to the bottom of the container to prevent movement during transportation. The samples were observed under a scanning electron microscope (SEM) (Tescan Vega3 LMU) to visually examine and chemically analyse the particles deposited on the surface (Redondo-Bermúdez et al., 2021). The SEM was used at 15 kV, in low vacuum mode (LVM) with a low vacuum secondary electron detector (LVSED). No conductive coating was applied to the leaves. Energy dispersive X-ray analysis (EDX) (Oxford Instruments X-Max 50) was used to qualitatively assess the elemental composition of 18 random particles (three particles per sample). The PM sizes analysed ranged from 2-30 µm, and large regions of agglomerated particles were present on the leaf surfaces. The Aztec Software (Oxford Instruments) was used to evaluate the chemical elements present in each sample.

3. Results and discussion

3.1 Impact of green barrier on playground air quality

Air quality results indicate that the green barrier has mixed impacts on Sch-GB's playground levels: a consistent decrease in NO_2 concentrations, and an environmental conditions-dependent decrease in $PM_{2.5}$ concentrations.

For NO_2, both, de-seasonalised and weather-influenced data analyses indicate an overall negative concentration trend in Sheffield from 2019 to 2021 (Table 4). Not only has Sch-GB site seen a reduction in NO_2 levels since the green barrier was built in its playground, but also concentrations have decreased at both control sites. The city's NO_2 reduction is most likely related to changes in car mobility caused by covid-19 pandemic restrictions, as the main NO_2 source in Sheffield is motorised vehicle traffic (Munir et al., 2020). Traffic flow during post-gb21 period was most similar to pre-pandemic levels (Table 2), making it the most representative period for observing solely the green barrier's impact. Hence, comparing NO_2 concentrations from post-gb21 with pre-gb indicates that this gas pollutant decreased at all sites, however, Sch-GB had a greater reduction than City and Sch-NoGB sites (Figure S3 in Supplementary Material). Subtracting Sch-GB's conc. difference from averaged control sites' conc. difference (Table 4), de-seasonalised results showed an NO_2 reduction of about 13% in the playground, whilst weather-influenced results showed a reduction of about 23%. It is worth noting that direct comparison of fixed monitors and diffusion tubes results is not possible due the de-seasonalisation process of the former, however, each provide complementary information about NO_2 concentration changes in time.

Table 4. De-seasonalised air pollutant mean concentrations and difference (%) against baseline scenario (pre-gb) at city scale.

Air quality data collection	Period	Sch-GB Mean ± SE ($\mu g\ m^{-3}$)	Sch-GB Conc. diff.	City Mean ± SE ($\mu g\ m^{-3}$)	City Conc. diff.	Sch-NoGB Mean ± SE ($\mu g\ m^{-3}$)	Sch-NoGB Conc. diff.
NO_2 – fixed monitor (**de-seasonalised**)	pre-gb	27.53 ± 0.05	-	19.04 ± 0.10	-	24.82 ± 0.11	-
	lock	NA	NA	14.37 ± 0.03	-24.43%	18.50 ± 0.03	-25.44%
	post-gb20	NA	NA	16.02 ± 0.08	-15.76%	19.02 ± 0.06	-23.34%
	post-gb21	22.88 ± 0.11	-16.88%	17.67 ± 0.10	-6.98%	24.73 ± 0.10	-0.37%
NO_2 – diffusion tubes (**weather-influenced**)	pre-gb	24.58 ± 2.17	-	22.25 ± 0.66	-	28.58 ± 0.30	-
	lock	11.50 ± 1.50	-53.22%	14.22 ± 0.29	-36.09%	19.05 ± 0.31	-33.36%
	post-gb20	16.08 ± 1.17	-34.58%	17.83 ± 0.46	-19.87%	26.33 ± 0.51	-7.87%
	post-gb21	14.11 ± 0.63	-42.62%	16.43 ± 0.41	-26.16%	25.12 ± 0.59	-12.12%
$PM_{2.5}$ – fixed monitor (**de-seasonalised**)	pre-gb	5.98 ± 0.01	-	6.74 ± 0.01	-	6.64 ± 0.01	-
	lock	7.50 ± 0.01	25.32%	7.96 ± 0.03	18.16%	7.98 ± 0.03	20.13%
	post-gb20	6.09 ± 0.01	1.71%	6.63 ± 0.01	-1.52%	6.62 ± 0.01	-0.27%
	post-gb21	5.85 ± 0.01	-2.31%	6.74 ± 0.01	0.033%	6.65 ± 0.01	0.078%

Conc. diff. = concentration difference. NA = not available. Green colour indicates pollution reduction and red colour indicates pollution increase, compared to baseline period. *Table in colour

Furthermore, from the three study sites, only Sch-GB had a statistically significant NO_2 decrease trend over time (trend = -2.51 $\mu g\ m^{-3}$ per year, 95%CL = -2.71,-2.19 $\mu g\ m^{-3}$ per year, $p < 0.001$), which suggests that only the site with the GI intervention experienced a sustained NO_2 decrease from pre-gb to post-gb21 periods (Figure 6).

Spatial analysis supports the overall reduction of NO_2 in the city (Figure 7). Moreover, spatial analysis within the playground shows that for pre-gb there was a natural dilution of NO_2 from the roads, i.e. the further away from the road the diffusion tube was located, the lower the NO_2 concentration. On the other hand, once the green barrier was planted, this pattern changed. For all post GI periods, NO_2 levels were lower at diffusion tubes immediately behind the green barrier, suggesting that the greatest AQ impact covers certain range and dilutes with distance from the green barrier (Table 5 and Figure 7). Based on the (Greater London Authority, 2019)'s calculation of the area of protection related to green barrier's height (area of protection in metres = 3height – 3), Sch-GB's green barrier protects up to 4.2 m behind it under ideal conditions.

Table 5. NO_2 mean concentrations in Sch-GB at playground scale, from diffusion tubes.

Air quality data collection	Period	North tube Mean ± SE ($\mu g\ m^{-3}$)	North tube Conc. diff.	South tube Mean ± SE ($\mu g\ m^{-3}$)	South tube Conc. diff.	West tube Mean ± SE ($\mu g\ m^{-3}$)	West tube Conc. diff.
NO_2 – diffusion tubes (**weather-influenced**)	pre-gb	24.75 ± 2.24	-	20.75 ± 3.33	-	28.25 ± 2.29	-
	lock	NA	-	10.00	-51.81%	13.00	-53.98%
	post-gb20	15.75 ± 1.11	-36.33%	14.25 ± 1.11	-31.33%	18.25 ± 1.11	-35.39%
	post-gb21	13.72 ± 1.70	-44.57%	13.25 ± 1.21	-36.14%	15.35 ± 1.55	-45.66%

Conc. diff. = concentration difference. Green colour indicates pollution reduction, compared to baseline period. *Table in colour

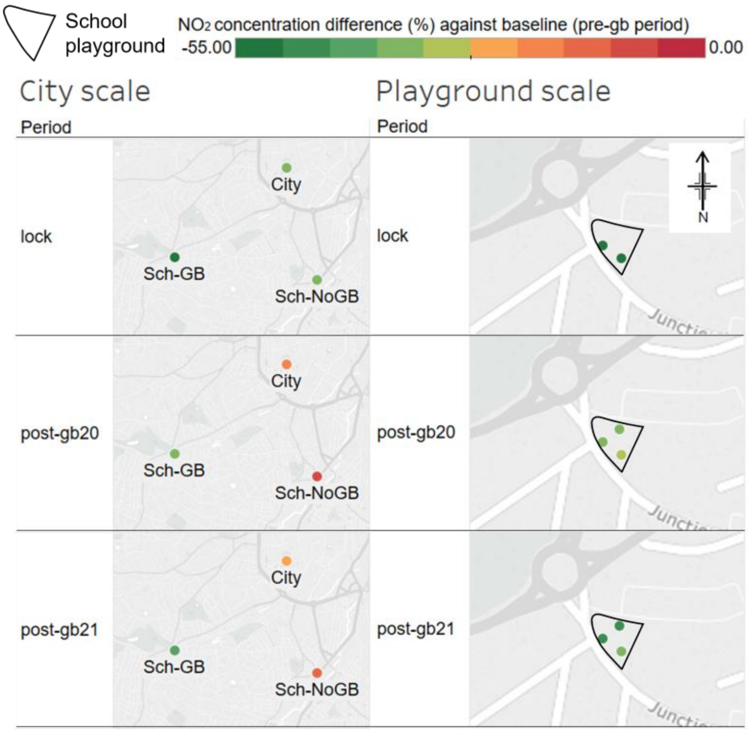

Figure 7. NO_2 mean concentrations difference (%) of sampling periods against baseline (pre-gb), data collected with diffusion tubes. Data is displayed at city scale for inter-sites comparison, and at playground scale for within site (Sch-GB) comparison. *Figure in colour

In contrast to NO_2 results, de-seasonalised $PM_{2.5}$ concentrations do not follow the same declining trend in Sheffield. $PM_{2.5}$ levels greatly increased during the lockdown period and do not substantially differ among pre-gb, post-gb20, and post-gf-21 across the city (Table 4 and Figure S4 in Supplementary Material). Nevertheless, when comparing only pre-gb with post-gb21 as indicated above, $PM_{2.5}$ concentrations decreased about 2% at Sch-GB's playground, whilst increasing at the control sites and, similarly to NO_2, only Sch-GB experienced a statistically significant and sustained $PM_{2.5}$ decrease from pre-gb to post-gb21 (trend = -0.32 µg m^{-3} per year, 95%CL = -0.67, -0.14 µg m^{-3} per year, p < 0.001) (Figure 6).

Previous studies have shown that wind direction highly influences GI's PM reduction efficiency (Abhijith et al., 2017; Deshmukh et al., 2019; Kumar et al., 2022; Pearce et al., 2021). We found that it is also the case for our $PM_{2.5}$ de-seasonalised data at Sch-GB. Prevailing wind directions around the playground come from the west, northwest, and southeast to a lesser extent (Figure 4). Our results show that $PM_{2.5}$ decreases with all wind directions ($PM_{2.5}$ trends over time are all negative and statistically significant to at least the p<0.05 level, Figure 8). However, the conditional probability function visualisation at the 90th percentile (=3.5) showed that south-easterly winds bring the highest level of $PM_{2.5}$ pollution into the playground (Figure 8). This might be related to airflow entering through the open-metal school gate (Figure 4) and could be solved by supplying the gate with a material that hinders air movement (e.g., bamboo/wooden mesh), as a GI implementation is not suitable there. Furthermore, spatial analysis signal to a more restricted airflow inside the playground due to the green barrier (Figure 9). During the pre-gb period, higher $PM_{2.5}$ concentrations occurred on the sampling points next to the divisionary wall between the playground and the streets, and lower concentrations in the middle of the playground. Whilst for post-gb20, $PM_{2.5}$ levels were more homogeneous across the playground.

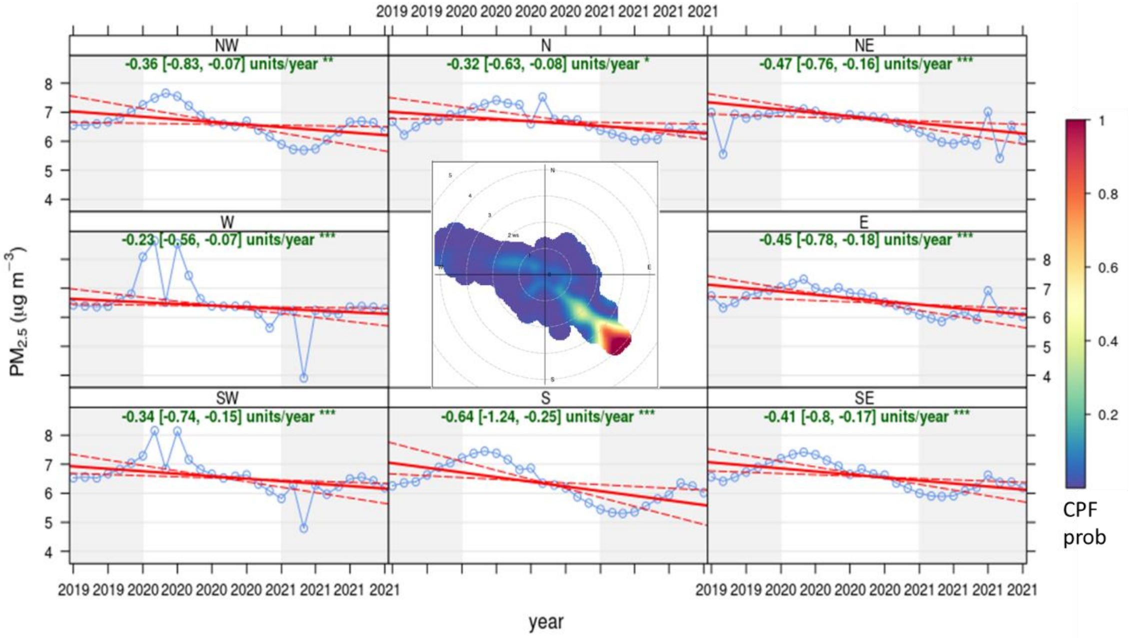

Figure 8. De-seasonalised mean $PM_{2.5}$ concentration trends (in µg m^{-3}) by wind direction at Sch-GB site across time. The solid red line represents the trend estimate, and the dashed red lines represent 95% confidence intervals for the trend based on resampling methods. Statistically significant trends are valid at * p<0.05, ** p<0.01, and *** p<0.001 levels. CFP prob = conditional probability function, for the centre plot at the 90th percentile. *Figure in colour

Other weather covariates impact $PM_{2.5}$ concentrations, such as humidity (15.7%) and temperature (6.4%) (Figure S1), which had an influence on mobile device data. Weather-influenced results from that device showed that relatively hotter and less humid days (i.e., similar to British summer conditions) displayed a reduction in $PM_{2.5}$ concentrations, in contrast to colder and more humid days (Table 6). Overall, seasonality and weather patterns have a considerable impact on PM behaviour. Despite de-seasonalised outcomes indicating a positive impact on playground air quality due to the green barrier, it is small compared to the effect of the underlying weather component.

Table 6. $PM_{2.5}$ mean concentrations and difference (%) between street and playground sampling points during two weather conditions in the Sch-GB site. Data collected with mobile monitoring device.

Weather conditions	Period	Sampling points	Mean +- SE (µg m^{-3})	Conc. diff. against street
High hum - low temp	pre-gb	street	5.82 ± 0.21	-
		playground	6.45 ± 0.20	10.95%
	post-gb20	street	7.03 ± 0.17	-
		playground	7.07 ± 0.11	0.60%
Low hum - high temp	pre-gb	street	5.63 ± 0.12	-
		playground	5.79 ± 0.11	2.79%
	post-gb20	street	6.34 ± 0.14	-
		playground	6.04 ± 0.06	-4.69%

Green colour indicates pollution reduction and red colour indicates pollution increase, compared to mean street sampling points concentration. *Table in colour

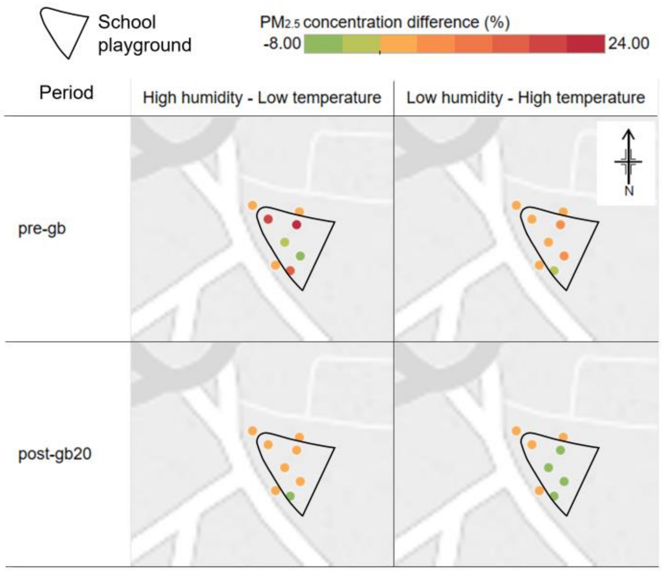

Figure 9. $PM_{2.5}$ mean concentrations difference (%) of playground against street sampling points – data collected with mobile monitoring device. Data is displayed for two sampling periods pre-gb and post-gb20, and two weather conditions. *Figure in colour

The limited protection that the green barrier provides against $PM_{2.5}$ is possibly related to two factors: the narrow width of the barrier, and the multiple and diverse PM sources around the playground. Sources of PM in the case study school include cars, diesel buses (Ropkins and Tate, 2021), light and heavy vehicles, and woodburning stoves from residential areas nearby. In the UK, domestic combustion accounts for 25% of the total $PM_{2.5}$ emissions, with 70% from the use of wood as fuel (DEFRA, 2022b). Moreover, secondary PM formation caused by agriculture fertilizers used for crop growing, especially in spring, could also be a source of PM in the city. Alternatively, there might be internal sources of PM in the playground, for instance from debris plant material generated by the three mature trees on the northwest corner (Figure 4) which can be resuspended by children's movement/play. PM resuspension inside schools has been the case for sandy playgrounds in Barcelona, where sand was resuspended by children's activities and added to the local PM concentrations (Amato et al., 2014).

Regarding GI width, research suggests that thicker green barriers are more effective at AQ provisioning (Baldauf, 2017; Morakinyo and Lam, 2016; Neft et al., 2016). Some studies suggest up to a minimum width of 10 m, although such wide thickness approach seems to be more suitable for protecting populations near long open roads, such as motorways (Baldauf, 2020). In the urban environment, green barriers need to be more accommodating to the different landscape morphologies, where often planting space is scarce. For Sch-GB's playground, the maximum width the school could spare for planting was 1.30 m in its widest section (northwest corner), hence, plant selection assured full coverage of the green barrier's height and low porosity. As such, the green barrier in Sch-GB's playground illustrates successful GI application in an intricate urban layout. Other studies have explored the use of green barriers in open roads or urban street canyons, and conclude that GI's design should be site-specific and context-dependent to foster AQ provisioning (Abhijith et al., 2017; Morakinyo et al., 2016; Tiwari et al., 2019; Tomson et al., 2021). That being said, thin green barriers (1.00-2.20 m) have a place in cities, as modelling studies have shown air pollutant reductions from 2 to 54% (Li et al., 2016; Pearce et al., 2021) and up to 37% in real life case studies (Al-Dabbous and Kumar, 2014; Kumar et al., 2022; Temper and Green, 2018). Our estimates are within those reported ranges, which suggests that the green barrier design seems to be adequate for Sch-GB's playground in reducing NO_2 and $PM_{2.5}$ concentrations, most likely by primarily deflecting air pollution.

3.2 Elemental composition of PM captured by green barrier plants

The green barrier plants used in the GI at Sch-GB were effective in capturing airborne PM (Redondo-Bermúdez et al., 2021), and SEM imaging revealed PM particles distributed across the leaves both individually and in regions of agglomerated particles. Figure 10 illustrates chemical analysis of a large individual pollution particle, and from an extended cluster of $PM_{2.5}$ particles. Overall, the elemental composition of particles deposited on the green barrier plant *Hedera helix* 'Woerner', (planted along the whole length of the GI – Figure 4), indicate both natural and anthropogenic PM sources' contribution. Specifically, seventeen elements were identified on PM deposited on the *Hedera helix* leaf samples. Elements carbon (C) and oxygen (O) were found in all particles and particle clusters analysed and were the most abundant, comprising about 70-80Wt% (mean weight percentage) and 10-20Wt%, respectively. Iron (Fe), aluminium (Al), calcium (Ca), silicon (Si), and platinum (Pt) were the second most frequent and abundant elements. Additionally, chlorine (Cl), sulphur (S), nickel (Ni), potassium (K), phosphorus (P), sodium (Na), magnesium (Mg), Ruthenium (Ru), barium (Ba), and bromine (Br) were identified in trace levels.

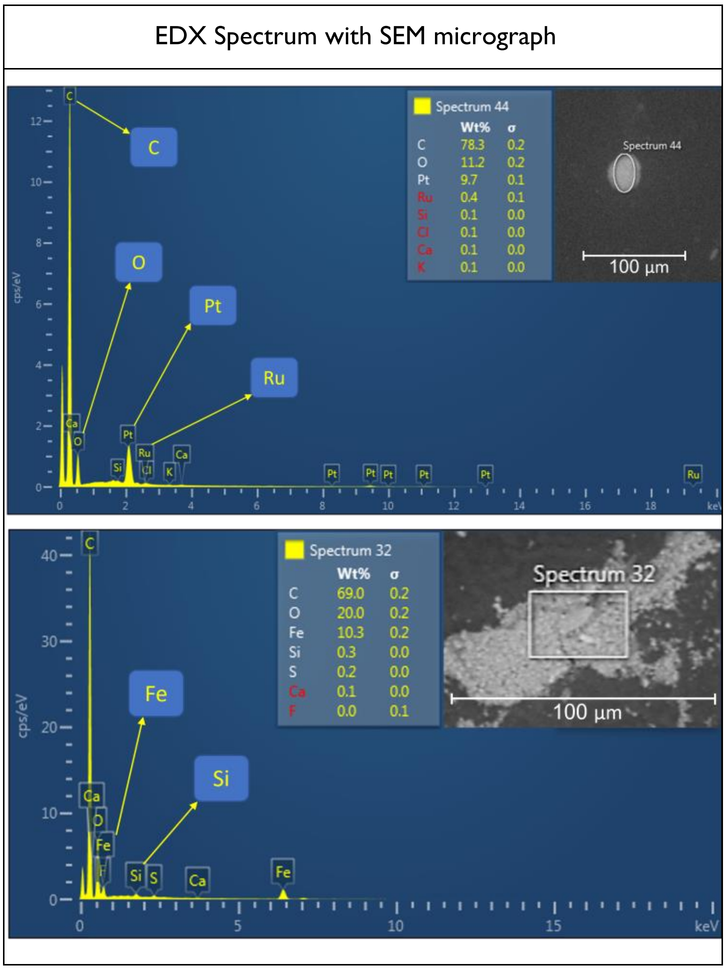

Figure 10. Sample SEM and EDX spectra of elemental composition analysis of PM captured on *Hedera helix* 'Woerner' leaves from green barrier. cps/eV = counts per second/electron Volt; Wt% = mean weight percentage; σ = standard deviation. *Figure in colour

The high abundance of C and O, combined with other elements identified here (P, Ca, K, Na, Fe, Cl, Mg, Al, Si) is typical of the so called 'biogenic aerosols', which are particles of biological nature (living matter, e.g. pollen, fungal spores or plant tissue) (Pachauri et al., 2013; Zeb et al., 2018). In addition, some of the C and O X-rays may originate from the surrounding background leaf tissue. Particles containing Si, Al, and Fe, are classified as 'geogenic particles', or natural particles derived from the Earth's crust like salts (Zeb et al., 2018).

Based on the local air pollution sources, the presence of certain elements within the assessed particles is also consistent with anthropogenic origins. The significant quantity of C identified in all particle spectra partially originate from the presence of organic and elemental carbon from vehicle exhausts (Zhang et al., 2017). Moreover, C and O may also signal the presence of polycyclic aromatic hydrocarbons (PAHs), which are caused by incomplete combustion of organic matter (i.e., from diesel or petrol) and are carcinogenic (Pachauri et al., 2013). Particles containing the transition metals Fe and Ni may be related to abrasion of vehicle parts, especially brake and tyre wear (Gonet et al., 2021; Pant and Harrison, 2013). Less attention has been given to transition metals Pt and Ru, which we found in six and two analysed regions respectively. Pt and Ru signal traffic air pollution because they are used in motors' catalytic converters. Although the aim of catalytic converters is to transform exhaust emissions into less polluting forms, their internal catalyst rare-earth metals leak into the environment. According to (Wiseman and Zereini, 2009), platinum group elements are increasingly found in airborne PM and, although in small concentrations, they may be more bioavailable and toxic to humans than expected. For instance, the platinum group elements are known to cause allergies, respiratory sensitisation, and oxidative damage (Ravindra et al., 2004; Wiseman and Zereini, 2009).

Although it was not possible to determine the exact nature or share of each PM source in this study, the presence of Pt and Ru shows that part of the PM found here corresponds to vehicle exhaust emissions. Additionally, as leaf samples were collected in January, a winter month in the UK, vehicle traffic and home heating with solid fuels (e.g., for woodstoves) are likely to be part of the anthropogenic sources. Our results are similar to other studies that found anthropogenic elements that originate from exhaust and non-exhaust vehicle sources of PM on GI in the UK, such as living walls in Birmingham and hedges in Guildford (Abhijith and Kumar, 2020; Weerakkody et al., 2017).

PM deposition is considered a green barrier mechanism to clean the air, but secondary to air pollution dispersion effects (Diener and Mudu, 2021). Nevertheless, there is clear evidence on PM capture by plant structures and, therefore, a preference to include evergreen species in green barriers (Barwise and Kumar, 2020). Plant selection for Sch-GB's green barrier included not only five structural plants that could indeed form a barrier all year long, but species highlighted in the literature as potential PM sinks due to their micromorphological structures. SEM results here confirm PM deposition on *Hedera helix* 'Woerner' leaves, and a prior study also confirms effective PM capture by other two green barrier plants (Redondo-Bermúdez et al., 2021).

3.3 Impact of low-vehicle traffic and low-citizens' mobility period (covid-19 lockdown) on air quality

Sheffield faced unexpected conditions across the two years of study due to measures imposed by the British government to control the spread of the covid-19 disease. The global pandemic forced a strict first national lockdown from end of March to June 2020, in which people's mobility was restricted and vehicle traffic considerably decreased (Institute for Government, 2022). For the study sites, traffic flow decreased 40-64% compared to 2019 levels (Table 2). Analysis of air pollution during this exceptional lockdown period demonstrate AQ improvements regarding NO_2, but not for $PM_{2.5}$. This NO_2 reduction is greater than the impact of the green barrier alone.

De-seasonalised data indicates that NO_2 concentrations decreased about 25% at the control sites, which was the highest reduction of all periods (Table 4 and Figure S3 in Supplementary material). Moreover, weather-influenced results showed that Sch-GB's playground also experienced a major NO_2 reduction during the lockdown period, greater than post-gb20 by 18% and than post-gb21 by 10%. This decreased in NO_2 pollution was greater at Sch-GB than at the City and Sch-NoGB sites, potentially indicating a double effect of lower traffic plus green barrier. In any case, reduced traffic flow had the greatest positive impact on Sheffield's air quality regarding NO_2, more than the green barrier alone. This finding is consistent with vehicle traffic being the major source of NO_2 in Sheffield (Munir et al., 2020) as well as in the UK (DEFRA, 2022a). These results emphasise the importance of reducing pollution at the source as the first and most effective way to protect children's health, for example reducing motorised vehicle traffic around schools and/or preventing its proximity during pupils drop-off/pick-up times. Consequently, green infrastructure has a place in the set of measures to tackle air pollution yet, as pointed out by (Hewitt et al., 2019), only after 'reducing emissions and extending distance between sources and receptors'.

In contrast, $PM_{2.5}$ levels during the lockdown period substantially increased, with an averaged de-seasonalised $PM_{2.5}$ concentrations about 21% larger across Sheffield. Despite vehicle traffic not being the main source of PM in the city (Munir et al., 2020), a slight decrease in $PM_{2.5}$ could have been expected from the reduced traffic's share during lockdown. However, that was not the case, and PM increased during that period as a result of other particle sources increasing. For example, domestic combustion activities increased, such as cooking or woodstove use, due to people spending more time at home. Garden fires for waste burning also saw a spike during lockdown (London Fire Brigade, 2020), potentially adding to the local PM load. Alternatively, Munir et al. (2021) attribute high PM concentrations to long-range transport of European pollution. Their study in Sheffield used back trajectory of air masses and concluded that winds originating from central and eastern Europe brought pollution and caused secondary PM. These findings evidence the high complexity of PM formation, dispersion, and meteorology interaction. It also highlights the difficulty of PM reduction via GI or other measures.

4. Conclusion

This study has evaluated site-specific green infrastructure, specifically green barriers, as an air pollution mitigation measure in schools. By co-creating and constructing a multi-species green barrier in a real school playground, we were able to understand air pollutant concentrations pre- and post intervention. De-seasonalised data showed that the thin green barrier (0.9-1.30 m max width) reduced NO_2 and $PM_{2.5}$ concentrations by about 13% and 2%, correspondingly, after two years of plant establishment. The downward pre-post intervention trend was statistically significant. The observed reductions were most likely due to air pollutant deflection/dispersion by the green barrier, yet PM deposition on plant structures is also identified as another mechanism of pollutant removal. PM deposited on *Hedera helix* 'Woerner' leaves, a structural plant of the green barrier, was consistent with natural and anthropogenic pollution sources, especially from vehicle traffic including catalytic converters.

The effect of the thin green barrier on school AQ improvement was quantifiable, however, low-mobility measures (principally reducing traffic volume) adopted during the first covid-19 pandemic lockdown had a stronger impact on NO_2 reduction (about 25% at the control sites). This highlights the importance of working towards systematic changes, such as cars' phasing out, low traffic neighbourhoods, and school streets initiatives, to make a direct and strong impact on air pollution mitigation and protect children's health. $PM_{2.5}$ did not decrease during the lockdown period, rather, it increased. This behaviour was caused by change of an array of potential sources: increased domestic burning (including cooking and heating) during lockdown, spring fertilizer pollution, continued diesel bus services, and long-range transport of air pollution from central and eastern Europe. The variety of PM sources highlights the volatility and difficulty of PM pollution mitigation due to its interrelation with meteorology and its cross-continental range, making a case for site-specific intervention to improve local air quality, such as green barriers in school playgrounds.

Green barriers can improve school air quality and, despite their limited potential, changes are quantifiable and significant even in our space-constrained site. Moreover, this nature-based solution can complement other tools and efforts to create healthy environments for children, as well as offer multiple co-benefits to the school community due to the added greenery. Further studies looking at real-case scenario green barriers in other school configurations and other climates could help to supplement our findings and the green barrier design.

6. Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7. Authors contributions

Conceptualisation, MCRB, MVM, RWC; Methodology, MCRB, RC, MVM, BJI; Data curation and formal analysis, RC (fixed monitors data), MCRB (mobile monitor, diffusion tubes data and SEM/EDX); Writing - original draft preparation, MCRB, RC; Writing - review & editing, MCRB, RC, MVM, BJI; Project administration, MCRB; Supervision, MVM, RWC, BJI; Funding acquisition, MVM, RWC, BJI.

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'Green barriers' for air pollutant capture: Leaf micromorphology as a mechanism to explain plants capacity to capture particulate matter☆

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ABSTRACT

Finding ways to mitigate atmospheric particulate matter (PM) is one of the key steps towards fighting air pollution and protecting people's health. The use of green infrastructure is one option that could help improving urban air quality and promoting more sustainable cities. Detailed knowledge of how plants capture particulate matter can support plant selection for this purpose. Previous studies have primarily focused on 2D techniques to assess the micromorphology of plant leaves. Here, 3D optical profilometry and SEM imaging (2D) are used to quantify leaf roughness and other micromorphological leaf traits of three contrasting plant species (*Hedera helix* 'Woerner', *Thuja occidentalis* 'Smaragd', and *Phyllostachys nigra*) located within a mixed-species green barrier. These techniques have allowed us to identify the relative distribution of adhered atmospheric PM with respect to the surface topography of leaves, with high spatial resolution. Leaf surface roughness did not show a direct relationship with PM deposition; however, the descriptors width, depth and frequency of the grooves are important to explain PM capture by the leaves. Additionally, the presence of wax on leaves was relevant for PM adherence. All species captured PM, with their overall PM capture efficiency ranked from highest to lowest as follows: *Thuja occidentalis* > *Hedera helix* > *Phyllostachys nigra*. All green barrier species contributed to air quality improvement, through PM capture, regardless of their location within the barrier. Having multiple species in a green barrier is beneficial due to the diverse range of leaf micromorphologies present, thus offering different mechanisms for particulate matter capture.

1. Introduction

Particulate matter (PM) is considered one of the most harmful air pollutants to human health. In the urban environment, sources of outdoor particulate matter are primarily related to combustion, for instance, from landfill waste incineration, domestic wood burning, industrial activities or petro-chemicals from motorised vehicle traffic (WHO, 2019). The use of vegetation to help mitigate urban air pollution has been explored and applied in recent years as part of the 'nature-based solutions' agenda (European Commission, 2015; McDonald et al., 2016). The growing evidence of plants (green infrastructure) to improve air quality has led to the research of more plant species and combinations to be used in the outdoors urban environment.

It is known that trees and hedges can block and divert airflow containing air pollutants (Hewitt et al., 2019), inhibiting them from accumulating and reaching harmful PM levels. Additionally, PM can be captured by the large surface area of foliage (McDonald et al., 2007), acting as a filter to clean desired areas. The variation in foliage type between species can foster or hinder particle deposition; specifically, the micromorphology of the leaves' surface can impact their ability to capture PM (Zhang et al., 2018). Therefore, it is important to consider leaf micromorphology for the selection of plants for air quality improvement.

The micromorphological traits of plants as a taxonomic function have been extensively studied using Scanning Electron Microscopy (SEM) due to its high-magnification imaging (Yigit, 2017). Ottelé et al. (2010) were pioneers in the development of a methodology for the use of SEM to quantify PM pollution on leaf surfaces. This technique has been used to investigate which are the most conducive micromorphological leaf traits for PM capture in a limited number of plant species (Chen

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et al., 2017a; Weerakkody et al., 2018a; Wang et al., 2019; Zhang et al., 2019; He et al., 2020). Some studies suggest that the most influential micromorphological features for PM retention are leaf surface roughness, presence of trichomes/hairs, cuticular wax, and stomatal density (Weerakkody et al., 2017; Zhang et al., 2018). However, the details and descriptors of leaf roughness for PM capture are still unclear, especially because the topography of leaves is complex in three dimensions (x, y, z).

SEM imaging provides very valuable information on leaf micromorphology and PM location. It is limited to two dimensions, however, causing depth and height of grooves not to be taken into consideration when attempting to identify the locations where particles get deposited. Here, to deepen the understanding of foliar micromorphology, SEM imaging (2D) is combined with 3D surface profiling, which can help to analyse if leaf surface roughness is a factor that influences PM capture, distribution, and retention. Specifically, 3D optical profilometry is used to quantify local leaf roughness across adaxial and abaxial leaf surfaces for different species and evaluate if surface roughness is a key factor in PM capture.

In this study, we aim to identify the variation in air pollution-filtering mechanisms of three plants (*Hedera helix* ‘Woerner’, *Thuja occidentalis* ‘Smaragd’, and *Phyllostachys nigra*) that are part of a mixed-species green barrier in a school playground. SEM and 3D optical profilometry enable determination of the micromorphological traits of each plant species, especially the details of local leaf surface roughness, and PM capture capacity. Specifically, the combined techniques allow us to answer the following research questions: 1) Does leaf surface roughness correspond to higher particle capture? 2) Do the micromorphological mechanisms of PM capture differ within the green barrier plants? 3) Under similar exposure conditions, does PM density differ within the green barrier plants?

2. Materials and methods

2.1. Study site and sampling

The plant species under study are part of a green barrier installed during late October 2019 around a school playground in south west Sheffield, UK. The 60 m green barrier was constructed using different plant taxa and arranged in two layers to serve as a physical barrier to divert pollutants in the local airflows. We selected a green barrier section that comprises three key taxa with different leaf morphologies: *Hedera helix* ‘Woerner’, *Thuja occidentalis* ‘Smaragd’ and *Phyllostachys nigra* (see Table 1 in Appendix A - Supplementary Data). The former two plants are specific cultivars of ivy and white cedar, correspondingly, and the latter is a particular species of bamboo. Here, they will all be referred to as species.

The selected green barrier section is located within 2.5 m of a street with vehicle traffic. The plant species are arranged in the space as a *Hedera helix* climber fence facing the street, immediately followed behind by five specimens of *Thuja occidentalis* and four of *Phyllostachys nigra* that are situated less than 10 cm apart from the climber. The *H. helix* plants climb up a metal grid up to 2.20 m height, whilst the *T. occidentalis* and *P. nigra* are semi-mature specimens of around 2.40 m in height (Fig. 1). Gaps within the *Hedera* (Fig. 1c), also result in some of the lower leaves of *Thuja* and *Phyllostachys* being directly exposed to the roadside conditions. On February 24th, 2020, eight leaf samples oriented towards the street were manually collected from each species for SEM analysis; and on August 12th, 2020, a second sampling event of two leaves per species took place to complement the 3D optical profilometry observations. Mature and healthy leaves sampled at 1.25 m from the ground were stored in plastic containers, attaching the stem to the bottom of the container to prevent movement during their transportation to the laboratory. Samples were stored until lab analysis within two days.

For the inner-city school, potential local sources of particulate matter pollution are motorised vehicle traffic and woodstove burners from residences and businesses close to the school. Based on the flow of vehicles passing through a traffic sensor, approximately 5,200 cars/day circulated on the street adjacent to the green barrier during February 2020 [dataset] (Urban Flows Observatory at The University of Sheffield, 2020). PM pollution at the study site was assessed using an air quality monitor (AQMesh MK3, Environmental Instruments Ltd, UK), which is fixed inside the playground to give continuous measurements, every 15 min. The air quality monitor uses an optical particle counter to calculate PM mass-based fractions. During the two weeks prior to leaf sampling in February, the study site’s particulate matter pollution averaged (±SE) 0.49 ± 0.02 μg m^{-3} for PM_1, 2.01 ± 0.08 μg m^{-3} for $PM_{2.5}$, and 7.95 ± 0.26 for μg m^{-3} PM_{10}. The weather conditions during those two weeks were standard for the winter season in Sheffield: light but constant rain and temperatures below 10 °C. The weather station on site (WS700-UMB, Lufft, Germany) recorded rain 24 % of the time with an average intensity of 0.38 (±1.05) mm h^{-1}, and the temperature averaged 6.13 (±2.50) °C.

2.2. Leaf micromorphology analysis

The collected green barrier leaf samples were examined by Scanning Electron Microscopy (Hitachi TM3030Plus SEM, Japan). Three leaves per species were used to image the adaxial side and three different leaves to image the abaxial side. Sections of 5.0 × 5.0 mm for broadleaves (*H. helix* and *P. nigra*) and 5.0 mm long for the conifer (*T. occidentalis*) were cut from each chosen leaf and observed by SEM using back scattered electron (BSE) imaging in low vacuum mode (15 kV). No

Fig. 1. Images of the green barrier section used for the study in February 2020. Plants viewed from the school playground (a) front and (b) side view: (c) plants viewed from the street. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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conductive coating was applied to the leaves. Micrographs of three randomly chosen spots per leaf section were taken at two magnifications, 600× and 1,200×, accounting for108 micrographs in total.

Leaf samples imaged at 600× and 1,200× were examined for their micromorphological traits. The primary descriptors included surface structures, trichome and hair presence, wax presence, leaf roughness and stomatal density (stomata mm^{-2}). The latter was quantified by counting the number of stoma per unit leaf area of the SEM images, as in Sgrigna et al. (2020):

$$Stomatal\ density = \frac{Stomata\ count}{SEM\ micrograph\ area} \quad (1)$$

Leaf topography was examined in 3D using optical profilometry (ContourGT, Bruker, USA). Quantitative 3D surface profiling of the examined leaves allows determination of leaf roughness values in chosen locations, and assessment of local topographic features, including the 3D shapes, sizes and repetition distances of grooves, creases, stomata and hairs on the leaf surfaces. Areal average roughness (S_a), a standard roughness parameter for manufacturing, was used to quantify roughness of leaves. The higher the S_a value, the higher the roughness. The areal average roughness (μm) is defined as below (Hutchings and Shipway, 2017), where Z_i denotes height of each point, and N denotes number of measured points:

$$S_a \cong \frac{1}{N}\sum_{i=1}^{N}|Z_i| \quad (2)$$

For a given leaf surface profile, the maximum peak height (S_p) and maximum valley depth (S_v) were used to determine the maximum and minimum points within the data, and to assess macroscopic curvature of the examined leaf samples. Here, masked leaf regions of 250 × 250 μm area were used for S_a, S_v and S_p calculation, in order to remove no-signal points around the edges of measurement frames. A Gaussian regression filter was used to remove leaf curvature (low frequency modulation), and roughness values are presented with and without this filter. The application of the Gaussian filter enabled the assessment of the contributions to the leaf roughness from both the broad underlying curvature of the leaf and its localised grooves and ridges.

2.3. Foliar particulate matter density and distribution analysis

The lower magnification 600× SEM leaf images were selected for quantitative analysis of PM count, size and location. In the SEM images, particulate matter could be identified due to higher BSE emission (bright spots) compared to the underlying leaf (darker background) (see Fig. 1 in Appendix A - Supplementary Data). The higher local BSE emission originates from a local chemical composition with higher average atomic-number (Z) compared to surrounding material, or from topographic contrast due to surface edges/regions inclined to the incident e-beam. In this case, the BSE contrast of PM arises primarily from chemical Z-contrast compared to the leaf, which might include combustion products containing metal constituents. For the analysis conditions used, namely BSE imaging and 600× magnification for large area statistical PM analysis, particles <0.2 μm in diameter cannot be identified. These might entail some semi-volatile organic compounds, some sulfuric acid derived compounds, and some organic/carbon PM with chemistry close to the leaf (Harrison, 2020).

The SEM micrographs were processed with ImageJ software - FIJI project (Schindelin et al., 2012), to count the number of particles on each leaf section. Each micrograph was subjected to the unsharp mask, thresholded with the auto threshold tool to minimise researchers' bias, and then processed with the fill and watershed tools before particle analysis. For each quantified particle, the diameter was computed directly from SEM particle image analysis following the same assumptions as in Ottelé, Bohemen and Fraaij (2010), who did not allocate a limit to the circularity value in order to include all various particle shapes.

Taking into account the spatial resolution limit of the micrographs (0.2 μm for 600× and 0.1 μm for 1200×), the particles were then assigned into one of the following categories: PM_1 (from 0.2 to 1 μm), $PM_{2.5}$ (>1–2.5 μm) and PM_{10} (>2.5–10 μm). The Total Adhered Particles (TAP) is the total sum of the PM categories. The particulate matter investigated here is of size dimensions that can be affected by leaf roughness.

Particulate matter areal number density (PM mm^{-2}), referred to here as PM density, was calculated for each species and each leaf side as follows:

$$PM\ density = \frac{PM\ count}{SEM\ micrograph\ area} \quad (3)$$

The imaging and PM density analysis followed was systematically the same for all leaf-types to determine trends between the different plant species. The results derived from these represent PM deposited on the leaves and are not equal to atmospheric PM concentrations.

2.4. Statistical analysis

Statistically significant differences between PM density by species and leaf side were analysed using the R statistical software version 3.6.3 (R Core Team, 2020). The PM density data presented a Gaussian curve behaviour skewed to the right; therefore, non-parametric tests were used to assess statistically significant differences. The Kruskal-Wallis ranks sum test was used to assess the variation in PM density among different plant species, proceeded by post hoc Dunn's test, using the Bonferroni correction. The Wilcoxon rank sum test was used to identify PM density variation between the adaxial and abaxial side of the leaves. Statistical difference was considered at $p < 0.05$ value.

3. Results

3.1. Leaf micromorphology

3.1.1. Leaf surface

Optical and SEM imaging of the green barrier plants revealed markedly diverse structures on the leaves of the different species. *Hedera helix* showed abundant tubular grooves on the adaxial and abaxial sides of the leaves (Fig. 2a and b), and a network of fibres on both sides which was more prominent on the abaxial surface (Fig. 2d). Muhammad et al. (2020) reported that *H. helix* is covered in epicuticular wax of platelet shape, which was not clearly defined in our uncoated samples. The stomata were ~12 μm long, and the guard cells surrounding them formed an oval of ~30 μm in diameter with a deep edge.

Thuja occidentalis exhibited rectangular-shaped aligned ridges of irregular sizes, from 5 to 50 μm long (Fig. 2e). The surface also had a network of fibres like on *H. helix*, but the fibres were less frequent (Fig. 2f). Both leaf sides were covered in a dense wax layer, which was difficult to observe in detail as it tended to melt under the intensity of the SEM beam at high magnification (Fig. 2g). According to Muhammad et al. (2020), the epicuticular wax of most conifers is tubular in structure. The stomata were ~10 μm long and were surrounded by a raised ring of guard cells of ~20–40 μm in diameter.

Phyllostachys nigra had the most notable variation between the adaxial and abaxial sides. The adaxial surface comprised 50–80 μm long, well-regimented aligned cells with undulate margins that interlock neatly with each other. The interlocking cells were located between, and aligned with, the ribs (Fig. 2i) and sometimes interspersed with potential silica bodies (Fig. 2i,k), typical of the Poaceae family (Vieira et al., 2002). The abaxial side also had a distinctly aligned structure, but with a visually more complex surface with protuberances and occasional microhairs (Fig. 2j,l). Both leaf sides displayed a sparse fibres network on their surface. The stomata were ~10 μm long, with the surrounding oval guard cells appearing slightly recessed with respect to nearby cells (Fig. 2l).

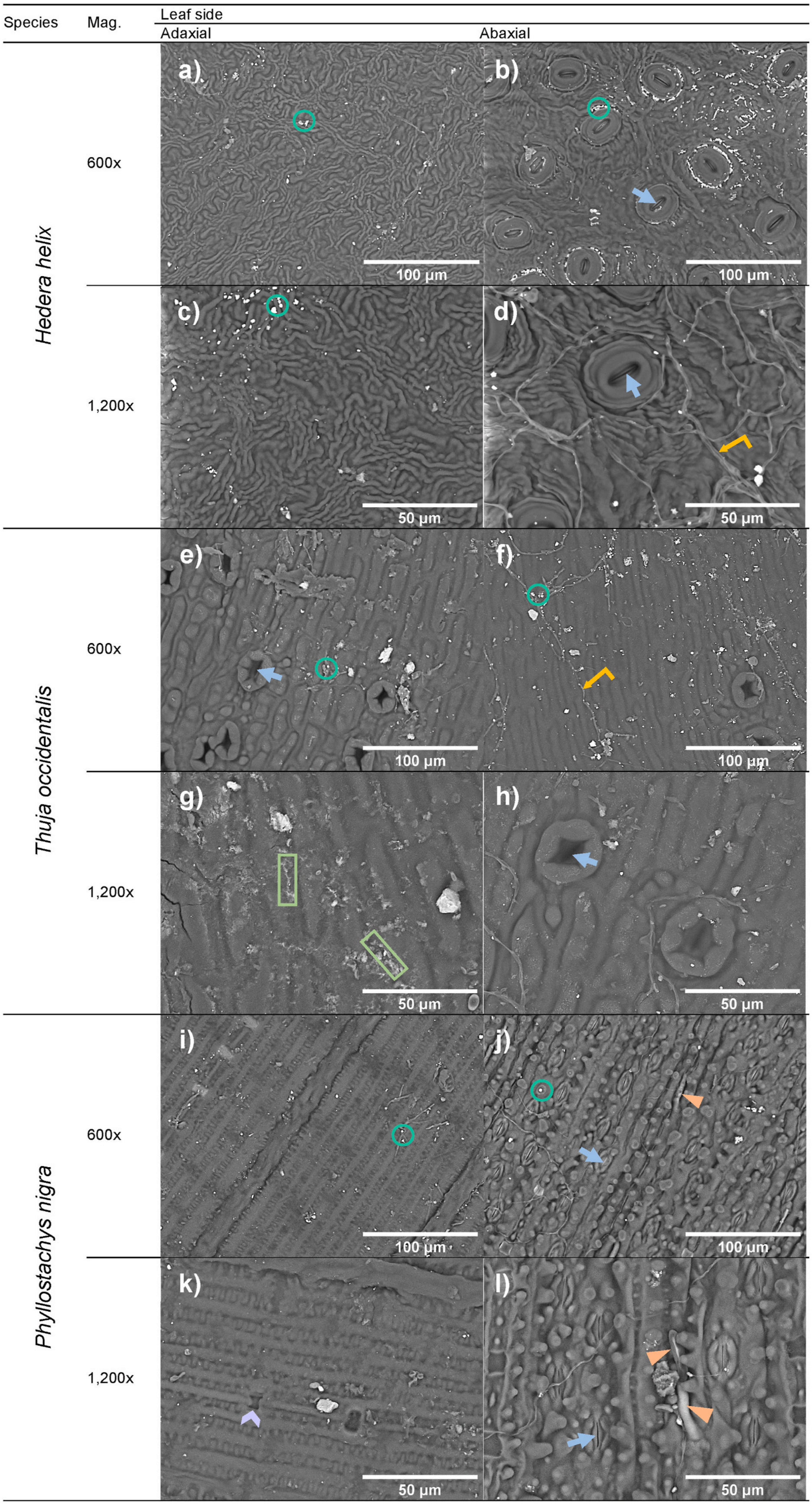

Fig. 2. SEM BSE images of leaf samples exposed to PM pollution, shown by species and magnification (Mag.). (a–d) *Hedera helix*, (e–h) *Thuja occidentalis*, (i–l) *Phyllostachys nigra*. Linear blue arrows point at examples of stomata; L-shaped arrows point at fibres network; triangles point at leaf microhairs and a chevron points at a potential silica body of *P. nigra*; circles encapsulate examples of adhered particulate matter and rectangles encapsulate examples of melted wax in *T. occidentalis*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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3.1.2. Stomatal density

Stomatal density varied considerably among the three species. Stomata were found only in the abaxial side of *H. helix* and *P. nigra* leaves, as they are part of the so called hypostomatous leaves (Xiong and Flexas, 2020). *H. helix* exhibited a well dispersed distribution of stomata, which were ~20–80 μm apart in the studied samples, with random aperture orientation but radial to a central principal stoma. Stomata in *P. nigra* occurred in aligned lines with a zig-zag pattern (Fig. 2j and k) having ~15–30 μm between each stoma, and ~60–80 μm between lines. On the contrary, both leaf sides of *T. occidentalis* had stomata, with uneven separation among them and located close to the intersection between the scales that form the leaf (Fig. 2e,h). It is known that slow-growing species like gymnosperms are part of the amphistomatous leaf group (stomata in both sides of the leaves) (Drake et al., 2019), and our studied conifer falls in this category. Despite having stomata in both surfaces, *T. occidentalis* showed the lowest mean stomatal density of 36.82 ± 12.43 stoma mm^{-2}, being eleven times less than *P. nigra* 413.49 ± 21.19 stoma mm^{-2}, which had the highest density. *Hedera helix* had stomatal density values of 207.69 ± 9.30 stoma mm^{-2}, approximately half of *P. nigra* (Table 1).

3.1.3. Leaf roughness

3.1.3.1. Leaf curvature. Leaf shape and local roughness was measured for the three species using 3D optical profilometry. Due to gentle macroscopic leaf curvature, it was evident that *T. occidentalis* (adaxial side) had the greatest variation in leaf surface height (Fig. 3e). *Hedera helix* (Fig. 3a) was intermediate in this effect, with *P. nigra* (Fig. 3i) having the least macroscopic leaf curvature and surface height variation.

3.1.3.2. Micromorphological level. A Gaussian filter was used to remove the broad leaf curvature in order to better analyse the variations in local leaf roughness (Figs. 3 and 4). Leaf roughness at the micromorphological level (S_a) was greatest for abaxial *P. nigra* from all samples. Roughness for both adaxial and abaxial surfaces were in the order: *P. nigra* > *H. helix* > *T. occidentalis* (Table 1). Despite showing the same order, the magnitude of S_a varies considerably based on leaf side. On the adaxial surface, *P. nigra* (S_a = 0.83 μm) is slightly rougher than the other two species; whereas on the abaxial side, its roughness (S_a = 2.57 μm) doubles that of *H. helix* and is four times greater than *T. occidentalis*.

The abaxial surface of *P. nigra* had the largest distance between maximum peak height (S_p) and valley depth (S_v), of 28.89 μm. The leaf structure comprises a complex pattern of aligned papillae, stomata and grooves (Fig. 3l) that creates a large deviation from the mean line, leading to the highest S_a. The second highest roughness was found for the abaxial side of *H. helix*. Here, the presence of raised stomata and guard cells (Fig. 3d) and the size of the deepest groove (S_v = −20.53 μm) increase the deviation from the mean line. For both, *P. nigra* and *H. helix*, leaf surface roughness was greater on the abaxial side than on the adaxial side. In comparison, *T. occidentalis* had the lowest roughness at the micromorphological level from all species. Its grooves and ridges are less pronounced, ranging from 4 to −2.5 μm depth, and it has no evident deep structures except for stomata (Fig. 3g); which led to a high S_v on its adaxial side (Table 1).

The 3D optical profilometry height maps enable surface height line profiles to be extracted across surface features (Fig. 4). The surface height line profiles reveal notable differences in the size and shape of the micromorphological traits, among species. *H. helix* showed deep grooves of approximately ≤5–10 μm width and −2 to −18 μm depth (Fig. 4a), and its stomata are deep, reaching −20 μm depth (Fig. 4b). Similarly, *T. occidentalis*, had grooves of mostly ≤5–10 μm width (Fig. 4d); however, they were shallow (−1 to −2.5 μm depth); except for stomata which were deeper and wider (~-11 μm depth and ~10 μm width) (Fig. 4c). For *P. nigra,* besides the large surface height difference among its structures, the profiles showed wider grooves ranging from ≤5 to 18 μm width, and these were predominantly above the mean height line because they are created by the raised nearby structures (Fig. 4e and f).

3.2. Foliar particulate matter density and distribution

Particulate matter deposited on the leaves showed a broadly homogeneous distribution of the different fractions for all species (Fig. 5). Regardless of the leaf side, the surfaces were highly dominated by PM_1, with a proportion of particles identified ranging from 78.76 % to 80.26 % among species. In comparison, $PM_{2.5}$ and PM_{10} had a much lower number ratio; with $PM_{2.5}$ ranging from 11.6 % to 17.63 %, and PM_{10} ranging from 2.21 % to 4.60 % of particles (Table 2). Here the spatial resolution limit of the identified particles/particle clusters in the PM_1 category is 0.2 μm (micrographs at 600× magnification). The particles smaller than 0.2 μm which are not detected would further increase the PM_1 proportion, further emphasizing the identified trend of $PM_1 > PM_{2.5} > PM_{10}$ number ratio of captured particles.

SEM imaging revealed that the primary location of adhered PM was in recessed troughs, grooves and edge features (e.g. Fig. 2c), with particularly striking PM capture by the groove around stomata in *H. helix* (e.g. Fig. 2b). Particles were also found at the network of fibres that all species had on their leaf surface (e.g. Fig. 2d,f), and occasionally on protuberances in *T. occidentalis* and *P. nigra* (e.g. Fig. 2j).

Thuja occidentalis had the greatest PM density, when data is combined for both adaxial and abaxial surfaces (Table 3). This was the case for all size fractions. PM density was significantly greater for PM_1 and TAP compared to the two other species. Nevertheless, PM density of $PM_{2.5}$ and PM_{10} fractions were significantly greater for *T. occidentalis* only when compared to *P. nigra*, but not *H. helix*. This fact seems to indicate that both *H. helix* and *T. occidentalis* perform adequately at capturing small PM, but that additional mechanisms promote higher PM capture of the larger fractions for *T. occidentalis*.

Except for PM_1 on *H. helix,* the adaxial side of leaves appeared more effective at capturing PM than the abaxial side (Table 4; Fig. 5). The capacity for *P. nigra* to capture particulate matter (Table 4) reflects its considerably different adaxial and abaxial leaf surface

Table 1
Leaf roughness and stomatal density of plant species measured by 3D optical profilometry, (1) With curvature from leaf as mounted in ContourGT, and (2) Broad leaf curvature removed by Gaussian filter.

Species	Stomatal density	Leaf side	1) With curvature (μm)			2) Leaf curvature removed (μm)		
			S_a	S_p	S_v	S_a	S_p	S_v
H. helix	207.69 ± 9.30 stoma mm^{-2}	adaxial	2.37	7.47	−21.54	0.77	5.34	−18.20
		abaxial	2.57	8.16	−23.39	1.23	5.72	−20.53
T. occidentalis	36.82 ± 12.43 stoma mm^{-2}	adaxial	4.10	12.71	−15.29	0.63	5.54	−11.60
		abaxial	3.06	11.30	−9.20	0.49	2.52	−2.27
P. nigra	413.49 ± 21.19 stoma mm^{-2}	adaxial	1.39	8.41	−9.72	0.83	4.36	−13.82
		abaxial	2.84	14.09	−18.68	2.57	11.12	−17.77

S_a = areal average roughness, S_p = maximum peak height, S_v = maximum valley depth, stomatal density values are calculated as mean ± SE of both adaxial and abaxial sides.

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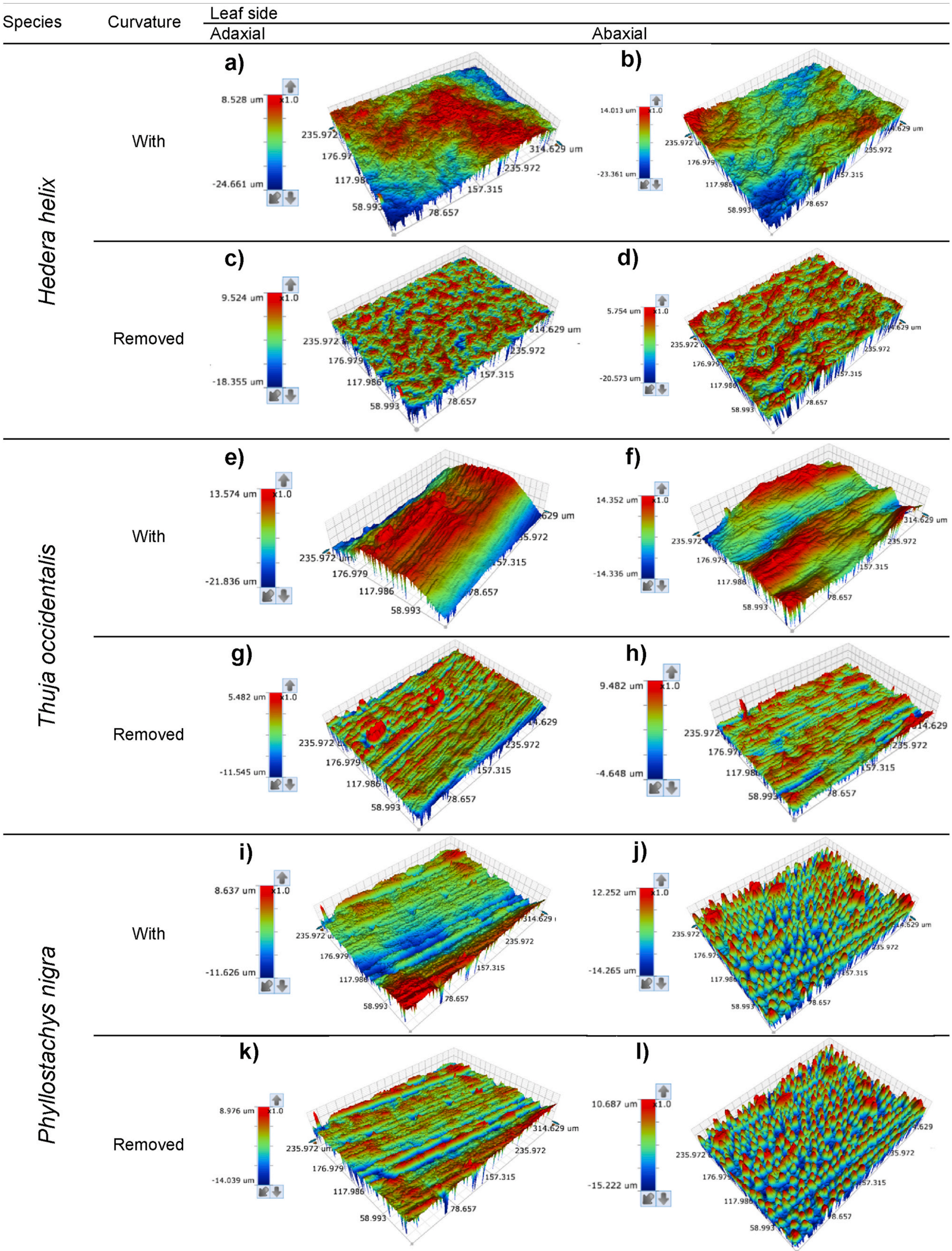

Fig. 3. Leaf surface topography: 3D profiles of adaxial and abaxial leaf surfaces measured by optical profilometry, shown with the curvature of the leaf as mounted ('With'), and with underlying curvature removed by Gaussian filter to show solely the local micromorphology of the leaf surface ('Removed'). (a–d) *Hedera helix*, (e–h) *Thuja occidentalis*, (i–l) *Phyllostachys nigra*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.32

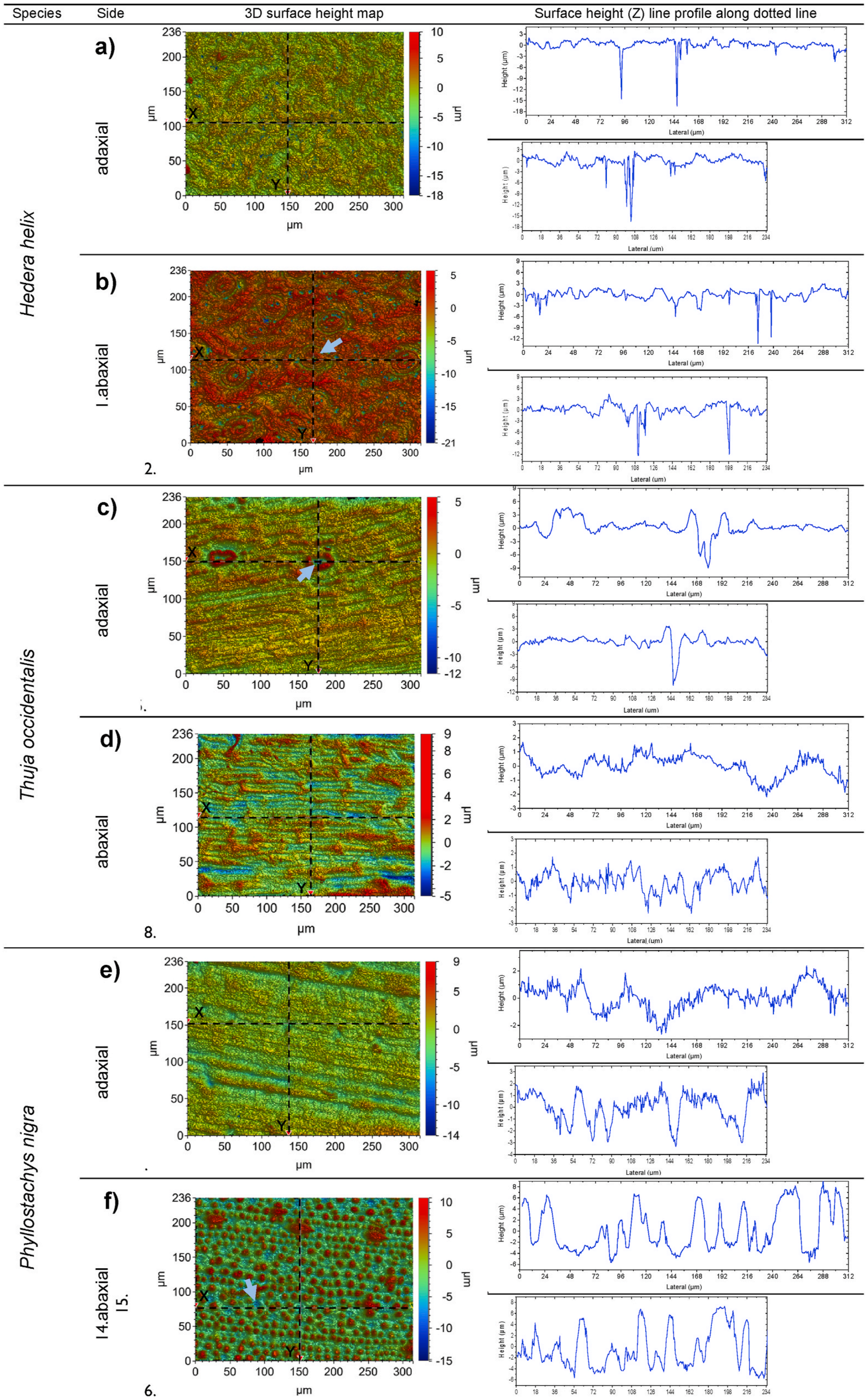

Fig. 4. Leaf surface topography shown by 3D optical profilometry surface height maps (left; curvature removed) of adaxial and abaxial leaf surfaces (a–b) *Hedera helix*, (c–d) *Thuja occidentalis*, (e–f) *Phyllostachys nigra*. Linear blue arrows point at examples of stomata. Surface height line profiles (right), illustrate the variation in surface height due to micromorphological leaf traits such as grooves and stomata along two perpendicular directions (X, Y dotted lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.33

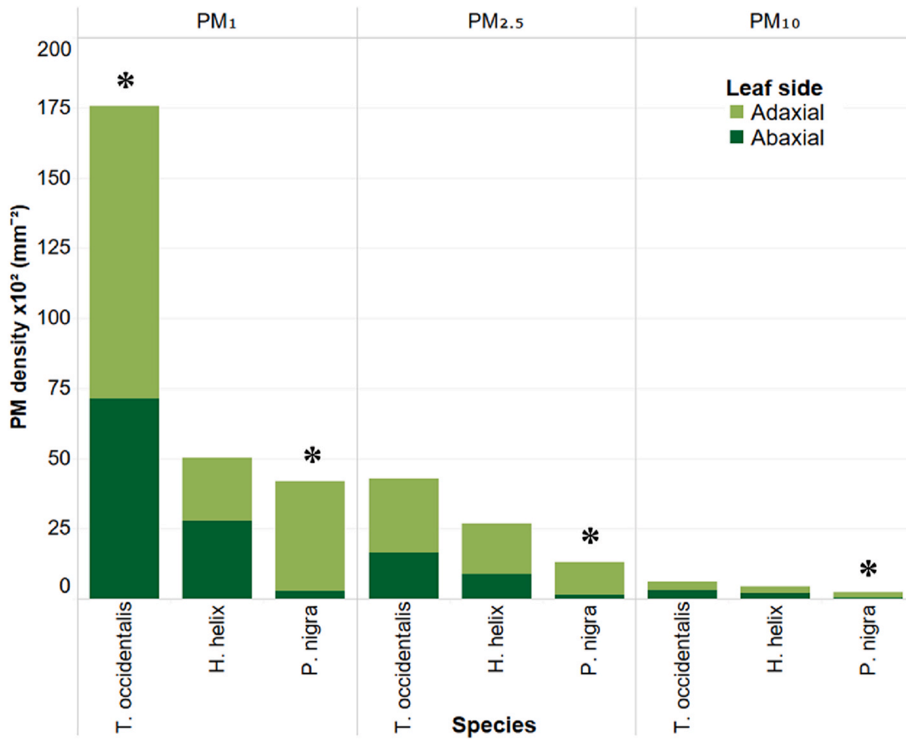

Fig. 5. Median PM density of PM_1, $PM_{2.5}$ and PM_{10} identified on the adaxial and abaxial surfaces of each green barrier plant species, in descending order. IQR not shown for clarity. * indicates statistical differences between the adaxial and abaxial surfaces of the same species. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Particle count and proportion of PM_1, $PM_{2.5}$ and PM_{10} observed on the leaves, per species.

Species	Leaf side	Particle count			Proportion		
		PM_1	$PM_{2.5}$	PM_{10}	PM_1	$PM_{2.5}$	PM_{10}
H. helix	adaxial	1142	366	54	83.61 %	14.29 %	2.11 %
	abaxial	1210	333	146	71.43 %	19.66 %	8.62 %
	both	3352	699	200	78.76 %	16.42 %	4.70 %
T. occidentalis	adaxial	3482	433	138	85.74 %	10.66 %	3.40 %
	abaxial	1341	197	43	84.77 %	12.45 %	2.72 %
	both	4823	630	181	85.47 %	11.16 %	3.21 %
P. nigra	adaxial	1133	255	32	79.79 %	17.96 %	2.25 %
	abaxial	140	23	3	84.34 %	13.86 %	1.81 %
	both	1273	278	35	80.26 %	17.53 %	2.21 %

The remaining proportion to complete 100 % corresponds to particles of more than 10 μm in size, which is less than 0.14 % in average for *H. helix* and *T. occidentalis* species. *Phyllostachys nigra* did not show adherence of any particles above 10 μm diameter.

Table 3
Median (IQR) PM density (1×10^2 mm^2) of PM_1, $PM_{2.5}$ and PM_{10} observed per species, combined for abaxial and adaxial surfaces, and inter-species variation.

Species	PM_1		$PM_{2.5}$		PM_{10}		TAP	
	Median (IQR)	$H(2) = 18.84$ $p < 0.05$	Median (IQR)	$H(2) = 12.84$ $p < 0.05$	Median (IQR)	$H(2) = 9.43$ $p < 0.05$	Median (IQR)	$H(2) = 17.32$ $p < 0.05$
H. helix	**24.30** (18.99–56.63)	a	**12.32** (6.67–25.53)	ab	**2.12** (0.89–7.05)	ab	**42.74** (26.76–88.15)	A
T. occidentalis	**76.47** (57.95–101.45)	b	**19.03** (13.93–26.51)	a	**3.06** (2.21–4.25)	a	**93.46** (84.11–132.20)	B
P. nigra	**24.30** (3.06–39.25)	a	**3.40** (1.87–11.72)	b	**0.51** (0.34–2.21)	b	**28.21** (4.59–49.28)	A

Species that share the same letter have PM density values that are not significantly different from each other, according to post hoc Dunn's test. TAP = Total Adhered Particles, total sum of the PM categories.

micromorphologies (Fig. 5). For the ensiform leaves of *P. nigra*, PM density was statistically lower on their abaxial side for all fractions, being approximately a tenth of the median values from the adaxial side. In contrast, *H. helix* leaf sides did not show any significant difference in the median PM density, for any fraction. Finally, *T. occidentalis* was close to the significant difference threshold ($p < 0.05$) for TAP, most likely

3.34

Table 4
Median (IQR) PM density (1×10^2 mm^2) of PM_1, $PM_{2.5}$ and PM_{10} for plants' adaxial and abaxial leaf surfaces.

PM fraction	Leaf side	*H. helix*	*T. occidentalis*	*P. nigra*
PM_1	Adaxial	**22.43** (20.90–78.17)	**104.25** (75.96–143.93)	**39.25** (29.23–68.14)
	Abaxial	**27.86** (18.35–40.95)	**71.19** (48.77–78.17) [a]W = 14, p < 0.035	**2.71** (2.21–4.29) [a]W = 0, p < 0.0006
$PM_{2.5}$	adaxial	**17.84** (9.01–27.87)	**26.42** (13.89–43.71)	**11.72** (8.67–14.44)
	abaxial	**8.84** (6.63–18.01)	**16.31** (13.93–20.73)	**1.36** (0.42–2.25) [a]W = 0.5, p < 0.0007
PM_{10}	adaxial	**2.38** (1.36–5.78)	**3.23** (2.17–12.45)	**2.21** (1.19–4.08)
	abaxial	**1.87** (0.68–7.48)	**2.89** (2.38–4.25)	**0.25** (0.0–0.38) [a]W = 4, p < 0.002
TAP	adaxial	**50.30** (29.06–98.73)	**146.31** (92.02–192.02)	**49.28** (37.55–82.75)
	abaxial	**35.17** (26.00–81.40)	**90.23** (60.66–105.86) [a]W = 16, p < 0.059	**4.33** (3.57–5.86) [a]W = 0, p < 0.0006

[a] Represents significant differences of PM density between both sides of the leaves, according to Wilcoxon rank sum test. TAP = Total Adhered Particles, total sum of the PM categories.

influenced by the higher and significantly different PM density of the adaxial leaf side for PM_1. The other fractions, $PM_{2.5}$ and PM_{10}, were more evenly distributed on both sides of *T. occidentalis* leaves (Fig. 5).

4. Discussion

The SEM imaging and 3D optical profilometry revealed considerable differences in the leaf micromorphology among species, as well as significant variations in their capacity to capture particles.

4.1. Leaf roughness and PM capture

Leaf surface roughness is frequently estimated as the quantification of grooves and ridges by their width (2D distance measure), morphology or the proportion they cover of the leaf surface. This foliar characteristic is considered to have strong positive correlations with PM capture (Liang et al., 2016; Shao et al., 2019). In this study, an alternative measure of leaf roughness was used, namely areal average roughness denominated S_a, which is calculated from the leaves' 3D surface profiling and which takes into consideration the depth/height of the grooves/ridges (z axis) (Figs. 3 and 4). When looking purely at the effect of leaf surface micromorphology, roughness quantified without the influence of the leaf sample's broad curvature is preferred (S_a, Table 1), and it is discussed below.

Our study showed a weak relationship between PM capture and S_a on both, the adaxial and the abaxial, sides. *Thuja occidentalis* had the lowest surface roughness but showed the highest PM density, despite being located in the inner section of the green barrier. On the other hand, *P. nigra* had the highest leaf roughness; however, it showed the lowest PM density. *Hedera helix* was the only plant matching leaf roughness and PM density when compared to the other species. Shao et al. (2019), who used another 3D technique to calculate leaf roughness (confocal laser scanning microscopy), also found a weak relationship between abaxial surface roughness and the amount of PM on the leaves of 8 common garden plants from China. They calculated leaf roughness as the arithmetic average roughness of the leaf surface (R_a), i.e. the average difference between peaks and valleys; which is similar to S_a.

We explain the weak relationship between PM capture and S_a using the rationale that underpins the determination of S_a: surface height deviation from the mean line. The 3D micromorphology of certain leaf structures creates 'extremely high' deviation from the mean height line which, in turn, creates overall high S_a leaf roughness values. In other words, S_a quantifies the range of height/depth (z axis) change across a leaf, rather than focussing on local density or morphology of protuberances. For example, the abaxial surface of *P. nigra* showed a sizeable difference between S_v and S_p, that is to say, there is a large difference between its deepest groove and its tallest ridge, of 28.89 μm. This large S_v-S_p range causes high deviation from the mean surface height, and some of the extreme deep values correspond to the location of stomata, which are highly recurrent on the abaxial surface – *P. nigra* had the highest stomatal density. Examples of the extreme depth of *P. nigra* stomata and other deep structures of *H. helix* can be seen as deep blue areas in Fig. 3l and d, respectively.

The analysis shows that leaf roughness, computed as S_a, is not the optimum method to estimate PM capture by plant species. The 3D optical profiling analysis (Figs. 3 and 4), however, helped to understand the subtleties of PM adherence to the leaf surface. The total surface area does not directly correlate to PM capture; instead, the 3D analysis revealed that three leaf roughness descriptors: grooves' width, depth, and frequency, are relevant to PM capture (§4.1.3.2). The leaf surface area supports PM capture as long as its micromorphology (i.e., surface grooves) creates an accessible deposition area to the particles. Moreover, as Weerakkody et al. (2018b) suggested, different groove types can perform better than others at PM capture as some would create more accessible deposition areas.

A key factor in PM capture is the relative size of the leaf surface grooves compared to the dimensions of the airborne particles. Consequently, here we define four groove types based on their combined groove width (x/y dimension in the leaf surface plane) and groove depth (z dimension perpendicular to leaf surface) dimensions. The groove widths here are described here as narrow (≤5 μm) or wide (>5 μm), whilst the z axis is described as shallow (≤2.5 μm) or deep (>2.5 μm). The four groove types have different PM capture potential, and their characteristics are as follows:

- Shallow/narrow: Grooves of ≤2.5 μm depth and ≤5 μm width. They have the potential to capture small PM, such as PM_1 and $PM_{2.5}$, dependant on the relative groove to particle size.
- Shallow/wide: Grooves of ≤2.5 μm depth and >5 μm width. Depending on the width dimension, this groove type might trap PM_{10} and it is not likely to be a good sink of PM_1 and $PM_{2.5}$ because the particles could be remobilised by surface airflow and subsequent incoming pollution particles.
- Deep/narrow: Grooves of >2.5 μm depth and ≤5 μm width. They can capture small PM and the depth of the groove can impede particles from being easily remobilised.
- Deep/wide: Grooves of >2.5 μm depth and >5 μm width. This type could trap larger PM sizes, from $PM_{2.5}$ to PM_{10}.

When PM particles are trapped in grooves which are wide enough for them to enter but narrow/deep enough to protect them from the main airflow/particle bombardment, then the probability of long-term adhesion increases. Because of the range of PM sizes, e.g., PM_1, $PM_{2.5}$, and PM_{10}, there are likely different optimum dimensions of leaf surface grooves to trap the different PM sizes and shapes, especially since larger particles, and particles with high aspect ratios such as fibres, cannot enter grooves that are smaller than themselves.

Based on its leaf roughness descriptors, *P. nigra* seems suited for capturing only small PM by its adaxial leaf side that predominantly has shallow/narrow grooves and some shallow/wide (Fig. 4e). This upper surface was able to accommodate more PM_1 than *H. helix*, and particles

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were found clustered around the irregularities of the leaf (Fig. 2i). Its abaxial surface has deep/wide and shallow/wide grooves, being up to 18 μm wide, which is much larger than the PM fractions studied. Consequently, the abaxial surface of *P. nigra* is not optimum for PM adherence. *Hedera helix* had deep/narrow grooves on both leaf sides, of ≤5–10 μm width (Fig. 4a and b). Overall, its grooves were highly effective at trapping particles, especially the smaller PM_1 and $PM_{2.5}$, the grooves were very frequent, increasing its PM capture capacity. *Thuja occidentalis* had shallow/narrow grooves, except at and around stomata (Fig. 4c and d), but had the highest PM capture for all range of particle sizes. This indicates that other micromorphological traits, besides leaf roughness, also influence PM capture efficacy.

4.2. Other micromorphological mechanisms affecting foliar PM capture

From the plants studied, *H. helix* seems to have the most conducive grooves for PM capture due to their size, shape, and frequency. Despite this, it was not the species with the greatest measured PM density. Instead, *T. occidentalis* had the highest PM density, where PM_1 and TAP density were statistically different between both species (Table 3). Therefore, the interaction of other macro and micromorphological traits and environmental factors can outweigh the influence of just one feature, in this case, foliar roughness, as suggested by Sgrigna et al. (2020).

The presence of wax on the leaves of *T. occidentalis* might partially explain its higher PM density compared to *H. helix*. Both species exhibited epicuticular waxes on both sides of the leaf; nevertheless, the wax layer on *T. occidentalis* was more prominent and visible in the SEM images (Fig. 2g). The existence of a significant wax layer hindered leaf observation under high SEM magnifications due to local electron beam-induced melting, similar to the observations reported by Stabentheiner, Zankel and Pölt (2010) on the conifer tree *Picea omorika*. Some studies have positively correlated wax on leaf surface, especially in conifer species, to their capacity to capture PM (Sæbø et al., 2012; Xu et al., 2019). Here, the notable wax layer on *T. occidentalis* appears to contribute to the adhesion and, therefore, immobilisation of the particles both in the grooves and additionally on top of ridges.

Some studies have reported hairy leaves as an effective mechanism to facilitate PM capture (Chiam et al., 2019; Wang et al., 2019). Here, only *P. nigra* had occasional microhairs (Fig. 2j,l), and the other species did not present any trichomes or hairs on their surface; therefore, it was not a significant PM capture mechanism in this study. Rather, the minimum presence and lack of this trait in the sampled foliage enabled a better understanding of the influence of the other micromorphological characteristics.

Divided opinions exist around the influence of stomata presence and density on PM capture, and no consent has been reached. For instance, Chen et al. (2017b) did not find a correlation between stomatal density and $PM_{2.5}$ capture after assessing 31 tree species from Beijing; Liang et al. (2016) found low stomatal size species effective at $PM_{2.5}$ capture; whilst Sgrigna et al. (2020) considers stomatal density to be positively correlated to PM deposition and suggests that its presence might add to leaf roughness. As depicted in Fig. 2b, a large number of particles (PM_1 and $PM_{2.5}$) were found locally adhered in the deep/narrow grooves around the edges of *H. helix* stomata; which was not the case for *P. nigra,* nor for *T. occidentalis*. The latter had the highest PM density but lowest stomatal density. On the contrary, *P. nigra* had the lowest PM density and highest stomatal density. The evidence here, from detailed 3D microstructural analyses, indicates that stomatal density will only have a positive correlation with PM capture if the grooves that surround the stoma have the right depth and width for the particles to be trapped, such being the case of *H. helix* (Fig. 2b).

4.3. Species variation in PM capture

The studied species performed differently at PM capture within the same green barrier. They can be ranked based on their overall PM density performance from highest to lowest as follows: *Thuja occidentalis* > *Hedera helix* > *Phyllostachys nigra* (Fig. 5). For all the samples analysed, the overall particle count of PM_1 was at least 5 times higher than $PM_{2.5}$, and $PM_{2.5}$ was four times higher than PM_{10}. The significantly higher PM_1 density adhered to *T. occidentalis* meant it was the top-ranked leaf-type in overall PM density performance from all species (Table 3).

All species had in common that the larger the pollution particle size, the lower the proportion of particles adhered on the leaves, which matches previous findings from Ottelé et al. (2010) and Weerakkody et al. (2017). Our observation of a lower frequency of adhered $PM_{2.5}$ and PM_{10} particles compared to PM_1 particles correlates both with the reduced number of suitably sized grooves which can effectively trap the larger PM_{10} particles, and the reduced efficacy of surface adherence by wax for heavier particulates. Other studies (Przybysz et al., 2014; Song et al., 2015) differ from the particle distribution found here, finding PM_{10} to be the most abundant fraction, due in part because their equivalent PM proportion calculation method is based on the gravimetric rinsing, filtering and weighing approach by Dzierżanowski et al. (2011). Tomson et al. (2021) found significant drawbacks from the gravimetric particle analysis approach and recommend using microscopy imaging techniques over gravimetric.

It is worth noting that PM density and distribution on the leaf samples are not equal to the atmospheric PM concentrations of the study area. PM pollution present on the leaves depends on impact (incoming flux, weather, green barrier design), adherence (e.g. leaf performance) and removal (incoming flux/impacts, weather). Additionally, there is a biological interaction between the PM compounds and the leaves, which might lead to the absorption/transformation of pollutants; for instance, of compounds containing nitrogen. Therefore, the adhered PM on the leaves is not identical to airborne pollution concentrations.

In this study, *T. occidentalis* and *P. nigra* were located immediately behind a *H. helix* fence, comprising together a section of the green barrier. There is a possibility of direct wind shadowing by the *Hedera* climber on the *T. occidentalis* and *P. nigra* specimens, or other disruptions to air flow patterns caused by the *Hedera* leaves and the gaps between these leaves (hedges and facades are thought to slow wind speed, not block air movement entirely, Chang, 2006). However, despite their location, all plants showed foliar PM deposition. In fact, *T. occidentalis* had the highest PM density for all fractions, meaning that its micromorphological mechanisms for PM capture outweigh the spatial conditions. Other studies have also found that conifers perform strongly at PM capture. For instance, another scale-like conifer, *Thuja plicata* was highly rated by Muhammad, Wuyts and Samson (2019), based on its leaf saturation isothermal remanent magnetisation (SIRM), a proxy for induced particle accumulation. Additionally, species from the *Pinus* and *Juniperus* genus have also shown superior particle adherence compared to broadleaved species (Przybysz et al., 2014; Zhang et al., 2018).

Here, *P. nigra* had the lowest PM density of the three analysed species but still was effective in collecting airborne particles, especially PM_1, despite being in the inner side of the green barrier. Some studies have shown that other bamboo plants capture $PM_{2.5}$ and PM_{10}, such as *Phyllosthachys bissetti* (Morina et al., 2013), or can lower the atmospheric concentrations of these contaminants, such as a *Phyllostachys edulis* forest in China (Bi et al., 2018). The *P. nigra* specimens in our study also helped shape the green barrier and make it denser, which is highly important for the deflection effect of the barrier on air pollution (Tomson et al., 2021).

Analysis of both the adaxial and abaxial sides of each leaf type clarifies the contribution of each surface to the overall particle capture efficacy. The most notable effect was found for *P. nigra*, where the PM load on its abaxial surface was significantly lower than the opposite side for all PM fractions, being approximately a tenth of the median values from the adaxial side (Table 4). This marked difference clearly affected its PM capture performance, which otherwise could have been similar to

H. helix performance since the adaxial side of both species exhibited similar PM densities. Our results for *H. helix* are aligned to the findings of Weerakkody et al. (2017), where the adaxial surface had significantly higher values; which is true for $PM_{2.5}$, PM_{10} and TAP from our sample.

Overall, we found that all examined green barrier species captured PM through the action of multiple mechanisms afforded by the range of leaf micromorphologies at the first and second layer of the green barrier. *Hedera helix* is an effective first layer for PM capture, which seems to be suited for PM_1 and $PM_{2.5}$ adherence due to optimum groove size and frequency. In the second layer, *T. occidentalis* possess a wax layer that enables it to capture a significantly higher number of particles, and *P. nigra* serves as a structural plant for PM deflection, and its adaxial side seems to adequately capture PM_1. Abhijith and Kumar (2020) suggest that multiple row green barriers should have the most pollution-tolerant species located closer to the pollution source, as per *H. helix* in our study. In addition to their findings, our results suggest that having a mixed-species green barrier fosters multiple opportunities to capture PM, potentially more when compared to a single species green barrier.

4.4. 3D optical profilometry in air quality science

The combination of the leaf examination techniques used in this study, specifically SEM paired with 3D optical profilometry, has contributed to a new understanding of the various mechanisms by which PM is deposited and retained on the foliage of three species once the macromorphological and environmental barriers have been overcome. Even though the determination of S_a leaf surface roughness was not found to be an optimum method to predict PM density, 3D optical profilometry is shown to be advantageous since it enables the detailed determination of localised leaf roughness/3D surface morphology on a size-scale similar to the PM particle size. The combined techniques have determined that 1) leaf micromorphology is highly heterogeneous on the nm-10μm size scale; 2) leaf roughness descriptors: grooves' width, depth and frequency, strongly influence PM capture and retention; and 3) stomatal density is not correlated to PM capture unless the surface surrounding the stomata has the ideal size and shape for PM capture. Further research on leaf roughness descriptors should be undertaken for more species to complement our observations.

5. Conclusion

The capture of airborne pollution particles by leaves is influenced by plant micromorphological traits, which determine the mechanisms for PM capture. In our study, the most conducive PM capture mechanisms were leaf roughness and the presence of wax.

Macro and microscale 3D leaf roughness was determined using 3D optical profilometry, which is a new method for the analysis of air pollution mitigation by plants. It was found that the roughness parameter S_a was not optimum to predict PM capture due to certain localised structures, such as stomata, causing high deviation from the mean leaf height, and producing high S_a that did not reflect the leaf surface conditions. Nevertheless, the 3D optical profilometry spatial maps and linescans, helped to identify the leaf roughness descriptors that most influenced PM deposition: namely grooves' width, depth, and frequency. The total surface area of the leaves did not directly correlate to PM deposition, instead, particle capture is influenced by the accessible area to the particles due to the leaf surface structures (i.e., surface grooves). For the range of analysed PM sizes, i.e. PM_1, $PM_{2.5}$, and PM_{10}, there are likely different optimum dimensions of leaf surface grooves to trap the different PM sizes and shapes. The descriptors clarified the suitability of *H. helix* for capturing PM_1 and $PM_{2.5}$ through frequent deep/narrow grooves, predominantly smaller than PM_{10} particles. In contrast, atmospheric PM primarily adhered to *T. occidentalis* leaves due to its abundant wax layer. Stomatal density did not seem to foster enhanced PM deposition unless the grooves surrounding the stoma/guard cells were of the right depth and width to accommodate the particles.

The green barrier species, *Hedera helix* 'Woerner', *Thuja occidentalis* 'Smaragd', and *Phyllostachys nigra*, were examined under the SEM and all showed to have captured PM pollution. The SEM method used here is effective to a resolution limit of 0.2 μm, and further work could explore the <0.2 μm particle capture by plants to investigate air quality gains at a lower scale.

For all three species, PM_1 was the most numerically abundant fraction adhered to the leaves, accounting for approximately 80% of all particles and followed in descending order by $PM_{2.5}$ and PM_{10}. *Thuja occidentalis* had the highest PM areal number density, having captured double the TAP of *H. helix* and triple of *P. nigra*, despite being located behind the ivy (*Hedera*) climber. *Phyllostachys nigra* had the lowest relative PM load, but it still has significant potential for air quality remediation, both for PM_1 capture and for pollution deflection as a plant that adds structure to the green barrier. The use of multiple plant species in the green barrier allows the concurrent action of multiple PM capture mechanisms and enables PM capture by leaf topology to occur at different size scales, fostering more opportunities to capture PM than using only one species for air filtering.

The study of foliar surface roughness and other micromorphological features helps to account for the subtle differences among plants in terms of their air cleaning capacity and to guide the selection of the best plant combinations to reduce air pollution and improve citizens' health. The use of 3D optical profiling is shown to enable a better understanding of the influence of leaf roughness/morphology on PM capture and retention, with 3D leaf surface height maps providing detailed information on the leaf surface structure at the scale of the pollution particles, thereby locating the places and structures most conducive for PM deposition.

Credit author statement

MCRB: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft and Editing. ITG: Investigation and Formal Analysis. RWC: Supervision, Conceptualisation, Writing - Reviewing and Editing. BJI: Supervision, Conceptualization, Resources, Writing - Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Chapter IV

Critical dimension for green barrier implementation in school playgrounds and perceived co-benefits

Publications included in this chapter:

Redondo-Bermúdez, M. del C., Jorgensen, A., Cameron, R.W., Val Martin, M., 2022. Green Infrastructure for Air Quality plus (GI4AQ+): defining critical dimensions for implementation in schools and the meaning of 'plus' in a UK context. Nature-Based Solut. 2, 2–13. https://doi.org/10.1016/j.nbsj.2022.100017

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Green infrastructure for air quality plus (GI4AQ+): Defining critical dimensions for implementation in schools and the meaning of 'plus' in a UK context

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ABSTRACT

Mitigating poor quality air is vital for children's health, especially in urban areas. In recent years, attention has been paid on how to improve air quality around schools to reduce children's exposure to airborne pollutants. In this paper, we explore the use of green infrastructure for improving air quality in schools as a multifunctional nature-based solution (green infrastructure for air quality plus, 'GI4AQ+'); a process that comprises additional (co-)benefits, trade-offs or disbenefits for the school community. We report on a collaborative, action-research project that implements a green fence in a school playground in Sheffield, UK with the specific aim of improving local air quality, but potentially provides other benefits as well as drawbacks. Our results suggest that GI4AQ+ provides multiple social, environmental, and economic co-benefits beyond air quality provisioning. Furthermore, four dimensions (place, physical and biological characteristics, and school-friendly considerations) were identified to facilitate the implementation of this type of project in other schools. Thus, GI4AQ+ appears to be a valuable strategy for school greening. These interventions may also encourage school communities to identify and procure the delivery of other co-benefits from green infrastructure.

1. Introduction

In recent years, harnessing the attributes of nature to solve socio-environmental issues has increased in popularity. The use of green infrastructure (GI) for the purpose of reducing air pollution has, consequently, been explored and suggested by several scholars [1–3]. Green infrastructure encompasses a network of managed vegetation that includes trees, hedges, green roofs, green walls [4], and green barriers or 'fences' composed of narrow lines of mixed vegetation. GI can help mitigate an issue that causes 4.2 million premature deaths annually, of which 7% are children under five years old [5]. Children are particularly vulnerable to the effects of air pollution due to their developing bodies. For example, children are likely to experience physical and mental health problems during their lifetimes, since air pollution is linked with increased respiratory disease [6], reduced immunity [7], cognitive impairment [8], and even a greater likelihood of suffering from depression [9,10]. Greater exposure to pollutants exacerbates poor health. For instance, on days with highest traffic-related air pollution, there is also increased respiratory hospitalisation of children in London [11]. Furthermore, studies in Mexico City, demonstrate that children exposed to the most severe air pollution under-perform in language and numeric cognitive tests [12].

Hewitt et al. [1] coined the term GI4AQ for GI that has been purposely designed to provide urban air quality (AQ) improvements. GI4AQ has a limited impact on city-scale pollutant loads [13], but it can make a more significant difference at the local scale. Accordingly, site-specific GI4AQ interventions in school facilities, the place where children spend about a third of their day, have the potential to improve outdoor air quality and protect children's health. In particular, green barriers or green fences – a mix of different vegetation types that create a physical and biological obstacle for air pollutants to reach an area of interest [14] – are shown to decrease site-specific air pollutant concentrations. For example, behind a green fence, particulate matter (PM) and nitrogen dioxide (NO_2) can decrease by up to 60% and 53%, respectively [15].

Introducing GI4AQ in schoolyards may provide other benefits to the place and its community. For example, the presence of GI correlates with increased physical activity in children, positive mental wellbeing and enhanced prosocial interactions in playgrounds [16–18]. In light of such potential to improve air quality and provide wider co-benefits to schools, we propose using the term GI4AQ+ (green infrastructure for air qual-

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4.1

ity 'plus') [19]. The 'plus' signifies co-benefits beyond air quality and derives from a nature-based solutions approach to GI4AQ, where multifunctionality is key. Nature-based solutions (NbS) are solutions inspired and supported by nature that address societal challenges and are multifunctional – they provide environmental, social, and economic benefits. NbS serve as an umbrella concept for different approaches to achieve this aim, such as GI [20].

Schools have an embedded community with specific needs, wants and interests, and our understanding of what 'plus' means when implementing GI4AQ+ in such schools is incomplete. However, demonstrating the co-benefits of green fences (and other NbS in general) is required to facilitate their implementation [21]. Additionally, access to comprehensive guidance on GI4AQ+ implementation in schools, sensitive to the school, its context and to its community, is lacking. Yet, it is known that insufficient knowledge and guidance on how to realistically achieve GI poses a barrier to its implementation [22,23]; and research in this area is limited [24].

Onori, Lavau & Fletcher [25] suggest four strategies for successfully implementing GI in schools. They encompass a technical aspect of planning and design, and three social aspects related to the value of GI to the community, its engagement with the project, and its working relationships. This indicates that both developing technical knowledge, and understanding GI's co-benefits to the school community, could contribute to GI4AQ+ uptake. Onori, Lavau & Fletcher's [25] conclusions, however, rely only on the school communities' opinion, and lack the perspective of other collaborators and stakeholders that are part of GI development; such as contractors, city governments, or volunteers. On this basis, we aim to explore GI4AQ+ by collating perspectives from multiple collaborators of a green fence implementation project in a school playground in Sheffield, UK. The research questions are the following: 1) What are the perceived co-benefits of GI4AQ+ interventions at UK schools? 2) Which critical dimensions need to be considered to implement GI4AQ+ in UK schools?

2. Study design

This study utilised a participatory action research approach to develop and implement a green fence in a case study school in Sheffield, UK. The entirety of the project is referred here as GF-Sheff project, meaning 'Green Fence in Sheffield' project). The green fence is the physical intervention that allowed us to explore our research questions with regard to GI4AQ+ in schools.

Action research is an iterative process where actions, data collection and analysis run simultaneously. It is 'rooted in participation' [26], with several actors shaping the project development and generating practical and theoretical knowledge, usually to respond to pressing issues [27]. For this study, the participatory approach was based on the co-production of the green fence. Co-production or 'collective making' [28] occurs when the end-users and/or stakeholders in relation to the object of design are actively involved in its design and delivery [29]. The co-production approach was adopted here due to previous studies [30,31] indicating that collaboration at different levels is important to achieve success with NbS. The GF-Sheff project collaborators included actors from the school community, the public and private sectors, and university researchers (Table 1), each with a set of skills and knowledge that was complementary and operating at different levels and scales. Van der Jagt *et al.* [32] have coined the term 'Learning Alliance' to define this kind of collaboration for knowledge building. Interactions between the collaborators, e.g. discussing different ideas and perspectives, generating knowledge and plans, and trying different approaches on the ground – took place within the context of developing a green fence to potentially improve playground air quality. These interactions were carried out with a spirit of experimentation in an Urban Living Lab (ULL) fashion. ULLs are real-life environments where an iterative co-production process occurs with multiple participants to achieve urban sustainability goals [33,34]. In short, action research was carried out during the co-production of a green fence in the school playground (i.e., the ULL), where multiple collaborators (i.e., the Learning Alliance) contributed to knowledge exchange and building.

Action research for the GF-Sheff project was carried out by four researchers who contributed in different capacities to six stages of the co-production process, detailed in Table 1. One researcher (MCRB) collected action research data in the form of fieldnotes, a collaborative online board (Trello® software, Atlassian) used to manage the project, key notes from meetings including the official debrief meeting, and notes from the literature review. Additionally, after the installation of the green fence, the same researcher conducted semi-structured interviews (n = 17) with the project's main collaborators and other stakeholders (school community, public and private sector, volunteers, a university staff, and a social enterprise representative) to understand the green fence implementation process and to capture their perceived co-benefits, trade-offs and disbenefits (see interview sample in Supplementary material). To elaborate on the school community's perception of the green fence, a survey (n = 110) was sent to all parent contacts and school staff. From the survey respondents, 98 were parents and 12 were school staff, comprising 89% and 11% of the participants respectively. The data collection periods are listed in the timeline shown in Fig. 1. The data collected were inductively analysed through thematic content analysis [35], which consists of assigning codes to similar data content and condensing them into meaningful themes that contribute to answering the research questions [36]. The analysis was performed using the software NVivo (QSR International Pty Ltd, 2020) and Microsoft Excel (Microsoft Corporation, Microsoft 365).

2.1. Case study description

The green fence was co-produced for and with an infant school located in a built-up area in the southwest of Sheffield, UK. It is a state school that hosts 270 pupils from 5-7 years old. The school building was completed in 1892 (i.e., it is late-Victorian in character). The school playground is adjacent to the intersection of three roads: A) a two-lane trunk road leading to the city centre, B) a single carriageway road joining this via a roundabout, and C) a 'one-way' single carriageway with angled parking bays and traffic calming measures (Fig. 2). Air pollution sources in the area include vehicle traffic, and domestic and commercial activities (e.g., the use of wood burning domestic stoves).

The green fence was planted along the playground's edge, next to a stone wall that separates the playground from the adjacent roads (Fig. 3a). It was planted into the ground (1 m deep) and optimised to playground space constraints (i.e. partially raised ground toward road C and valuable play space). It comprised 32 plant taxa forming a narrow, tall structure (Fig. 3b). Five taxa act as structural plants for the fence (see detailed information in Table 2), and the rest were added for sensory interest, including texture, scent, and colour. Plants were introduced in an almost-mature stage and established readily over 20 months (Fig. 4). During the development of the GF-Sheff project, air quality was monitored and this data will be reported elsewhere. Additionally, results from some of the green fence plants on their pollution removal potential is presented in Redondo-Bermúdez's [37] study.

3. Results

3.1. GI4AQ+, explaining the 'plus' for UK schools

Acting as a multifunctional NbS, the 'plus' of GI4AQ+ entails all the other benefits that can derive from its implementation beyond air quality provisioning. Fig. 5 presents a summary of the thirteen perceived co-benefits of GI4AQ+ in schools resulting from analysis of the interviews and survey.

4.2

Table 1
Overview of the GF-Sheff project - stages and timeline.

Project stage	Time period	Main collaborators	Project activities
Introduction and goal setting	October 2018 – January 2019	(Sch) School headteacher, parent governors including project lead, 'eco-lead' teacher. (Uni) University researchers: MCRB, AJ, RWC, MVM. (Pub) City's air quality lead.	Discussion of the air pollution issue in the local context and the desire to use GI in the playground.Literature search of plant species and GI4AQ research and practices.Action plan and goal setting agreement.Identification of key stakeholders and development of a stakeholders' communication and engagement plan.
Green fence design	February – July 2019	(Sch)School headteacher, parent governors including project lead, 'eco-lead' teacher. (Uni) University researchers: MCRB, AJ, RWC. (Pub) City's air quality lead. (Priv) Landscape architecture consultant, business connection partner, construction company workers, engineering consultant, arboriculturist.	Continuous engagement of key stakeholders.Site survey and assessment of existing tree's health.Frequent meetings to discuss potential green fence design.City council permissions to work request, and consultation with the Building Regulation Department.
Construction - Hard works	August 2019	(Sch) School headteacher, parent governors including project lead, school staff. (Uni) University researchers: MCRB. (Priv) Construction company workers, arboriculturist, business connection partner.	Scan and assessment of ground and subsurface structures.Mechanical excavation of planting areas, hard works construction and backfilling with topsoil.Manual excavation of areas around sensitive tree roots, supervised by an arboriculturist.
Planting	October 2019	(Sch) School headteacher, parent governors including project lead, school staff, school caretaker. (Uni) University researchers: MCRB, RWC, MVM. (Priv) Landscape architecture consultant. (Vol) Volunteers (parents, university students, local businesses).	Vegetation fence installation and planting.Volunteer days to complete the planting activities.
Project debrief	January 2020	(Sch) School headteacher, parent governors including project lead, 'eco-lead' teacher, school caretaker. (Uni) University researchers: MCRB, RWC, MVM. (Pub) City's air quality lead. (Priv) Landscape architecture consultant, engineering consultant.	Meeting to capture the learning from all collaborators involved in the co-production of the green fence.
Maintenance	November 2019 - ongoing	(Sch)School headteacher, parent governors including project lead, 'eco-lead' teacher, school caretaker. (Uni) University researchers: MCRB, MVM. (Priv)Landscape architecture consultant. (Vol) Volunteers (parents).	Meetings to discuss a feasible maintenance plan for the school.Elaboration of maintenance plan.Volunteer days to carry out plant maintenance.

In the main collaborators' section, acronyms in brackets denote the stakeholder group involved: (Sch) school community; (Uni) university staff; (Pub) public sector (city council); (Priv) private sector; (Vol) volunteers. For university researchers' acronyms, please refer to the author section of this publication.

Fig. 1. Data collection timeline of the GF-Sheff project.

3.1.1. Social co-benefits

Place quality and attractiveness. Co-benefits with social value were the most frequently mentioned. Place quality and attractiveness was the most frequently recurring theme (71% of interviewees; 92% of survey participants) and is directly related to the visual change of the playground, from an open and predominantly hard-surface space to a greener enclosed place separated from the busy roads. The participants described the green fence as making a 'massive improvement' to the visual appearance of the playground. A school staff mentioned this was particularly important for the children: 'The view that they [pupils] see now, because they are forced to look up, goes directly toward the park and they can see the trees and sky, all green [and blue]'. Moreover, the smaller details of the green fence were also noticed; a school teacher mentioned: 'I love that kind of ivy backdrop we've got and then the plants that go within to give it more depth as well, and because we have colour with the other plants in springtime'.

School premises safety. Participants (59% of interviewees; 52% of survey participants) described the playground with the green fence as a safer and a more private place for children to play, where they only interact with adults responsible for their care. Additionally, the green fence has stopped undesired interaction with outsiders and reduced the litter problem (i.e., bottles and food containers that used to be thrown into the playground at weekends).

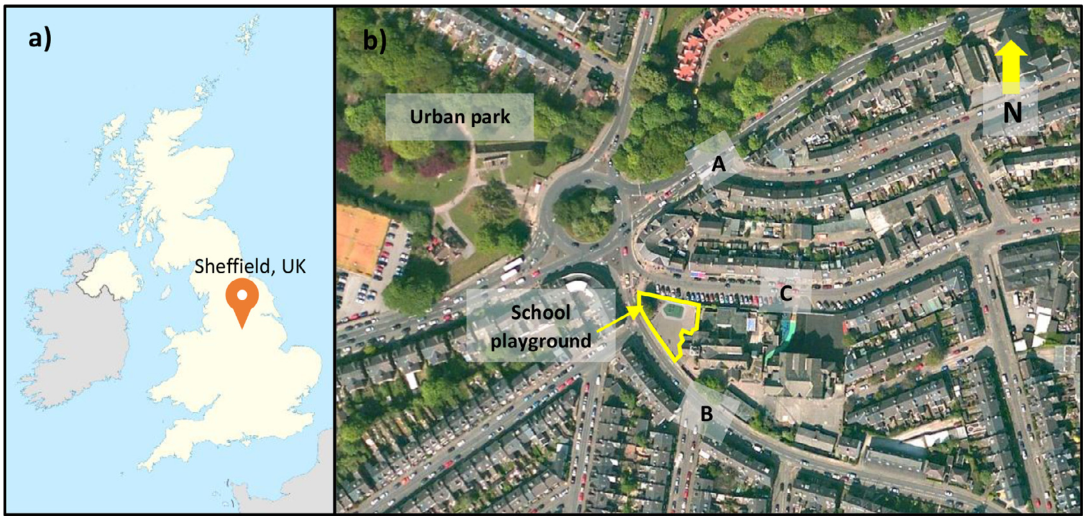

Fig. 2. School playground location (a) in the UK, and (b) in urban layout.

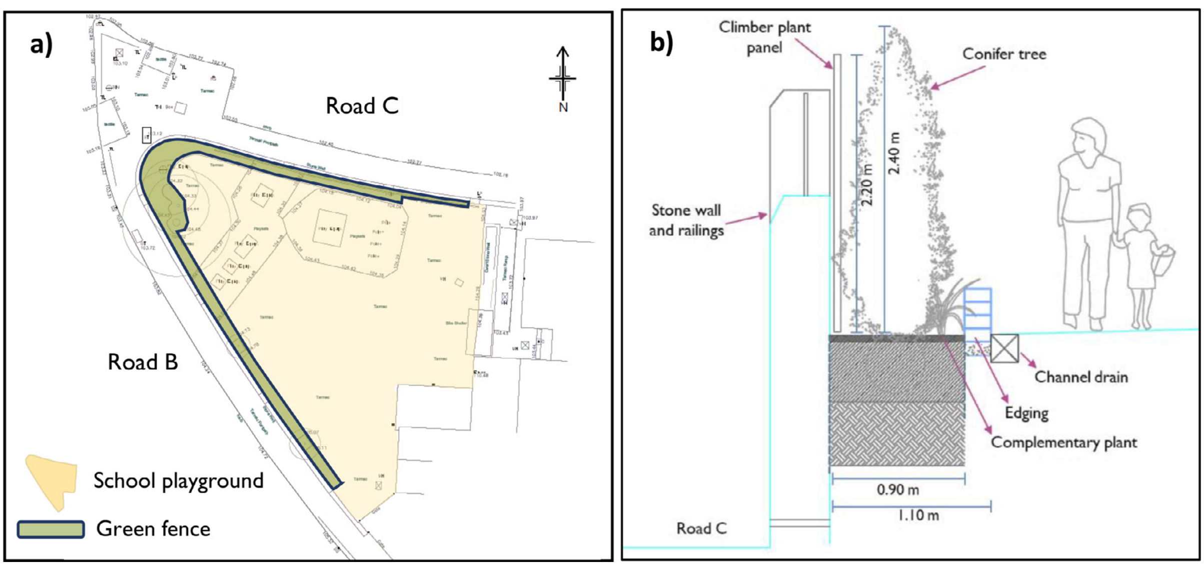

Fig. 3. Layout of (a) green fence in case study school playground, and (b)* illustrative detail of green fence section. *Modified from Urban Wilderness section drawings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Restorative environment and mental wellbeing. Although it was difficult for the participants to pinpoint the reasons why they felt an improved sense of wellbeing and restoration in the newly planted playground, this theme was frequently mentioned (76% of interviewees; 49% of survey participants). Moreover, the opportunities for children to interact with the plants were perceived as supportive of their wellbeing; e.g., teachers said that watering the plants was calming for children with special needs. The sensory impact of the green fence was mentioned by the parent of a child with autism spectrum disorder (ASD) and associated sensory overload, who testified: 'the reduction in pollution smells meant that my child was much happier in the playground'.

Learning opportunities. Another recurring theme was the learning opportunities that the green fence affords (41% of interviewees; 10% of survey participants = 11/110). The playground has been used as an outdoor learning space, and the green fence has provided cross-curricular resources in a large range of subjects; from biology and maths to mental health and arts, including respect and value for nature.

Community's active engagement. This was a highly important theme for the interviewees (59% of interviewees; 4% of survey participants). They considered that involving the local businesses and school community in the different stages of the GF-Sheff project (from fundraising to planting and the ongoing maintenance) promoted social cohesion and gave the school a sense of ownership of the green fence.

Child development and play. Participants who observed children during playtime raised the theme of child development and play (29% of interviewees; 4% of survey participants) because the green fence has features that foster pupils' cognitive and physical development. For instance, the wide wooden edging to the planted areas provides an elevated walkway allowing children to travel around the playground, helping to improve their balance. Additionally, the added greenery supports new ways of playing and stimulates imagination. For example, a member of staff believes that children really appreciate it: 'just by the sort of things that children would say to each other, like: "I'll meet you in the woods". It just took like a dozen trees gathered together. But to them that was the woods. Because the playground it's just full of concrete, and they [children] make the most from anything they've got'.

Table 2
Dimensions for GI4AQ+ implementation in schools and their link with the case study.

Implementation dimensions	Specific factors	Case study school example
Place characteristics	Land ownershipLandscape intervention potentialIntegrity of existing infrastructure	The school is a state school managed by the City Council. Permission for ground excavation needs to be granted by the City Council.The landscape intervention was possible in the playground but needed two phases for being completed:- Construction - hard works to create plant bed (assessment of ground services and utilities, assessment of existing trees' health, excavation for tarmac removal, installation of upright poles to support climbing plant panels, root barrier and soil addition, wooden edging construction)- Planting (installation of climbing plant panels and planting rest of the plants)Part of the playground is built above ground level (next to road C) and the existing wall and railings that delimit the playground function as a retaining wall. The integrity of the latter infrastructure was assessed.
	Built environment:- Open road- Street canyon	Open road conditions.
	Wind:- Direction- Speed	Predominant wind from NW, W, SE and 18.8% of calm.Predominant wind speed from 1 to 3 m s^{-1}, up to max. 5 m s^{-1}.
	Pollution source:- Location- Intensity	PM and NO_2 emission from vehicle traffic, and commercial and domestic activities (e.g. wood burning stoves).
	Use of space and value to people	The school facilities have a heritage value from their construction during the late-Victorian period.A site assessment was conducted with the school community to understand their use of space and the value of each feature in the playground.
Physical characteristics (fence)	Planting space	Limited to 0.90 m to preserve playing space.
	Green fence dimensions:- Length- Height-Width	Length: 60 m.Height: 2.20 – 2.40 m.Width: 0.90 m or 1.30 m depending on the green fence section. Full height coverage with vegetation was ensured.
	Water management	Manual irrigation, weep holes installation to ensure free draining and channel drain fitting.
Biological characteristics (vegetation)	Structure plants:- Potential to create a vegetative barrier- Multiple species are preferred to a single species- Evergreen species for all year-round performance-Growth rate	Five taxa as structural plants:- *Hedera helix* 'Woerner'- *Phyllostachys nigra- Thuja occidentalis* 'Smaragd'- *Chaemacyparisus lawsonia* 'Ivonne'- *Juniperus scopulorum* 'Blue Arrow'
	Plant traits:- Macro-scale: small leaf size, high leaf complexity- Micro-scale: high leaf roughness, foliar wax, and hair presence	The planting scheme includes a variety of leaf types, some of which are highly complex or possess foliar hairs or wax.
	Pollution tolerance	The structural plants are relatively tolerant of environmental pollution.
	Low bVOCs emissions	Structural plants without significant isoprene emissions.
School-friendly considerations	Co-creation process	Carried out during the duration of the GF-Sheff project. It entailed collaborative work (site visits, regular meetings) with the school and other actors to understand the school-friendly considerations for the green fence design.
	Playground compatibility	The green fence was installed in an active playground. Plants were placed according to the uses of each playground section (i.e., ball games), and the edging provided practical protection to the plants.
	Child-safe vegetation:Low-allergy, non-poisonous and non-spiky plants are preferred	The planting scheme includes female trees only from the *Juniperus scopulorum* taxa, to minimise allergies. None of the selected plants produce fruits or berries that are harmful when ingested. The *Hedera* family may be mildly harmful if eaten, however it was already present in the playground and the school had no previous issues with it.
	Aesthetics:Form, texture, colour, and habit of the plantsBiodiversity enhancement potential	The planting scheme provides a visual grey to green transformation of the playground, where calming and uplifting colours are achieved by adding shrubs and ground cover.Almost half of the plants provide resources for pollinating insects (revised with the UK Royal Horticultural Society data).
	Integrated play	The edging of the green barrier also functions as a sitting area and fosters interactivity as children walk along it.
	Maintenance	Maintenance activities are a mix of interventions carried out by the caretaker, a hired gardener or during volunteer days with parents, children, and school staff.
	School delivery schedule	The groundworks and planting days were carried out during the summer holidays and autumn-term break.

Access to greenspace/connection with nature. Interestingly, only the parents interviewed (17% of interviewees; 0% of survey participants) mentioned that the green fence promotes pupils' easy access to greenery, and only parents completing the survey (0% of interviewees; 8% of survey participants) highlighted that the green fence promotes connection with nature.

3.1.2. Environmental co-benefits

Habitat provisioning and connectivity for wildlife. Some participants (29% of interviewees; 4% of survey participants) suggested that the added greenery in the playground creates space for wildlife and connects it to other green spaces, such as the green roundabout and the park opposite the school. Teachers mentioned that, due to the increased influx of insects in the playground, they now carry out 'mini-beast' surveys with children as an interactive and fun way to learn about invertebrates. There was also a desire to see more birds as the plants develop and to construct infrastructure to host more wildlife.

Sustainable living and environmental awareness. A dominant environmental co-benefit (71% of interviewees; 12% of survey participants) relates to participants' sustainable living and environmental awareness. This awareness focused on learning about air pollution and the role of nature in helping to solve environmental issues, and their root causes. Furthermore, some of this learning developed into actions (pro-environmental behaviours), such as home gardening, turning car engines off outside the school and engaging in more active ('low carbon') travel. Interestingly, the participants explained that this environmental co-benefit was partly triggered by the friendly and open communication of the project's aims.

Fig. 4. Case study school playground (a) before the green fence installation, (b) 8 months and (c) 20 months after its implementation. Note visual changes due to the green fence addition and playground equipment replacement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the words of a parent governor: 'what this project did was give something that people could understand. Like this is an issue, and that there is this potential solution to air quality but also all these other things [co-benefits]. So, it kind of made it palatable and user friendly, made the discussion user friendly within Sheffield'. In fact, all survey participants indicated that they had verbally shared the playground's transformation with an average of 10 individuals.

3.1.3. Economic co-benefits

School enrolment/interest. The least mentioned co-benefits relate to the economic pillar, in fact, this type of co-benefit was not mentioned by the survey participants. Interviewees, on the other hand, (35% of interviewees; 0% of participants) considered the green fence to be a bonus to the school's reputation, with potential to arouse interest in parents and result in the enrolment of new pupils. Parents stated that the green playground specifically encouraged them to choose the case study school for their children's education. They felt that the school proactively works towards a healthier environment for its pupils and that it now has more desirable facilities. Moreover, the GF-Sheff project, combined with other environmental projects carried out in the school, contributed to the school winning a national 'Environmental Champion' award. This award recognises the school's efforts to be environmentally oriented.

Property betterment. The green fence was also thought to enhance the aesthetics of the school visual appearance, with some local residents relaying to school staff that 'they love the look, and just [what] the difference it's made to the local environment here on the corner'.

Boosting the public image of business involved in the project. Several local businesses were involved in the GF-Sheff project, via in-kind work or monetary donations, which pragmatically supports achieving their Corporate Social Responsibility goals. Businesses that invest in their Corporate Social Responsibility have competitive advantages, such as winning bids over their competitors, and a positive public image that could support their expansion.

3.1.4. Trade-offs and disbenefits

Overall, the different participant groups' responses regarding the co-benefits derived from the green fence are similar. One exception regards concerns from some parents about the vegetation disconnecting the school from the wider community and parents not being able to see their children at playtime. For them, that is a disbenefit. On the other hand, teachers were relieved that parents could not 'spy' on their children anymore, perceiving it as a co-benefit. Another exception, expressed by some teachers, relates to the green fence impeding the use of street elements in teaching delivery. Yet, all teachers perceived it as a trade-off because they value the co-benefits highly. Finally, an agreed drawback expressed by parents and teachers was the need for resources (monetary and labour) to maintain the green fence, especially because it is a long-term commitment. However, they see it as a trade-off outweighed by the multiple co-benefits, backed-up by the existence of a maintenance plan.

3.2. Critical dimensions for the implementation of GI4AQ+ in schools

As evidenced in Section 3.1, GI4AQ+ in schools offers further benefits for society, the environment, and the economy. Nevertheless, its real-life application remains a challenge for schools. During our action research project and in-depth interviews, we were able to identify the dimensions to be taken into consideration for successfully achieving GI4AQ+ in schools. These dimensions emerged from the collaborative learning associated with the co-production process around the green fence in the case study school playground, which effectively served as an ULL. Similar knowledge building processes have been used by van der Jagt *et al.* [32] for adaptive co-management of urban GI.

Context can vary across schools, therefore, GI4AQ+ must be site-specific and adapted to its context. In that sense, the dimensions for GI4AQ+ implementation found here aim to be a guide that can be tailored as necessary, but which is detailed enough to highlight what should be considered in general terms (Table 2).

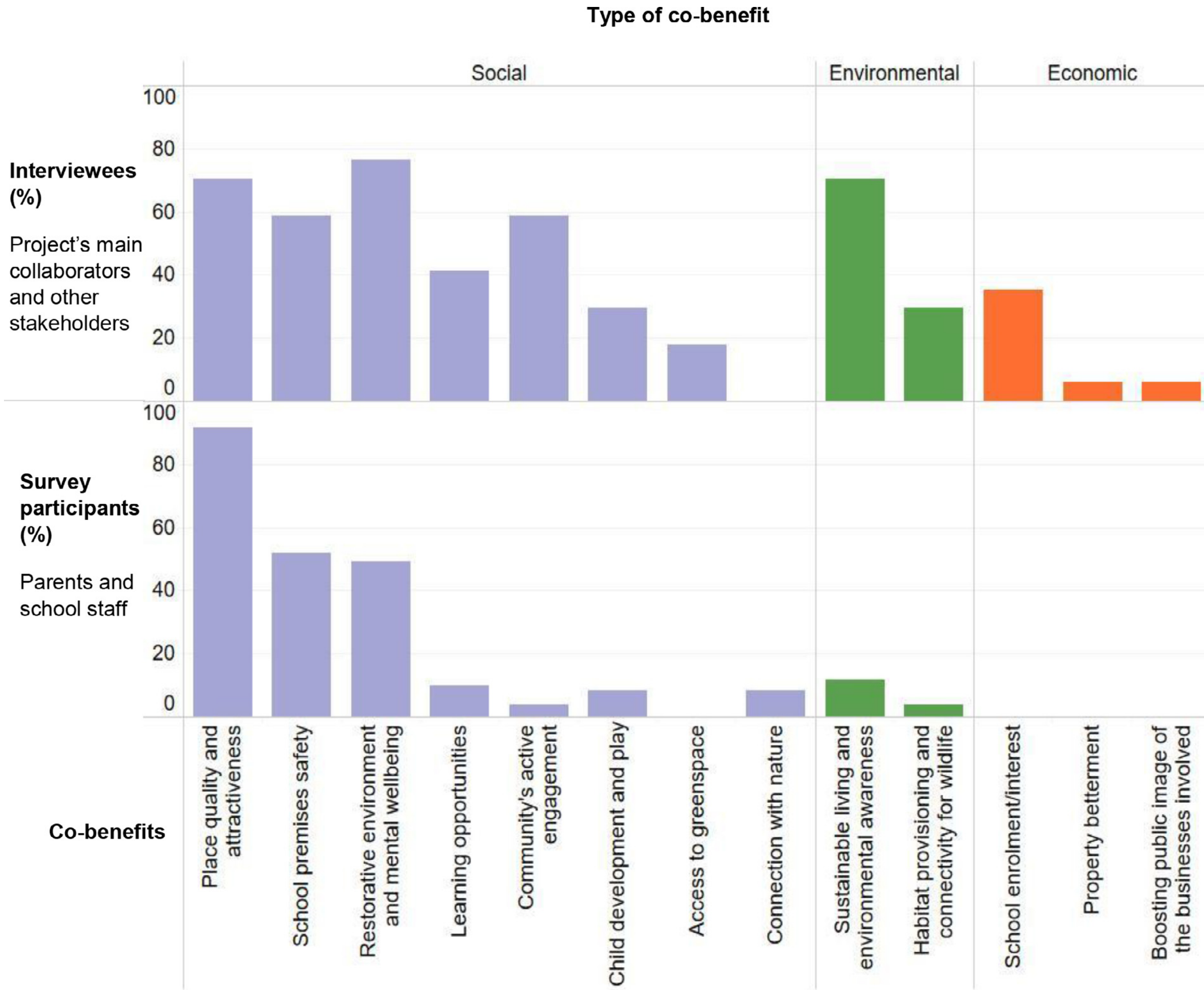

Fig. 5. Perceived co-benefits of GI4AQ+ in the case study school with the percentages of interviewees or survey participants that mentioned them. The co-benefits are depicted according to the 'tripartite model' of sustainability: social pillar, environmental pillar, and economic pillar [38,39].

3.2.1. Place characteristics

The context-dependent place characteristics were a limiting factor highlighted by the co-production process. The term 'place' is used in the sense of a physical space that is also shaped by the people who inhabit it and use it, and that might be attached to it [40]. Both, the physical characteristics of the playground and how it is used and valued by its community, indicate its suitability for a landscape intervention. It is, therefore, recommended to carry out playground visits and have the school communities' input (which emphasises the importance of co-production) and integrate it in the green fence design. On the other hand, the land ownership and management status determine which gatekeepers to liaise with and whether permission to modify the playground is needed (for instance, from the City Council or a private company).

Regarding the physical characteristics of the playground, assessments to value the integrity of the above and below ground infrastructure (including existing GI) are needed, *inter alia* to decide whether to plant into the ground or provide raised beds. The site's topography, solar aspect, the type of ground/soil, the direction of drainage and the location of water sources for irrigation will also inform the adaptations that the planting space requires to establish the plants. Once this information is gathered, planning the construction and planting stages is feasible.

Three place characteristics are relevant for GI4AQ+, including the built environment type, wind direction and speed [41], and the source of pollution. Information about these factors is essential for designing a green fence that will improve air quality instead of trapping polluted air. Understanding the built environment is essential because it determines the local wind flow (whether the school is in a street canyon or on an open road), which carries the pollutants from their source. Therefore, the location and intensity of the pollution sources should also be identified. The location of the green fence with respect to the wind direction determines its effectiveness [42]. The school playground should ideally be located downwind, but the wind does not come from a single direction all year long (there are seasonal differences and weather events). Therefore, AQ improvements may vary throughout the year.

3.2.2. Physical characteristics (fence)

One of the most relevant lessons learned from the design and construction stages is that the dimensions of the green fence are important in three planes:

- Length (x): it should cover the perimeter that delineates the area of concern and beyond to prevent airborne pollutants from infiltrating through the edges.
- Height (y): the minimum desired height of a green fence is 2 m, and, in schools, children's height represents the breathing area needing protection.
- Width (z): in general, the wider the vegetated area, the better, as there is more plant material to deflect/capture the air pollutants and a greater distance between the pollution source and the receptor.

Inner-city schools may have limited space for planting; therefore, ensuring full coverage with vegetation to the desired height is recommended. To sustain planting success, managing the water resource that will supply the irrigation for the plants is as important as the soil drainage. The water source as well as the type of irrigation system should be considered.

3.2.3. Biological characteristics (vegetation)

The green fence design process highlighted the need to recognise green fences as both physical deflectors and biological filters of air pollution. Understanding of the plants' typology and spatial arrangement is needed to create the physical barrier, and of their macro and micromorphological characteristics for choosing species that will filter air pollutants.

There are multiple plant combinations for achieving a physical barrier — a mix between trees, hedges, shrubs, grasses, or climbing plants on trellis. Preferably, the mix should encompass different species to promote multiple mechanisms for pollution reduction, and foster other ecosystem functions and co-benefits, as listed in Section 3.1. Evergreen species are preferred because they provide protection all year long, but it is important to consider their growth rate. Plants should also be tolerant to the environmental pollution common in cities. Moreover, although a plants' biological volatile organic compounds (bVOCs) emissions might be insignificant in small-scale GI, this should be a selection factor to consider as these can generate the secondary air pollutant ozone (O_3). Consequently, low bVOCs emission plants are preferred [1].

In terms of appropriate plant characteristics to deal with air pollution, there is no perfect 'high tolerance, low sensitivity' species, but the scientific literature has started to offer compelling summaries of the appropriate plant traits for deflecting and capturing air pollution [43]. For PM deposition, current information suggests utilising plants with small leaf size and high leaf complexity (macro-scale), and with high roughness and wax or hair presence on the leaf surface (micro-scale) [37]. There is no clear advice for plant traits that will contribute to the reduction of gas pollutants, but evidence suggests that NO_2 absorption is negligible [44]; and consequently, GI4AQ+ has a more tangible potential to reduce gas pollutants by dispersion than by absorption [45].

3.2.4. School-friendly considerations

The school community emphasised that pupils should be at the centre of the green fence design. As this GI intervention takes place in their play area, great care must be taken to provide a space that satisfies all the children's needs and does not harm them. Understanding and integrating this principle was possible due to the co-creation process with the school.

A playground is a space for movement and play. Consequently, the green fence plants should not pose a risk during these activities. Generally, vegetation should be 'child-safe', meaning that low-allergy, non-poisonous and non-spiky plants are preferred. However, there can be flexibility in the plant selection when older children use the place. In all cases, the green fence design and plant selection need to respond to the different playground uses and levels of interaction with the plants. Moreover, it is possible to integrate play in the green fence design through benches, levels, or shape of the planting area.

The school playground also offers a space for restoration and enjoyment; therefore, to promote these feelings, the green fence should be attractive to the school community. The use of complementary plants, set around the anchor plants (key plants for pollution reduction), provides an opportunity to add attractive colours and textures (see Fig. 6). The planting scheme colours (both shades of green and other colours) can be used to promote a relaxing or energising environment. Referring to local biodiversity plans and guides could also assist plant selection for biodiversity support.

Finally, the green fence installation and maintenance activities must be compatible with the school schedule and accessibility (e.g., term breaks or holidays). The maintenance activities should be feasible within the schools' resources, preferably involving the school community in delivering them.

4. Discussion

4.1. Importance of co-production and action research

Successful NbS projects are collaborative and engage the community and stakeholders [46]. Co-creating the green fence and experiencing 'the process from the inside' through action research, allowed researchers and stakeholders to gain insiders' knowledge and understand the subtleties of GI4AQ+ implementation. Moreover, these chosen research methods led to overcoming hurdles and to learning from them.

School playgrounds are unique in terms of their location, function, ecosystem and indeed the dynamics that occur there. Discussions among the diverse collaborators involved in the GF-Sheff project allowed the exchange of different perspectives, which matured into creating a green fence design that is sensitive to that place and its community. Similarly, the active involvement of all the collaborators and the broader school community created a sense of ownership which was critical for achieving GI implementation, and continues to be essential for the success of the project in the long run. Long-term involvement is crucial for GI maintenance, which tends to be inhibited by multiple social and knowledge barriers, such as misalignment between short and long-term vision or its perceived high costs [22]. The green fence maintenance activities remain on the school's agenda despite the covid-19 pandemic and are currently carried out by the school caretaker, occasionally by a hired gardener, and continuously by parents and staff during volunteer days. The latter proves that the previously-mentioned barriers can be overcome by actively engaging the stakeholders in the NbS implementation process. Additionally, research has shown that stakeholder participation in NbS implementation creates opportunities for benefits including social cohesion, environmental education, and long-term partnerships to obtain funding; it also prevents conflicts, and encourages public acceptability [47].

It is expected that building evidence on co-created NbS will persuade governments and private practice to facilitate spaces for social innovation and NbS implementation [31], and draw interest into working *with* rather than *for* communities (such as the school community) to achieve successful GI projects.

4.2. Co-benefits or the 'plus' of GI4AQ+, trade-offs, and disbenefits

During the GI4AQ+ implementation process, discussion among the collaborators about the aims and ways to achieve them prompted interest in other topics beyond air quality, including the social, environmental, and economic co-benefits identified in this research. Although some of the co-benefits were unintended, others were discussed as the collaborators got immersed into the possibilities that such NbS could offer, for instance, the value of the green fence as a teaching resource.

Social co-benefits were the most frequently reported by the participants. They outnumber greatly the environmental and economic co-benefits. This shows that the identified co-benefits are anthropogenic-centred, which may be a consequence of acknowledging the human-related sources of air pollution in cities and their direct impact on the young. Ferreira *et al.*'s [47] review shows that the NbS literature also focuses mainly on social benefits and, to a lesser extent, environmental benefits, rather than economic impacts. There was some commonality between perceived co-benefits here and those in the Ferreira *et al.*'s [47] NbS study. These were primarily aesthetic value, mental wellbeing, biodiversity and increase in property value. Additional co-benefits not identified in our study include shade, water runoff mitigation and food provisioning. Possibly, this was due to the strong air pollution mitigation theme, or the focus on detailed design in this particular planting scheme. Nonetheless, the participants' recognition of environmental and economic co-benefits in this study demonstrates that the 'plus' of GI4AQ+ goes beyond the human dimension to the ecosystem level and incorporates elements for increased livelihoods.

Fig. 6. Detail of the colours and textures of the green barrier plants; (a) and (b) show the eastern aspect and (c) the southern aspect of the green fence. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A very relevant co-benefit for schools is the learning opportunities that participants referred to. These go beyond the official curricula to premise that short-term nature exposure promotes learning by inducing attention restoration and stress reduction [48]. Beyond academic achievement, personal development and environmental stewardship are other learning outcomes, which are caused by a mix of effects by nature on the learner (e.g., more engaged, more focused, better self-disciplined, more physically active) and on their learning context (e.g., calmer, safer, more cooperative, with more play elements) [49]. Parents and teachers believe that the green fence provided a teaching resource, initiated value for nature discussions, and promoted other mental abilities through imagination and play in equal measure.

Another significant co-benefit was the school community's increased environmental awareness, which elicited interest in other dimensions of sustainable living such as gardening and active travel. Research shows that 'environmental knowledge' is connected to pro-environmental behaviours [50–52], although it is not always enough to foster behavioural change [53,54]. However, in this study, environmental knowledge led some individuals to take further action. These results are related to both the green fence implementation and the communication programme around the aims (the 'why' and 'so what') to the school and local community. One argument for this is that the green fence installation was a visually impactful message of change. It made poor air quality in schools a visual issue and promoted discussions of the problem's root causes and how to tackle them. This narrative was mobilised by explicitly stating the GI aims and communicating them to the local community. Had we not developed a stakeholder communication and engagement plan, the environmental awareness co-benefit would have not been as prominent. Raymond *et al.* [55] argue that continuous communication of the aims and co-benefits, from simultaneous bottom-up and top-down approaches, is necessary to gather support on the NbS and maximise affording those co-benefits. Our communication plan used diverse media targeted at different groups and included talks at the school assembly, sending information to parents via the school newsletter and social media, invitations to fundraising events, local press and radio engagement. The plan palpably played a part in gaining local support, engagement and enjoyment of the outcome.

The School Air Quality Audit Programme for London, UK [56] identifies the use of GI as a mitigation factor, but categorises it as having a low impact on air quality and being medium-high in terms of stakeholder support. This Programme only considers that GI has three wider benefits: visual amenity, safety and increased biodiversity; failing to capture most of the co-benefits identified in this study. Therefore, research to evidence the 'plus' of GI4AQ+ in UK schools has a pivotal role for a more thoughtful assessment of GI in schools and its consideration by the government, especially because this initiative is reported to be backed by school communities.

Finally, two aspects were classified as trade-offs or disbenefits by the school community. These were the maintenance of the green fence and the physical separation it creates with the local area. The first one was counteracted by creating a maintenance plan and a schedule for the next few years, which satisfied the school community. However, the second aspect generated contrasting opinions from some parents and teachers that categorised it as a disbenefit or a trade-off, correspondingly. These contrasting perceptions illustrate the importance of surveying different stakeholder groups to fully account for the co-benefits, trade-offs and disbenefits of GI projects. This example is aligned with Giordano *et al.* [21] who conclude that differences in perception of co-benefits could lead to trade-offs among the different stakeholders. Nevertheless, none of the perceived trade-off and disbenefits led to opposition to the project by the school community; on the contrary, the school playground's green fence was mainly regarded as a positive outcome to tackle a shared concern.

4.3. Relevance of GI4AQ+ dimensions to implementation in schools

We recommend considering the four dimensions for GIA4Q+ implementation in schools (place, physical, biological and school-friendly) to maximise the gains of the school community and provide it with the co-benefits attained from a multifunctional NbS approach. Such dimensions are transferable to the implementation of other GI projects; as they always entail a place, vegetation, and a community.

The place dimension combines social and landscape characteristics. From a pragmatic approach, it should be considered first when assessing the feasibility of GI4AQ+ interventions to prevent trapping polluted air and ensure air quality gains. Naturally, understanding a place simultaneously means understanding a particular context and its community, and being responsive and adaptive to that context is highly relevant for developing GI. The importance of the place context has also been demonstrated for biodiversity-led GI in cities, where contextualised interventions have helped to provide multifunctional ecosystem services, such as biodiversity provisioning or amenity space, and addressed barriers to implementation [57].

Once the place dimension is covered, we can move onto the interrelated physical, biological and school-friendly dimensions of green fences in schools. The physical and biological dimensions are highly relevant for air quality. Plant selection supports achieving a green fence design with a length, height, and width that will divert polluted air and filter pollutants from the remaining airflow that passes through the fence. The green fence vegetation choice was largely dictated by our understanding of the literature, besides aligning it to the school playground needs and practical and safe school management. Nevertheless, there is not a definitive list of plants suited to improving air quality, rather, a limited list of studied taxa primarily from Europe, the US, and China [58]. Therefore, a pragmatic approach to green fence plant selection involves following the general recommendations listed in the literature (refer to Section 3.2.3 and Table 2) and adapting it to the local plants commercially available to achieve a mixed-species fence. Moreover, the

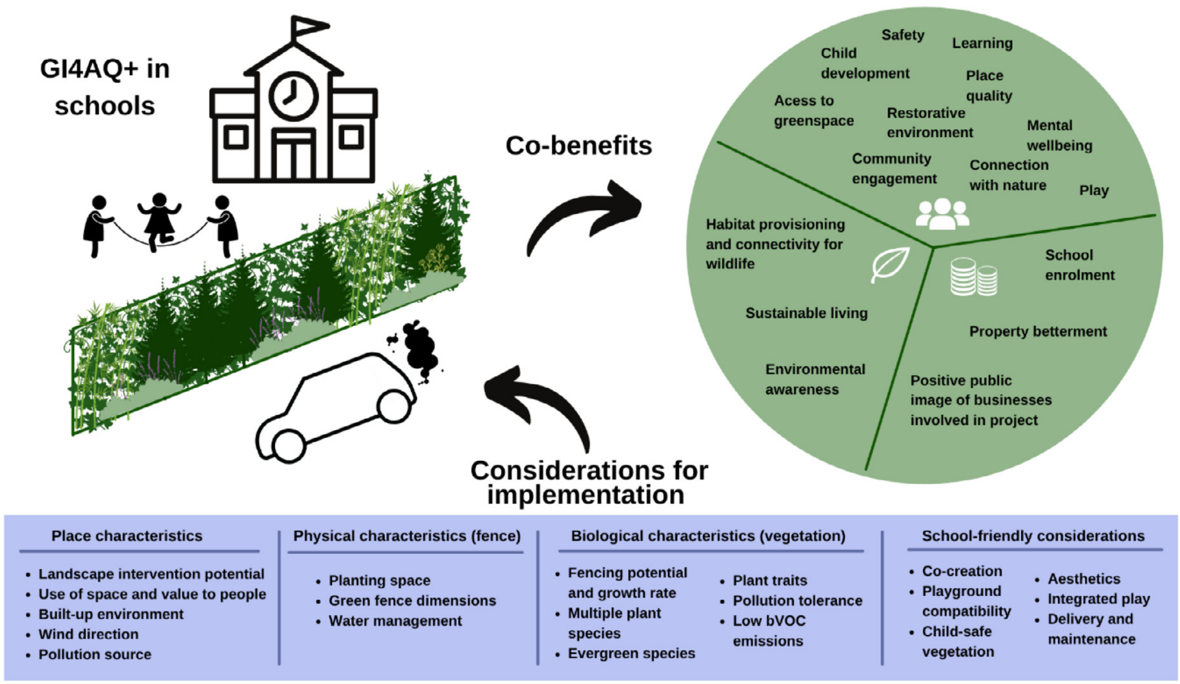

Fig. 7. GI4AQ+ dimensions for implementation in schools and their derived perceived co-benefits beyond air quality provisioning.

school-friendly dimension is vital to the success of the GI4AQ+ interventions and plays a big part in promoting co-benefits and preventing disbenefits. A summary of these dimensions for GI4AQ+ implementation and the connection with resulting perceived co-benefits is illustrated in Fig. 7.

It is important to acknowledge that this type of NbS may not offer the same level of air quality gains all year long. In real case scenarios, environmental, social or economic factors may hinder optimal green fence function. A clear example is the changing wind direction relative to the green fence, which influences the level of AQ improvement [59]. Therefore, accounting for the co-benefits and communicating them to the school community and other stakeholders is crucial in promoting GI in schools. Overall, the co-benefits may compensate for the variable effects of greenery on air quality.

4.4. GI4AQ+ for school greening

The collaborators involved in the green fence implementation process developed criticality toward air quality provisioning and to the co-benefits found here. It seemed that their involvement in the project allowed them to appreciate and expect other aspects of playground greening and quality. To illustrate the case, about eighteen months after installing the green barrier, the case study school replaced its play equipment with more inclusive and organic shaped pieces that foster child development and outdoor learning (see Fig. 4c). Moreover, the school community also identified multiple co-benefits from the grey-to-green playground transformation. The study findings suggest that discussions and implementation of GI4AQ+ encourage not only identification of other GI co-benefits, but also the desire to afford them and boost their actual delivery.

Despite the small space that many inner-city schools have for school greening, our study suggests that GI4AQ+ implementation can positively and significantly impact school communities' wellbeing even where the available space is limited. Other studies show that the impact extends to wildlife, as small green spaces in the UK, such as private gardens, assist wildlife by providing habitat and corridors to other green areas [60,61]. Moreover, implementing GI4AQ+ in schools could open doors to green space access for all children. This is especially important in urban environments where neighbourhood configuration, and sometimes neighbourhood deprivation, pose a barrier for children to engage with nature due to green space inequalities (including low quality green space) [62–64]. Such inequalities may contribute to 'nature deprivation' health outcomes (e.g., higher incidence of childhood obesity, depression, anxiety disorder, and immune functioning decrease) [65], which could be reduced if children had greener schools.

It appears that using the concept of GI4AQ+, whilst potentially having a positive influence on air quality when properly designed, is a useful way to mobilise school greening. Accordingly, by focusing on the need – and right – for clean air to protect children's health and wellbeing, GI can be introduced in schools for that reason, yet certainly covering many more co-benefits to school communities, biodiversity, and the local economy. However, it is worth noting that the GI4AQ+ approach is recommended only as complementary to other efforts for reducing/eliminating air pollution at the source. Still, school communities can have significant gains from GI4AQ+ implementation.

4.5. Further research and limitations

The co-benefits identified here reflect the collaborators' and school community's experience and perception during the co-produced GF-Sheff project. Nevertheless, there may be further co-benefits that could be identified via other research approaches. For instance, there is evidence regarding noise reduction by green infrastructure [66–68] and, in a school playground setting, noise levels and pupils' wellbeing could change after the plants addition. Regarding behavioural changes, nature connectedness mediates better cognitive and emotional self-regulation [69] and green schoolyards are related to more friendly and cooperative social interactions [18]. Hence, the effect of the green fence on children's interactions, such as inclusion or aggression, could be explored. Moreover, evidence links attention restoration with exposure to greenery [70], which influences children's concentration and, in some studies, has been positively associated with academic performance [71,72]. Attention tasks and academic performance could be monitored to examine those links. In terms of the environmental co-benefits, carrying out formal biodiversity surveys (e.g., butterfly counts, insect species richness, pollinator season length) before and after the green fence implementation could indicate the extent of the increased biodiversity observed by the participants. Therefore, innovative approaches to study multifunctional GI in schools are encouraged to help evidence wider benefits and add to the appeal of NbS.

Finally, after March 2020 the research was carried out online in accordance with the measures imposed by the British government to prevent the spread of the covid-19 pandemic. This situation also limited the school community's participation on green fence maintenance activities and limited their number. However, they were carried out on-site when safe and still provide an insight into green fence management by the school community in the long-term.

5. Conclusion

This study elaborates on the implementation process of GI4AQ+ and the co-benefits offers in a UK school context. Besides the potential for air quality betterment, action research carried out in the school case study showed that place users and stakeholders noticed other social, environmental, and economic co-benefits. The social co-benefits of implementing a green fence in the school were particularly dominant. The most frequently mentioned were the enhanced quality and attractiveness of the school playground, children's safety on school premises, the positive impact of the green fence plants on mental wellbeing, and the learning opportunities they offer. The environmental co-benefits mainly focused on the awareness acquired from co-creating, experiencing, and understanding the aims behind the newly planted playground. Finally, the economic co-benefits are primarily related to the local uplift created by the school playground's improvement and the positive public perception of the GI4AQ+ intervention.

This study also showed that well-planned GI4AQ+ interventions are context-specific. Thinking critically about the four dimensions for implementation found here – place, physical and biological characteristics, and school-friendly considerations – could help maximise air quality and co-benefits and mitigate any disbenefits for a particular place. Moreover, GI4AQ+ appears to be a valuable strategy for school greening and delivering the multiple functions GI can provide for schools and their communities. These interventions may also encourage school communities to identify and procure the delivery of other GI co-benefits.

Evidencing the co-benefits and pragmatically defining the dimensions that support GI4AQ+ implementation will contribute to supporting schools, practitioners, and governmental institutions to assess and achieve the development of green fences and GI more efficiently in schools.

NBS impacts and implications

- This study contributes to building knowledge that will foster the mainstreaming of green infrastructure in schools, derived from a co-production approach, for the purpose of improving air quality and protecting children's health. It also identifies ten social co-benefits for the school community, some of which are just as important as air pollution reduction.
- These interventions benefit schools' economies by offering a more desirable environment for pupils, which increases parents' interest in the schools and might translate into increased enrolment.
- Evidencing the social and economic co-benefits of GI in schools helps to mobilise school greening. This, in turn, provides environmental co-benefits that are often not considered when designing GI project targeted to communities, but that are important for urban nature. For instance, we have identified habitat provisioning and connectivity for wildlife as an environmental co-benefit.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

María del Carmen Redondo-Bermúdez: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Project administration. **Anna Jorgensen:** Funding acquisition, Conceptualization, Methodology, Writing – review & editing, Supervision. **Ross W. Cameron:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing, Supervision. **Maria Val Martin:** Conceptualization, Methodology, Supervision, Funding acquisition.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2022.100017.

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Chapter V

Green barriers outside the European context, implementation in Buenos Aires, Argentina

Publications included in this chapter:

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Article

Green Fences for Buenos Aires: Implementing Green Infrastructure for (More than) Air Quality

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Abstract: Schoolyards in North America and Europe are increasingly using green fences as one measure to protect vulnerable populations from localised air pollution. This paper assesses the possibilities and limits for mobilising this format of site-specific green infrastructure in cities in low- and middle-income countries beset by air pollution and multiple other socio-environmental challenges, and particularly questions the definition of green fences as a green infrastructure for air quality (GI4AQ). We applied several qualitative and action research methods to the question of green fence implementation in Buenos Aires, Argentina—a Latin American city with weak air-quality policies, limited green infrastructure, and little experience with nature-based solutions. Firstly, we conducted a literature review of the role that urban vegetation and ecosystem services may play in AQ policy and the implementation barriers to such approaches globally and in the city. Secondly, we planned, designed, constructed, maintained, and evaluated a pilot green fence in a school playground. Thirdly, we carried out supplementary interviews with stakeholders and expert informants and compiled project members' narratives to respectively characterise the barriers that the project encountered and delineate its attributes based on the associated actions that we took to overcome such barriers to implementation and complete the pilot. Our findings identify multiple barriers across seven known categories (institutional, engagement, political, socio-cultural, built environment and natural landscape, knowledge base and financial) and highlight examples not previously considered in the extant international literature. Furthermore, learning from this experience, the paper proposes an expanded model of green infrastructure for air quality *plus multi-dimensional co-benefits* (GI4AQ+) to increase implementation chances by attending to local needs and priorities.

Keywords: action research; nature-based solutions; air quality; green infrastructure; urban environmental policy; Latin America

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1. Introduction

Air pollution poses substantial threats to human health, making air quality (AQ) management a key policy area. In 2016, 4.2 million people died prematurely due to illnesses related to poor ambient AQ globally. According to the World Health Organization (WHO) [1], over 90% of these deaths occurred in low- and middle-income countries. The United Nations Environment Programme (UNEP) lists weak AQ regulations, lax vehicle emission standards, and remaining coal-burning power plants as potential reasons for disproportionate air pollution-linked deaths amongst the poorest populations [2]. Poor AQ compromises children's health in particular. They are smaller and breathe more air

5.1

per unit body weight; therefore, the effects of pollutants are amplified [3]. Additionally, children's lungs are still in development, and early exposure to air pollution has a negative association with lung function later in their lives [4,5]. Air pollution also renders children more susceptible to developing asthma and other respiratory problems [6,7]. Other consequences include cognitive impairment, depression, and anxiety symptoms [8].

Whilst efforts to abate urban air pollution date back decades, the study and practical use of GI to improve AQ is a relatively new field. The scientific literature has surged since 2017 [9]. Multiple GI formats can potentially mitigate air pollution. These include urban forests, green walls, green roofs, tree-lined streets, and green fences. The latter are gaining recognition as a valid approach to mitigate urgent air pollution problems in urban settings across the USA, Europe, and the UK. Moreover, Hewitt et al. [10] recently coined the term green infrastructure for urban air quality (GI4AQ) to designate GI that has been specifically and effectively designed to protect specific sites from air pollutants. The authors assign a 'third order' rank of priority to such GI, behind the overall reduction and removal of pollution sources from urban environments where vulnerable populations live and spend time. They conceptualise this as a Reduce-Extend-Protect model. More broadly, the consensus on GI4AQ includes the following three mitigation mechanisms: (1) dispersion of pollutant gases, such as nitrogen dioxide (NO_2), and of particulate matter (PM); (2) deposition of PM on plants' external structures; (3) distance elongation between air pollution sources and receptors [11]. Further guidance has been given by governmental institutions, such as the United States Environmental Protection Agency (US EPA) [12] and the Greater London Authority [13], demonstrating the case for GI to be incorporated into AQ policy and practice. In fact, the US EPA [12] specifically recommends using green fences to mitigate air pollution in school campuses exposed to vehicular traffic.

The GI4AQ model is not the sole approach. The potential for urban vegetation to contribute to AQ management is of interest for proponents of nature-based solutions (NbS), which are defined as a set of integrative principles and actions inspired by natural processes to address environmental, economic, and social challenges through ecosystem-based services [14,15]. The NbS perspective indicates that there is much to be gained by envisioning GI as a component of multi-pronged, multi-purpose urban sustainability strategies rather than isolated interventions with limited site impact. In fact, the European Union (EU), one of the major promoters of NbS, define GI as "a strategically planned *network* of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services" (emphasis added) [16] (p. 3). Calfapietra [17] (pp. 144–154) reviewed several EU-funded research and innovation projects seeking to ascertain NbS' role in AQ management. Many of these include related objectives of 'co-benefits', such as microclimate regulation and thermal comfort, human health and wellbeing, and urban biodiversity improvements.

This paper makes the case that green fences need not be limited to a single AQ function. Instead, they could contribute to a transformative urban environmental agenda. Strategically designed and curated green fences in schoolyards can produce multiple socio-environmental gains in the short run in synergy with longer-term educational and awareness-raising actions. These will address the root causes of air pollution and other forms of environmental degradation in cities. We call this the green infrastructure for air quality *plus socio-environmental co-benefits* (GI4AQ+) model for green fences. GI4AQ+ can be applied in schools to protect children at the place where they spend one third of their days, but green fences can also be adopted by those aiming to provide co-benefits beyond the reduction of air pollutant concentrations on site. Considering green fences as an urban NbS also requires grappling with their implementation potential and barriers in real-life contexts. Chatzimentor et al. [18] argue the need for more socially oriented NbS research and find that implementation constitutes the most recommended topic for future studies (in 62 out of 196 scientific publications from the EU and UK). Global scalability remains a challenge for this literature, however, and there is practically no specific discussions on green-fence formats.

There is a growing global consensus to incorporate GI and NbS into the urban policy toolbox, with endorsement by institutions such as the United Nations [19]. Nevertheless, implementation varies markedly across nations and cities, which have developed comprehensive schemes through regulatory reforms, policy innovation, and creative incentives. Research coverage is also uneven. This is particularly the case for site-specific GI formats (similar to green fences) such as green roofs and green walls, for which Liberalesso et al. [20] identified six mechanisms worldwide to support adoption. These include tax reductions, financing, construction permits, sustainability certifications, legal mandates, and agile administrative processes. However, these mechanisms cluster in Europe, the US, and Canada, whilst South America and Asia have considerably fewer examples. This justifies the need for further studies from cities in underrepresented regions, which could also address gaps in the broader field of GI research; studies using related concepts such as ecosystem services, NbS, and natural capital are mostly produced in Europe, the US, and Canada [21]. In fact, these three regions had more than 2000 publications each by 2017, followed by Asia (mainly China), with more than 1000 publications about GI/ecosystem services. In comparison, Latin America and the Caribbean, this paper's world region of interest, had under 500 publications [22]. In Latin America, GI adoption has focused on biodiversity conservation, climate change mitigation, and recreation and health. Regarding AQ, studies mostly link with climate change research. Air quality benefits are explored in relation to large landscape interventions, such as urban forests in Chile [23] and Mexico [24,25]. Some countries, such as Brazil, Mexico, Peru, Colombia, and Argentina, have introduced the GI concept in the climate change/air quality context. However, Vásquez et al. [21] argue that GI adoption in these countries' current policies is minimal, with insufficient implementation by planners and practitioners.

The low coverage of GI and AQ mitigation research in low- and middle-income countries, such as Latin American countries, does not reflect the fact that these nations have vulnerable populations at high risk from air pollution. Furthermore, the assessment of barriers to implementation for green fences in Latin American cities cannot easily build on policies underway. In Buenos Aires, for example, no such scheme existed previous to our pilot. To close these knowledge gaps, mitigate a serious health threat, and contribute to the broader NbS agenda, this paper discusses the actual implementation experience of a pioneer green fence and development of the GI4AQ+ model. We first list the range of qualitative and action research methods used and then present and discuss our findings. Our main concern is implementation potential in the city and Latin American region, and thus our analytical focus lies in the identification of barriers and mitigating strategies.

2. Methods

This study combines (i) a literature review of key concepts related to GI implementation and its use in AQ policy with (ii) a case study of a green fence built through researcher-initiated action research. We first carried out a preparatory literature review on global barriers to GI implementation and on the current approach of Buenos Aires with respect to GI and AQ. We then engaged in the process of building a green fence in a schoolyard (playground) in Buenos Aires, which we used as the basis for an explanatory case study of barriers to GI implementation in the city and potential strategies to overcome them. From here on, we refer to the pilot as the GF-BA project (Green Fence in Buenos Aires project). GF-BA was a researcher-initiated co-production project that involved planning, designing, constructing, maintaining, and assessing a pilot green fence in a school playground; this was the first of its kind in Buenos Aires. Figure 1 presents a summary of our study's research design.

The GF-BA project involved multiple city government units and various social stakeholders in a collaborative network (see Figure 2), focused on obtaining practical insight on green fence implementation [26,27]. The GF-BA incorporated urban living lab (ULL) principles from the outset, particularly in what concerns the green fence's experimental character at the complex intersection between environmental science and sustainability innovations, and the active involvement of various stakeholders and community users beyond researchers and policy makers [28–30].

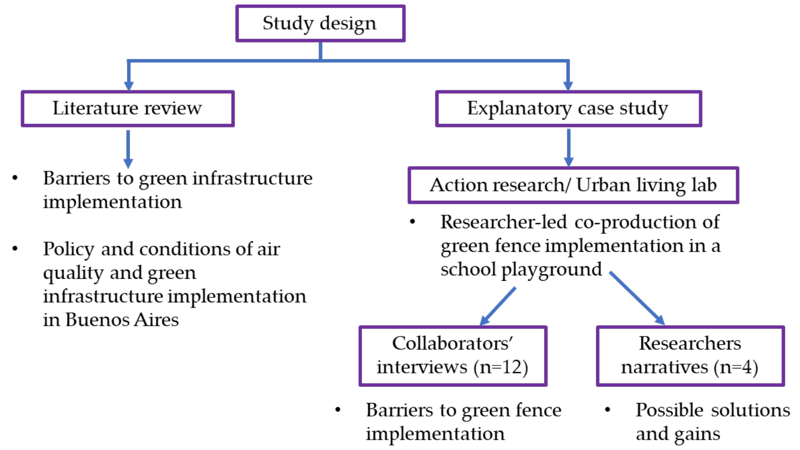

Figure 1. Research design of the study.

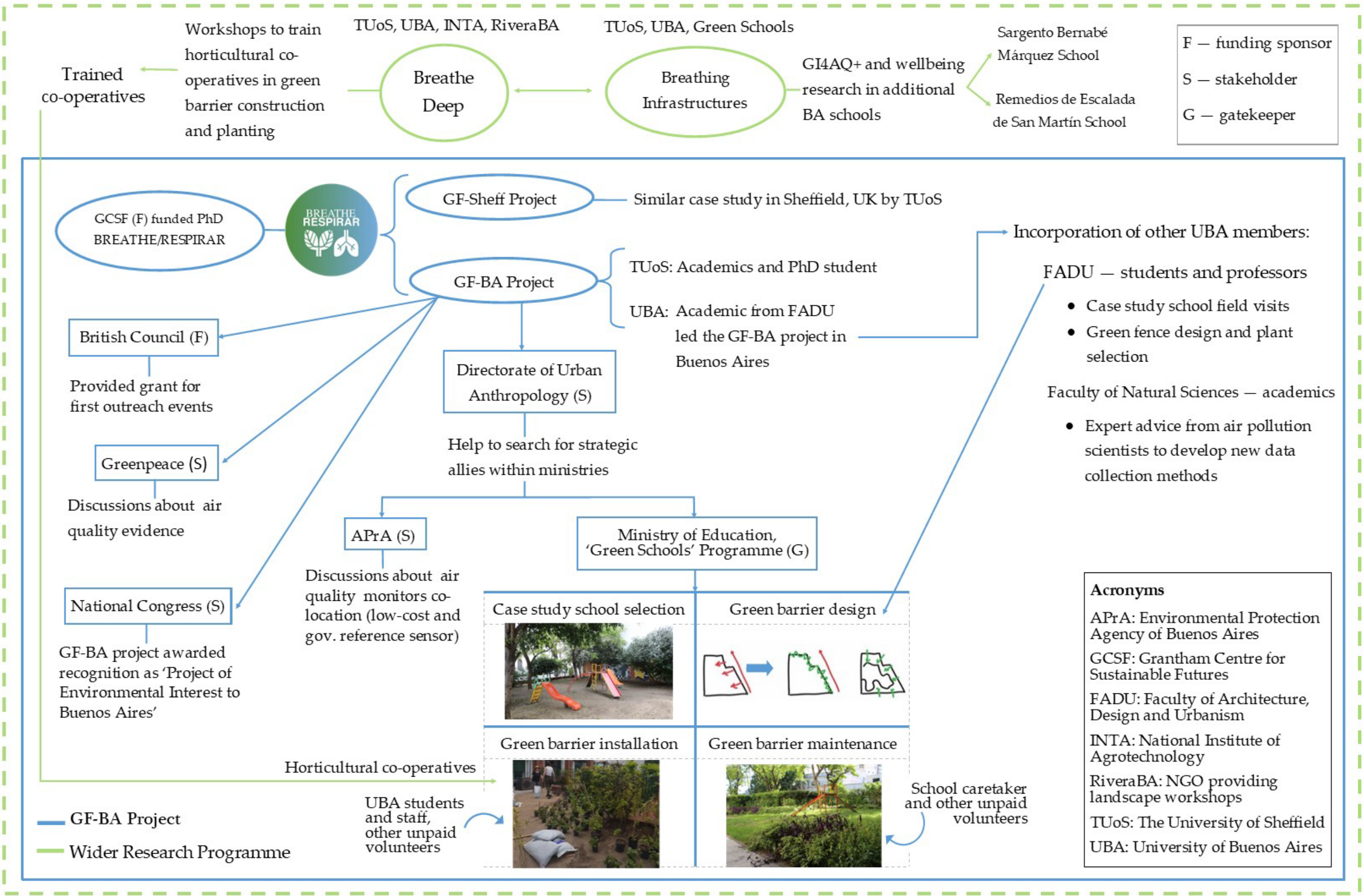

Figure 2. Overview of actors involved in the GF-BA project.

2.1. Literature Review

Our literature review on the international current state of the art regarding barriers to green infrastructure implementation aimed to identify analytical categories to structure our primary data collection in Buenos Aires. This was not limited to the AQ field due to the very limited number of publications addressing this issue within this field and the fact that barriers to other GI formats may also apply to green fences. The international typology of barriers that we developed also helped us identify barriers specific to the Buenos Aires context and to categorise the various actions taken to lead the GF-BA project to fruition. This also required in-depth understanding of the local context in terms of AQ and green infrastructure policy, for which we carried out an additional review of scientific sources and policy documents in both English and Spanish.

2.2. Explanatory Case Study Based on Action Research—The GF-BA Project

Our data collection pivoted around action research. Action research refers to a repeated cycle of action and reflection. It is anchored in an ethos of transformative interventions, whose beneficiaries lead or participate actively in their creation [31] (pp. 90–95). We selected action research for its potential to effect change by generating solutions to practical problems while empowering people to engage with activities on the ground and participate actively in the research [32] (pp. 1–24). This makes action research particularly suitable to advance NbS research in settings without robust policy mechanisms for GI provision, where researchers are unable to study pre-existing examples. Previous to the GF-BA pilot, there was no provision of vegetation to mitigate air pollution in Buenos Aires. We started from the assumption that action research projects can support participants (researchers and practitioners/stakeholders) in co-creating GI whilst also observing and analysing its effects. Ideally, participants will work together in a collaborative way, including contributing ideas, trying things out, sharing experiences, generating knowledge, adjusting course within systematic cycles of action, and reflection [33] (p. 5). Therefore, as problems emerged and were dealt with in an iterative 'learning by doing' approach, action research provided us with 'unique access to insider knowledge' [34] (p. 5), which we leveraged to ascertain latent barriers to GI implementation.

In November 2019, we installed the pilot green fence at a school in the western neighbourhood of Floresta (see Figure 3). This location was selected at the end of a year-long process of liaising with multiple stakeholders and gatekeepers. We visited multiple city-run schools until finding the right fit. There were requirements from the city government's Green Schools (GS) unit and from the GF-BA research team. Most notably, for GS, the school needed to be affiliated with their programme, have an 'Environmental Reference' teacher and track record of a school garden. For the GF-BA research team, the school needed to have measurable pollution levels (i.e., high traffic flow) and have an open schoolyard facing the street, where a landscape intervention was possible.

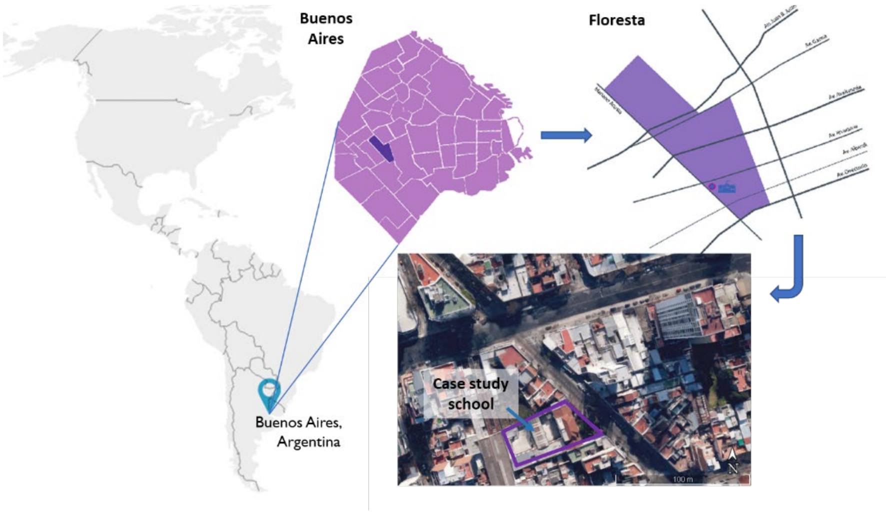

Figure 3. Location of case study school where the GF-BA project took place.

The pilot school's layout is appropriate for a green fence installation, with a playground located at the front and facing a two-lane street. The school's building was constructed in the 1940s and is listed as a cultural heritage site for its neocolonial style. Children of 4–5 years of age use the playground, whilst cars, public transport, and some heavy vehicles produce heavy traffic on the front street and a main road within 60 m of the school. We planted along the perimeter fence between the playground and adjacent sidewalk. The green fence comprises a row of the *Hedera helix* climber growing vertically over railings; two species of bamboo (*Phyllostachys aurea* and *Bambusa multiplex*) to create a second vertical layer behind this, and shorter plants (17 species) towards the playground's interior. Two years after initial installation, the plants were 2.00 m high and 0.50 m wide and were expected to grow in width as the green fence matures. Figure 4 shows illustrative photographs of the green fence in the school playground at earlier stages. We initially attempted to use basic AQ monitoring mobile equipment to measure the green fence efficacy. However, we had to abandon this strategy due to the lack of local staff available to carry out the monitoring amidst COVID-19 restrictions and an extended school lockdown. Instead, we opted for fixed devices (diffusion tubes) to monitor nitrogen dioxide over approximately three months (three cycles of 21 days each), with support from a local expert who advised us to use this method.

(**a**) (**b**) (**c**)

Figure 4. Green barrier in case study school (**a**) before the installation of the green barrier; and 1.2 years after its implementation, from (**b**) street view and (**c**) playground view. Source: Author's own images.

We used this two-year action research experience to develop an explanatory case study on potential solutions for the barriers to implementation that may be preventing broader use of green fences and other GI formats in Buenos Aires. Case studies provide context-specific analysis and thus constitute an appropriate format to capture and present results from action research [32]. With a processual concern on 'how' questions, the case study methodology develops an in-depth description of social phenomena [35]. Case studies are particularly appropriate when the focus is on contemporary questions within complex real-life contexts [35] (p. 18). An 'explanatory' case study provides insights towards theory-building on causal links occurring around a tightly bound process or a 'specific, complex and functioning thing' [36] (p. 175)—in this case the barriers to implementation that we identified and the actions that we took to overcome them. We used a two-step approach to first identify and classify implementation barriers related to the city's policy and social contexts and then reflect on how we cleared them by taking specific actions that redefined the GF-BA project as a GI4AQ+ intervention. The case study was also informed by results from two sets of qualitative methods, namely stakeholder and expert interviews and project members' narratives.

2.2.1. Stakeholder and Expert Interviews—Barriers to GI implementation in Buenos Aires

From the outset, it was clear that the challenges that we were facing were not unique to our project bur rather embedded in broader barriers to GI provisioning in Buenos Aires. Thus, whilst our unit of analysis was the GF-BA implementation process, we carried out interviews with stakeholders and expert informants that helped us interpret the specific issues that our green fence installation faced in the local context where AQ-focused NbS initiatives were underway despite a highly sympathetic policy discourse. We conducted the semi-structured interviews (n = 12) between November 2019 and August 2020. Some of these took place online due to COVID-19 pandemic disruptions. The list of interviewees comprises representatives from different city government units (Ministry of Education, Ministry of Urban Development, Environmental Protection Agency, and City Council), relevant social movements (environmental NGOs and grassroots gardeners' co-operatives), project collaborators from the University of Buenos Aires (staff and students), and landscape volunteers. Thematic analysis was used for interview transcripts alongside policy documents obtained during the literature review stage [37]. The method consisted of identifying codes, which could contribute to answering the research questions [38] (p. 4), and condensing them into meaningful themes based on code similarity. Using the NVivo software package, data were classified into seven categories, derived from the barriers to GI literature review to find common and emerging themes [39].

2.2.2. Project Narratives—The GF-BA Project Attributes

To better understand how implementation was achieved, overcoming the multiple barriers encountered, we constructed a post hoc collective project narrative on the process. A four-member international team had previously conducted participant observation whilst partaking in various activities and interacting with multiple stakeholders, gatekeepers, and contributors. A fifth researcher interviewed them to articulate a joint narrative, recognising that individual experiences would be influenced by respective fields of expertise (landscape planning, environmental science, and social science), positionalities (three female researchers at multiple career stages and one mid-career male researcher), and availability. Three of the members were based in the United Kingdom and travelled to engage in key project events, including the project launch, design workshops, and planting days. The fourth researcher was locally based in Buenos Aires and carried out continuous project management. The analysis focused on the identification of project attributes and associated actions that were either critical to overcoming various implementation barriers towards pilot delivery or outcome enhancement.

3. Results

3.1. Barriers to Green Infrastructure Implementation

This section presents findings from our review of the general GI literature. These studies analyse implementation challenges and the strategies to overcome them, and provide insight on how green fences research could turn towards questions of effective real-life implementation to realise the pollution-abating benefits calculated through computer models. Using individual case studies and GI compendiums, researchers have identified the most common barriers to implementation, and there is a growing literature on learning from what has worked in collaborative experiments with NbS [26,40,41]. Table 1 summarises findings on barriers across seven categories: (1) institutional and organisational, (2) engagement and coordination, (3) political, (4) socio-cultural, (5) built environment and natural landscape, (6) knowledge, and (7) financial. Extant studies show that lessons are drawn from situated projects often implemented in complex contexts [16] (pp. 8–10), such as our case in Buenos Aires.

Table 1. Barriers to green infrastructure identified in the literature, per category.

Categories	Barriers	References
1. Institutional and organisational	Sectoral silos Issues with partnership working Issues with multi-disciplinarity Staff turnover	[27,40,42–44]
2. Engagement and coordination	Unclear responsibilities and ownership Disconnection between short-term and long-term focus Lack of engagement by partners and stakeholders	[27,40,42,45–47]
3. Political	Lack of political will Lack of supportive legislation and regulatory frameworks Lack of law enforcement	[40,44,47,48]
4. Socio-cultural	Path dependency Lack of awareness of multifunctionality and benefits of GI Public preferences and perception Broad societal cultural barriers	[40,42,45,48,49]
5. Built environment and natural landscape	Design limitations Technical difficulties Public and private land ownership	[40,43,47–49]
6. Knowledge	Lack of knowledge of implementation processes Uncertainty as to GI impacts Lack of technical guidance for maintenance and monitoring	[40,42,44–47]
7. Financial	Lack of financial incentives Lack of financial resources	[40,42,46,47,49]

3.1.1. Institutional and Organisational

Green infrastructure projects are multidisciplinary and, as such, entail challenges of leadership and collaboration within and among the institutions involved. Each institution, department, or stakeholder operates on its own terms (e.g., agenda, timeframe, and values). When the different actors in a GI project work according to their own terms, or have goals incompatible with other actors, this is generally referred to as ‘sectoral silos’ in the literature [40]. Sectoral silos cause institutional fragmentation, which complicates and challenges the progress and success of GI interventions, the common goal. Additionally, leadership and monitoring of GI projects may be hindered by an institution’s internal governance issues or staff turnover.

3.1.2. Engagement and Coordination

Long-term engagement of all parties involved is a major barrier to GI projects. Outcomes and impacts are usually measurable after a sustained period, in which the role that each actor plays in the long term should be clear. Poor communication among actors causes misunderstanding of project ownership or lack of engagement, which is crucial for the monitoring and maintenance of GI. For instance, when local communities in South Africa claimed a natural park and wetland as part of job loss compensation, uncertainty regarding actual ownership of the area led to neglecting maintenance activities, creating a fire hazard to their farms [50]. Without stakeholder engagement over time, the multiple benefits of GI are potentially undermined.

3.1.3. Political

Transitioning from grey to green practices is related to political will. Lack of government support translates into lack of policy, legislation, and regulatory pathways to GI mainstreaming or to poor enforcement of laws and regulations relating to green practices. Lack of political will manifests as prioritising other pressing issues such as poverty or unemployment, aversion towards change, or simply not giving importance to GI as a multifunctional solution. For instance, Johns [48] identified that the persistent prioritising of grey infrastructure over the use of GI in storm water management in Toronto is a significant hurdle perceived as attributable to poor political will.

3.1.4. Socio-Cultural

The values of local cultures and gatekeeper institutions where GI interventions take place are important and may pose some socio-cultural barriers. Some of these barriers come from the lack of awareness of the environmental, social, and economic benefits of GI or from a lack of knowledge of successful projects. Past positive and negative experiences with GI at different levels (government, private practice, residents) may create bias towards their uptake or rejection, which is referred to as 'path dependency' in the literature [47].

3.1.5. Built Environment and Natural Landscape

The physical characteristics of the place where GI is to be implemented constrain the design and may even impede its development. Firstly, land ownership determines the activities that are possible in a place as well as the gatekeepers to liaise with. Secondly, the landscape morphology, available space, and built-up infrastructure pose technical difficulties in developing GI and dictate its design. Equally important, the availability and structure of adequate vegetation for GI pose technical barriers and constrain the design. For example, Li et al. [51] argue that the current use of a single 'sponge city model' for solving flooding through GI in China may not be successful due to the diverse geographical conditions of the pilot cities.

3.1.6. Knowledge

There is little guidance on the development, monitoring, and maintenance of GI, and it is challenging to provide standards because the system is alive (comprising, e.g., vegetation, soil, water) and context-dependent. Therefore, the lack of knowledge of GI practicalities and uncertainty as to its impacts remain as significant hurdles to implementation. Additionally, institutions may not have the capacity or expertise required to develop GI projects as, in some geographical contexts, GI innovation has primarily remained in academia or at pilot project level.

3.1.7. Financial

Financial barriers are related to the lack of dedicated resources for the potentially high up-front costs of GI investments as well as long-term maintenance costs. Moreover, a lack of financial incentives is a significant inhibitor to mainstreaming in some countries.

These barriers have by no means deterred cities from undertaking numerous GI and NbS projects. In fact, there is increasing literature documenting lessons learned from successfully implemented schemes. For example, in the European context, where NbS are often initiated by local governments, Frantzeskaki [26] points out that the development of trust between 'city and citizens' and collaborative governance among local government and other actors are important enablers. Yet, this may not translate easily to Latin American contexts with radically different state–community relations [52]. Dobbs et al. [22] calls for reflective practices that leverage global lessons to complement rather than replace existing local initiatives. These require consideration of socioeconomic inequalities and weak governance in the region. Therefore, we adopted an action research approach whereby implementation was collaborative yet researcher-initiated. We built a pilot green fence in Buenos Aires to investigate NbS contribution to addressing local AQ challenges.

3.2. Air Quality and Green Infrastructure Approaches in Buenos Aires, Argentina

The Autonomous City of Buenos Aires (hereafter referred to as Buenos Aires or BA) is the political capital of Argentina and the economic and administrative core of the country's largest urban region. Large motorised-traffic flows constitute the main contributor to air pollution [53], as the city's resident population of 3 million doubles during daytime hours. Large, radial boulevards channel traffic to central districts, compounding the problem along street canyons, which present little to no consideration for buffering traffic-related air pollutants, even if provisioned with some level of street-tree planting. Scientific studies have been raising AQ concerns for two decades [54–58]. These studies have correlated concentrations of motorised-vehicle traffic emissions with concentrations of particulate matter ($PM_{2.5}$) [55] and with harmful gases (NO_2) [54]. Despite this association, the automotive fleet in BA is on the rise, with 1,548,383 vehicles by June 2020, a 35% increase over 2010 [59], and with no governmental restrictions of traffic flows.

Levels of air pollution in BA sometimes exceed the parameters recommended by the WHO, and at times even the laxer local regulation, as summarised in Table 2. Whilst, according to limited government monitoring, the official maxima are not exceeded, local and periodic exceedances are likely to cause risks to public health. Meteorological factors such as continental winds influence exceedance occurrence, with winds coming from the northwest and southwest causing the largest exceedances in the city [58]. A non-peer-reviewed study commissioned by Greenpeace Argentina [60] to monitor AQ around schools and children's hospitals showed that at more than 40% of the sampling locations, NO_2 emissions exceeded the previous WHO limit (2005), and that 14 out of 17 schools had $PM_{2.5}$ concentrations above the same guidelines [61]; under the new WHO guidelines (2021) [62], schools have even greater air pollution exceedances.

Table 2. Summary of air pollutant limit guidelines and reported average concentrations in Buenos Aires.

Type	Reference	$PM_{2.5}$	PM_{10}	NO_2	O_3
Guidance	Legislature of Buenos Aires limits [63]	65 μg/m^3–24 h 15 μg/m^3–annual (mean)	150 μg/m^3–24 h 50 μg/m^3–annual (mean)	100 μg/m^3–annual (mean)	235 μg/m^3–1 h 157 μg/m^3–8 h (mean)
	WHO limits (2005) [61]	25 μg/m^3–24 h 10 μg/m^3–annual (mean)	50 μg/m^3–24 h 20 μg/m^3–annual (mean)	200 μg/m^3–24 h 40 μg/m^3–annual (mean)	100 μg/m^3–8 h (mean)
	WHO limits (2021) [62]	15 μg/m^3–24 h 5 μg/m^3–annual (mean)	45 μg/m^3–24 h 15 μg/m^3–annual (mean)	25 μg/m^3–24 h 10 μg/m^3–annual (mean)	100 μg/m^3–8 h (mean)
Reported in scientific study	Bogo et al. [55]	Summer: 41 ± 9 μg/m^3 Winter: 33 ± 5 μg/m^3 (mean ± sd)	-	-	-
	Reich et al. [57]	-	-	32.7 ± 0.56 μg/m^3 (mean ± SE) 1.5 months	15.88 ± 0.39 μg/m^3 (mean ± SE) 1.5 months
	Arkouli et al. [56]	15 μg/m^3 in one year	34 μg/m^3 in one year	-	-
	Pineda Rojas et al. [58]	-	29.33 μg/m^3 Daily mean for 2008–2010 period	38.23 μg/m^3 Daily mean for 2008–2010 period	-

The city's AQ policy framework is characterised as incipient. Early adoption of environmental management in the 1960s and 1970s was truncated by Argentina's military coup. National policies only reincorporated democratic engagement with the environment in the late 1980s in the wake of the Brundtland Report [64] and the international drive towards sustainable development. Momentum was gained in the post-Kyoto context of the early 21st century, again with the prominent intervention of international actors such as the Clinton Foundation, who emphasised the promotion of policies geared to reduce greenhouse gas (GHG) emissions. As a result, the existing monitoring infrastructure is inadequate to detect AQ indicators of critical importance for human health (such as $PM_{2.5}$) and provide reliable data on local exceedances. The General Directive of Environmental Control of the city's Environmental Protection Agency (APrA) has only three operational fixed air-quality monitors within the city, measuring carbon monoxide, NO_2, and PM_{10}; $PM_{2.5}$ is not monitored at all. Furthermore, efforts towards international compliance are dissociated from local concerns, and there is little integration across policy areas to address crucial AQ challenges in a context of limited government resources and multiple socio-environmental issues.

On the other hand, the BA government acknowledges the importance of urban greening. They have put forward an ambitious plan of GI provisioning as part of the city's commitment to the C40 international cities network of climate change leadership.

The local citizenry also mobilises around greenery, with the defence of public space as one of the priorities for both formal NGOs and neighbourhood groups [65]. The city government launched the ambitious Buenos Aires Verde (BAV) programme in 2014. A twenty-year plan, BAV aims to increase public green space in the city, improve local accessibility, and promote pedestrian travel. It relies on new green spaces such as green corridors, green roofs, green highways, urban tree planting, and macro-manzanas (mega-blocks where the built-up infrastructure is demolished and transformed into public green space and amenities). Additional goals include reducing energy consumption, mitigating urban heat island effects, preventing flooding, and ensuring that every resident can access a green space no further than 350 metres from their residence [66]. Yet, in this strategic GI focus on climate change mitigation and adaptation, which BA shares with other municipalities in the Greater Buenos Aires urban region, NbS remains secondary and ancillary to actions related to energy saving and waste reduction [67]. Murgida et al. [68] also point out that the policy framing of emissions abatement has not been properly linked with questions of human health and wellbeing. In Dadon et al.'s [67] taxonomic survey of the development of GI, none of the typologies (urban conservation areas, parks, green roofs, pocket farms) addressed air pollution directly, and in some cases (such as tree-lined streets), they may increase local concentrations of pollutants by preventing quick dissipation [10].

The low levels and uneven distribution of public green space in Buenos Aires is of concern for both strategic NbS and the everyday life of city residents. Buenos Aires reports a stock of green space covering 1827 ha across 1256 sites, with various configurations, including regional, neighbourhood, and pocket parks, squares of varying sizes, planters, and gardens on the median strip of city streets and avenues [69]. This equates to less than 10% of the city's land surface area and results in a ratio of approximately 6 m^2 per capita, well below the minimum recommended international standard (10 m^2 per capita). Furthermore, some of these green areas are not accessible to citizens, such as planters and gardens on the median strip of avenues, reducing the green ratio to at least 4.59 m^2 per capita [70]. Public green space is unevenly distributed, with most of the stock contained within three regional parks located in the city's southern, northern, and coastal edges. In residential areas close to the city's central business district, the formerly industrial south, and densely developed neighbourhoods along western corridors, provision is below average: less than 1 m^2 per capita in some districts [71]. The Bunge and Born Foundation's Atlas of Green Spaces estimates that 350,000 residents (12.5% of total population) lack direct access (within a ten-minute walk) to a public green space of at least half a hectare [72]. The advocacy organisation Asuntos del Sur [69] points out that the number of city trees (currently reported at 470,000) would need to more than double to 1 million for Buenos Aires to meet the ratio of one tree for every three residents as recommended by the WHO.

Localised deficits in public open space generate an unmet demand, which in turn results in patterns of overuse and a contested design process for new site provision. In this fraught context, NbS may be perceived as competing with, rather than acting in synergy with, citizens' demands for outdoor exercise and recreational opportunities. It is no longer only green space advocates who animate campaigns for new parks and green spaces. Since the 2001 economic and political crisis in Argentina, a renewed wave of neighbourhood activism has translated into these planning processes becoming more complex and contested [65]. Whilst all actors criticise the government for the ongoing privatisation of public land, with large vacant lots and interstitial lands being repurposed for real estate development instead of much needed green spaces [73], there is a mismatch between the relatively high social appreciation of existing parks [74] and their low levels of ecosystem services. Civeira et al. [75] estimate the latter based on a ratio of biomass to population density. The recently opened Manzana 66 (Plaza de los Vecinos), in Balvanera, provides an example of such tensions [76]. The results of grassroots neighbourhood efforts, the block has undergone regeneration as a neighbourhood park and primary school. Participatory design processes have resulted in a combination of green and activity sectors but with an overall low proportion of vegetation and exercise areas, with the school directly exposed to thoroughfares with high levels of vehicular traffic. Furthermore, residents raise concerns of deteriorating vegetation in planted areas due to lack of irrigation and upkeep [77].

In summary, BA has a policy framework in place for the creation of NbS. This framework, however, centres on climate change mitigation and adaptation and lacks any reference to how GI could help abate air pollution and protect human health and well-being. Accordingly, green fences do not feature in the city's policy toolbox. The under-supply of public green space, and strains on existing spaces, compound the challenges, which calls for innovation in the evidence-based promotion of NbS and a broader perspective on how and where a GI4AQ+ strategy could be feasible and useful.

3.3. Barriers to GI4AQ+ Implementation in Buenos Aires

The GF-BA encountered all the barriers commonly identified in the GI literature but also five emergent context-specific barriers. Table 3 provides a summary of both barrier types. The following sub-sections elaborate on the latter.

Table 3. Summary of identified barriers to green fences in Buenos Aires and links with existing literature. Orange colour denotes GI4AQ+ in Buenos Aires barriers aligned with previous research, and green colour denotes emergent barriers.

Barrier Categories	Barriers Identified in Buenos Aires (GI4AQ+)	Linked to Previous Research	Emergent Barrier
1. Institutional and organisational	1.1 Multi-disciplinary integration challenges	✓	
	1.2 Poor inter-governmental and inter-departmental integration	✓	
	1.3 School governance challenges	✓	
2. Engagement and coordination	2.1 Lack of clear pathways to formally engage with government		✓
	2.2 Poor diagnosis and communication of AQ		✓
	2.3 Gatekeeper institutions engagement	✓	
	2.4 School community engagement	✓	
3. Political	3.1 Unsupportive policies and legal frameworks	✓	
4. Socio-cultural	4.1 Lacking AQ awareness		✓
	4.2 Predisposition due to previous experiences	✓	
5. Built environment and natural landscape	5.1 Design limitations	✓	
	5.2 Plant availability		✓
6. Knowledge	6.1 Uncertainty regarding GI's effectiveness	✓	
7. Financial	7.1 Access to AQ monitoring equipment		✓
	7.2 Funding expenditure	✓	

3.3.1. Institutional and Organisational

Poor coordination between governmental units and other actors in the project produced multiple challenges. An interviewee recalled the GF-BA project team requesting the felling of a Ficus tree from the playground to prevent risks to children, increase sunshine, and enable greater flexibility in selection of plants. The school did not have the resources to undertake and/or pay for this. Furthermore, the two government authorities involved (the Ministry of Education and the Department of Communal Works and Maintenance) could not successfully negotiate the tree removal. Eventually, the project team succeeded in finding additional funds and completed the removal. Despite efforts by all parties involved, this event highlights the lack of clarity concerning ownership, responsibility, and relationships among government units. Additionally, challenges to initiate and maintain school community engagement resulted from how the city's education system is organised, with staff rotation and head teachers responsible for multiple schools. In our case, the head teacher oversees not only the pilot school, but also several other infant schools in the neighbourhood. Thus, her office is not located on site. This situation alone complicated the organisation of regular meetings to involve her in the project.

3.3.2. Engagement and Coordination

Engaging stakeholders and securing gatekeeper institutions is a common challenge for GI projects. However, we identified two context-specific barriers. Firstly, there was no clear knowledge of the pathways or means for civil society to engage directly with the government and propose GI projects expediently. This applied to both the executive and legislative branches of government. Some interviewees mentioned that they had to engage with the legislature and multiple ministries through informal mechanisms, relying on pre-existing connections. Our experience was similar. A contact at the Directorate of Urban Anthropology directed us to the relevant unit, the GS Programme from the Ministry of Education, who became the project's gatekeeper. GS promotes sustainable management and environmental education in schools. Yet, formalising a collaborative project was arduous and time-consuming. Despite our project's clear alignment with the unit's remit, an extensive and complex paperwork process of permits was required. Even as the collaboration consolidated over time and the programme's benefits for the pilot school became clearer, GS required the project not to contact school staff directly, as part of their mandate is not to interfere with curricular activities and create burdens on the already limited staff time. In consequence, co-design and co-production activities had to be severely curtailed.

Secondly, whereas engagement of social stakeholders in the GI planning process is often suboptimal due to funding and time limitations, for the GF-BA project, multiple factors compounded the gatekeeper-related barriers mentioned above. We faced pressure to install the fence first and demonstrate its benefits later, skirting around a participatory discussion on air pollution that might have led to community buy-in to site-specific remediation action for the schoolyard. We discovered that the citywide shortcomings in AQ monitoring and reporting were reflected in a local lack of concern with ambient air pollution, despite the school's direct exposure to heavy traffic. Without site- and neighbourhood-specific data, AQ did not prove to be an issue that would mobilise local stakeholders initially. We had to recruit unpaid volunteers more broadly, including landscape activists and various supporters, who contributed to planting without formal project roles. Expert interviewees corroborated our experience, describing the city's AQ data (provided by APrA's webpage) as 'raw' and 'difficult to visualise'. There are not only gaps in the variables reported (with the critical omission of $PM_{2.5}$) but also missing explanations of how high levels may affect human health.

3.3.3. Political

Several interviewees decried a lack of green policies, perceiving government as unsupportive of measures to address the city's environmental challenges. In fact, the mismatch between the city government's green plans and its actual commitment to concrete actions was remarkable. For instance, an interviewee pointed out that little attention is given to the remediation that street trees and other GI could effect on the city's heat island problem. The lack of supportive policy is a widely identified barrier in the GI and NbS literature. In Argentina, it might be related to prioritising immediate actions to solve the economic recession that the country has experienced in the past three years. It might also be related to real estate interests bypassing urban planning by the government, causing the loss of green space to housing. García-Jerez [78] refers to this as 'urban extractivism' and points out that it is an emerging problem in many Latin American cities.

3.3.4. Socio-Cultural

Lack of public awareness of air pollution's effects on human health constitutes a major barrier to the promotion of AQ-related GI initiatives in Buenos Aires. The lack of pre-existing NbS interventions to shape the agenda constitutes a contributing factor already identified in the international literature. Our findings also indicate that three case-specific factors contribute to perceptions that AQ does not constitute a major policy challenge for the city. Firstly, the governmental reporting (AprA) that the city (partially) complies with local and international regulations on 'environmental quality' does not consider pollution hotspots, which the public monitoring system is also unable to identify and document. Secondly, civil society campaigns and awareness-raising actions are few and far between. An interviewee reported major governmental pushback to their 'alarmism' and 'scaremongering regarding what is really a non-issue'. Thirdly, unlike other Latin American large cities such as Santiago de Chile, Mexico City, and Bogotá, air pollution is not sensorially evident citywide for extended periods of time, with numerous cases of poor health symptoms (headaches, eye irritation, coughs) reported [79,80]. Without educational and awareness campaigns, long-term effects and chronic health implications are less evident.

3.3.5. Built Environment and Natural Landscape

As in other urban environments, the introduction of GI in Buenos Aires schools faces design limitations. Some interviewees highlighted that the 'cultural heritage' status of certain school buildings with colonial features prohibits interventions that may change their appearance. This was the reason for the refusal of permission to install an irrigation system for the GF-BA. Other schools do not have suitable planting space. Planning and building code constraints are a common barrier in the literature, highlighting the importance of adapting the design to the specific contexts and proposing alternative GI typologies.

The availability of suitable plants for GI4AQ+ was identified as a barrier in Buenos Aires, which is not discussed in previous studies conducted elsewhere. Plant selection relies upon scientific literature primarily generated in Europe, the US, Australia, Japan, and China. Most of the species investigated in these countries are different to the ones commercially available in Buenos Aires, or they are considered a specialty in the local market, which increases costs. Additionally, there is resistance to the use of species that are not local and native to the region, as an interest in preserving native species has emerged and gained momentum across Argentina [81].

3.3.6. Knowledge

Our findings indicate scepticism regarding the efficacy of GI schemes among policymakers and stakeholders in Buenos Aires. This is consistent with findings from elsewhere reported in the extant literature and is compounded by the lack of awareness and data on air pollution. Even supportive policymakers requested primary evidence that green fences would work as intended once the pilot green fence was installed. In fact, this was a requirement before proceeding with implementation in additional schools (see Figure 2 for details). The process of AQ monitoring and data collection encountered difficulties related to the lack of familiarity with GI4AQ interventions among specialists and the need for them to adapt their techniques and research design to test the green fence's efficacy. Our first monitoring campaign with diffusion tubes indicated lower NO_2 concentrations within the green fence's perimeter and possibly accelerated pollutant dispersion in comparison to a control pair of diffusion tubes installed on a fence-less side of the school (see Supplementary Material). However, we decided to carry out a secondary campaign with a larger number of tubes on both the intervention and control sides to obtain a clearer indication of diffusion rates, and have yet to implement a $PM_{2.5}$ monitoring system suitable to the site conditions and local technical capacity. Whereas socio-ecological co-benefits proved easier to document, with a very positive response by the school community to the greenery that was installed, knowledge about these was also limited before the intervention, and detailed educational activities were required to familiarise various schoolyard users with the green fence beyond their initial sensorial reaction. Evidence about local plant species with bioremediation potential and AQ benefits is scarce. Yet, we found that exploring the potential use of local species, on which the literature is scant, would require further efforts and a large research infrastructure. This includes plant science labs, high-tech microscopes, and trained personnel, none of which are readily available currently.

3.3.7. Financial

A lack of clear financial incentives and dedicated resources is a frequent challenge to GI development, which we also identified in Buenos Aires. Whilst the city has a budget for planting in public spaces, this is not explicitly linked to potential socio-environmental benefits through landscape-level planning. Furthermore, evidencing air pollution beyond what the city reports required costly imported equipment, which constituted an emergent financial barrier not discussed in previous studies. We had options such as low-cost sensors, but these involved technical (internet and power in situ) and resource hurdles (human resources to regularly monitor in situ for a sufficient period). Therefore, establishing a reliable AQ monitoring system for the GF-BA project became a challenge that actually delayed the pilot's implementation. Paradoxically, our government partners required the project to evidence the green fence's effectiveness in terms of AQ improvements as a condition for continuing engagement, even when reliable city data was not readily available to benchmark the intervention.

3.4. The GF-BA Project Attributes: Overcoming Barriers and Producing Benefits

This section presents the results of the researcher narratives to provide an account of how we were able to successfully complete the GF-BA pilot project, overcoming the multiple barriers to implementation presented above. Furthermore, the (many unanticipated) actions that we needed to take led the project team to examine the project's core attributes, sustain the work through the implementation challenges that we faced, and eventually reformulate an expanded model of GI4AQ+ learning from the experience.

The GF-BA project features three salient attributes. The pilot's completion relied on (a) a relational commitment to the urban environment by multiple and diverse participants; (b) activities inspired by cross-boundary experimentation and innovation; and (c) the support of a horizontalist transnational research collaboration. These three project attributes informed multiple actions that enabled the pilot to overcome implementation barriers. Figure 5 shows the relationship between these 'actions of critical importance' and barrier categories. The actions were critical because, without them, we could not have kept the project advancing through its implementation stages, as some barriers would have been unsolvable. Other ancillary actions were also taken to enhance the green fence, including ongoing communication among project leads and efforts to publish and disseminate across multiple formats, but these are not shown here, for explanatory clarity. The figure shows that all three project attributes and their corresponding actions were a conduit to overcoming engagement and coordination barriers. Engaging with the BA government early on, finding the project's gatekeepers, and gaining acceptance to work with them relied on the relational, experimental, and transnational nature of the GF-BA project. Moreover, the relational commitment to the urban environment highly influenced all the barriers associated with social interactions. Cross-boundary experimentation and innovation helped to solve not only social barriers endemic to interdisciplinary efforts but also technical barriers happening on the ground. Finally, the horizontalist transnational research collaboration was highly important in allowing us to access funding and enabling design of the green fence, overcoming built environment, natural landscape, knowledge and financial barriers.

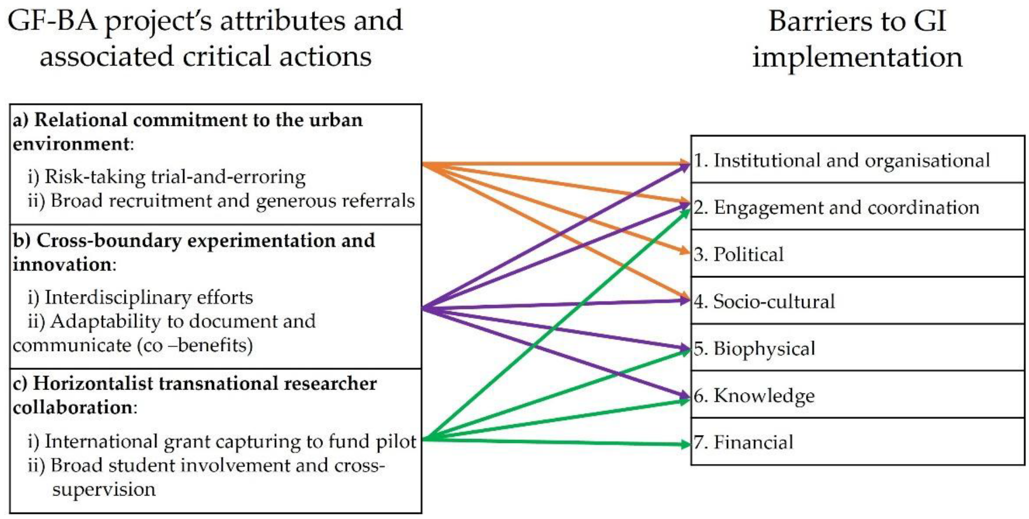

Figure 5. Relationship between barriers to GI implementation and the GF-BA project attributes and associated critical actions.

From the beginning, the project brought together diverse people committed to help improve the urban environment in Buenos Aires. Contributors worked in either higher education, government, NGOs, or the private sector. Project members and initial collaborators were willing to take professional risks and/or contribute personal time to a project with uncertain local outcomes. Enthusiastic responses to our project secured us broad recruitment and generous referrals that opened doors to various local and national institutions. Occasionally, we relied on contacts obtained through previous environmental actions. Once installed, the green fence itself helped us recruit further collaborators and supporters. The school's groundkeeper volunteered to water the plants over the summer recess month, which was essential for maintenance, given that we were not allowed to install an automated system. Acting on her own initiative, a neighbour started commenting on social media on the project's positive local impact. Whilst voluntarism may appear as a shaky foundation for a project's success, the many enthusiastic contributions that our green fence proposal received in Buenos Aires gives us grounds to believe that willingness to improve the urban environment may also be found elsewhere for similar catalyst projects focused on place-specific actions.

In the face of multiple local uncertainties and lack of precedent, and a globally evolving field of GI applied to AQ challenges, it was clear to us that the GF-BA project needed to be designed as an experimental pilot project. The challenge resided not only in ascertaining what type of fence design (including plant species selection) would produce some form of demonstrable AQ site improvements but also in how we could communicate these benefits effectively to secure social and policy impact towards broader green fence adoption in the city. This spearheaded a truly interdisciplinary effort, which was not limited to the initial collaboration between environmental scientists (including air quality specialists and a material science expert), landscape designers, and social scientists specialising in urban and environmental policy in Latin America. Our activities soon broadened to include local and international experts in epidemiology and public health, ecology and biodiversity, the popular economy (in issues pertaining to those workers who may be involved in the construction of green fences and other types of GI), environmental and nature-based education, and participatory methods with school-aged children. The emphasis that we placed in dissemination and knowledge exchange, with frequent seminars by invited experts and a programme of workshops with the school community, helped the project gain visibility with research and advocacy communities, but also provided us with feedback on how to adapt our programme of activities and communication strategy regarding early results. This strategy was needed to secure ongoing support from governmental gatekeepers and engagement from social stakeholders.

The collaboration between UK and Argentine researchers at the core of the GF-BA project (see Figure 2) was instrumental to the successful pilot completion. Both partners contributed essential, mutually complementary components. The former's participation secured British research funding required to jump-start the project and then build the pilot in the face of no initial local budgetary support and the inexistence of bespoke markets to lower the cost of interventions (including imported AQ monitoring equipment and even the relatively high cost of plants). It also provided a track record of previously documented GI4AQ interventions in the UK and the incentive for local government actors to participate in what may be seen as a high-profile international collaboration [73,82]. The latter contributed an intimate knowledge of tacit local policy barriers, the ability to increase the project's visibility among different professional and research circles in the city, and effective communication strategies vis-à-vis different stakeholders with specific preferences and needs. The Buenos Aires–based researcher tied her teaching practice to the project and involved university students who contributed to the fence design, construction, and monitoring. This not only helped mitigate high costs but also contributed to train a future generation of professionals with an understanding and sensibility for the locally untapped potential of urban greenery as GI. The UK side also involved students at multiple levels, including a doctoral project, masters' dissertations, and undergraduate involvement through coursework. Cross-supervision of students helped to build a sense of horizontal transnational collaboration without hierarchical differences, which could have been created by questions of who contributed what resource to the project.

4. Discussion and Recommendations

This paper engaged the research and innovation challenges of moving schoolyard green fence interventions from a model of GI4AQ with proven efficacy for site-specific remediation to an urban NbS with broader geographical and functional potential. We emphasised the need to better understand and take stock of implementation challenges. Therefore, lessons from the GF-BA project were used not only to identify barrier categories but also formulate strategies to overcome them and make recommendations for future intervention models. Our GI4AQ+ approach emphasises enhanced green fence designs, with the dual goals of producing multiple socio-environmental co-benefits and increasing the chances of stakeholder buy-in. We argued that in urban contexts of low- and middle-income countries, where air pollution is often not understood as an urgent urban problem or even a policy priority, schoolyard green fences can produce the cultural ecosystem-based service of raising awareness about AQ challenges. If properly designed, they can reduce harmful pollutants on site and visibly contribute to an urban green network to support biodiversity, improve human health and wellbeing, and strengthen the capacity of cities to generate ecosystem-based services.

The GI4AQ+ model moves green fences from a site-specific bioremediation to an urban environmental intervention, building upon the context specificity recommended as a NbS core principle [83]. Our results showed that considering the particularities of an urban landscape, society, and politics are crucial to implement a first pilot fence and avoid assumptions about the local potential of different GI formats. Such in-depth contextual understandings will also be of critical importance if the research and practice of urban NbS are to overcome current biases toward high-income countries, especially in the European context [9], and provide useful insights and workable solutions for the critical urban environmental problems for cities in low- and middle-income countries. The paper emphasises that Latin America constitutes a critical geography for a more thorough globalisation of urban NbS, and studies need to develop frameworks that integrate the region's ecological conditions and rich biodiversity with the dynamics of rapid and uneven urbanisation [84] (p.14), whereby speculative land use change and informal urban expansion without much governmental regulation have resulted in multiple inequalities, including the dramatic decrease of public green areas. Moreover, as Dobbs et al. [22] point out, approaches to urban greening taken in high-income countries may provide guidance and complementarity, but due to the uniqueness and diversity of the region, Latin American studies need specific approaches, avoiding overreliance on foreign research.

The action research and living lab approach of the GF-BA project was highly valuable in teaching us to devise a modified approach more suitable for the local context's needs and priorities. Abating local air pollution seemed less urgent than we expected to multiple local social and governmental actors—even if they remained sympathetic to the overall goal of building a green fence and enhancing the schoolyard environment. Fostering broad-based interdisciplinary conversations about the multiple social and environmental benefits of increasing urban vegetation at the planning stages helped us co-produce a research programme around the intervention's potential co-benefits, which we could then begin to document once the green fence was installed. Whilst these were key to maintaining momentum until we could confirm initial results on AQ (initial readings for NO_2 are shown in the supplementary materials section), the very process of setting up a monitoring system and communicating its objectives and findings helped us hold otherwise difficult conversations around questions of air pollution in the city and how they may be affecting the school community. Therefore, green fences built following an expanded GI4AQ+ could serve the long-term purpose of environmental education and awareness whilst immediately abating pollution and providing ecosystem services.

We are aware that our GF-BA green fence pilot implementation project only constitutes a first step towards the robust formulation and broad application of a GI4AQ+ model suitable for Buenos Aires, other Latin American cities, and potentially elsewhere. However, this case study contributes an evidence-based experience of GI co-production with policymakers and community buy-in, which faced several challenges but also succeeded as a pilot. Even if developing an urban NbS network of green-fenced schools may not be easily achievable through action research, pilots developed through this approach are useful as both proof of concept and sites for further experimentation and model refinement. When completed, our project was featured on the city government website and helped garner visibility for purposively designed green fences in Buenos Aires. Furthermore, our project has since expanded to include two more participating schools in the metropolitan area (see Figure 2) and develop a programme of site-based experimentation informed by urban living lab approaches [28–30]. This aims to generate further insight into effective green fence design and programming.

Plant selection and species availability/suitability are key items in our ongoing research agenda. Whilst the extant AQ-focused literature relies largely on plants available in China and Europe [85], efforts need to be made to extract generic plant traits from these studies and develop locally suitable plant selection guidelines. Future studies will need to ascertain the possibility of reducing costs and assuaging concerns of working with exotic species whilst not compromising efficacy regarding reduction of exposure to air pollution. Schoolyard use is also a topic for further examination, including how children's play may change after green fences are installed; parents, staff, and neighbourhood reactions to the transformed local environment, and what support may be needed for the incorporation of the NbS to (extra-)curricular contents and activities, must be included in further green interventions in the schoolyard or even the main buildings. Finally, green fences can inform policy-oriented research programmes, even whilst they are being planned and constructed, by steering questions to government officials and expert informants to concrete implementation questions that may not be captured otherwise, as conversations would be limited to the policy discourse and official frameworks.

5. Conclusions

This study probed the potential for mobilising GI to mitigate urban air pollution in Latin America, specifically through the use of green fences in schoolyards in Buenos Aires, Argentina. In this city, the policy response to air pollution levels is barely incipient, with greenhouse gases emissions receiving priority over those pollutants more harmful to the health of local residents. At the same time, the city has an ambitious GI policy framework but lacks effective provisioning, with concerns raised over the diminishing amount of open green space. We argued that this evidence of a low policy priority for AQ, alongside interest in GI, calls for an intervention model whereby green fences should not be limited to site-specific protection from nearby traffic pollution. Instead, the model of GI4AQ+ that we introduced could help raise awareness of the problem and educate citizens about its implications for public health whilst also contributing to their wellbeing through urban vegetation enhancement; it can be incorporated into even more ambitious NbS agendas of urban ecosystem-based services.

We do not assume this to be a simple task. All GI formats face several implementation challenges, including institutional, engagement, political, socio-cultural, geographical, knowledge base, and financial barriers. Through the co-creation process of the GF-BA project and supplementary in-depth interviews, we identified five additional barriers to the development of green fences in Buenos Aires. Three out of the five emergent implementation barriers relate to (i) insufficient and/or inadequate AQ monitoring, data sharing and communication; (ii) lack of citizen awareness of air pollution risks; and (iii) high costs and low availability of equipment for local AQ monitoring. The two other barriers speak to broader challenges to GI development, including (iv) limited clear avenues for co-producing projects with government actors; and (v) limited availability of plant species suitable for phytoremediation interventions. These may not be important issues for NbS initiatives in Europe and North America, but they could prove major hurdles to promote green fences in cities of low- and middle-income countries. Despite all the hurdles and challenges faced during the GF-BA project, the pilot green fence was successfully implemented. Three attributes of the project and their correspondent actions facilitated overcoming the barriers, which relied on the project incorporating 'urban living lab' principles from the NbS approach, mainly through a relational commitment of different people to improve the urban environment regardless of possible risks and setbacks; horizontalist collaboration across disciplinary silos and the North-South divide in support for urban environmental research; and an ethos of scientifically informed experimentation towards social innovation.

The GI4AQ+ model seems to be particularly suitable for cities in development contexts where environmental policy needs consolidation and AQ awareness is lacking. GI4AQ+ may not only reduce exposure to pollutants, but also effectively communicate the importance of improving AQ and practically demonstrate the multiple contributions that GI makes to urban life. This will gradually raise the awareness of students, possibly supported by curricular and non-curricular activities that leverage the green fences' appeal, promote visibility of the issue within the broader school and neighbourhood communities, and provide further eco-systemic co-benefits at multiple scales.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14074129/s1, Figure S1: Location of NO_2 monitoring devices (diffusion tubes) in relation to the case study school and green fence.; Table S1: Results of monthly NO_2 concentration monitoring (diffusion tubes) in parts per billion (ppb).

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Data Availability Statement: This study did not use secondary data. The data generated here are available on request from the corresponding author and has been archived and is accessible at https://doi.org/10.15131/shef.data.19434653. The data are not publicly available due to ethical restrictions. Please contact the corresponding author for access or follow the data repository site instructions.

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Chapter VI
Discussion and conclusion

Example of discussion session at the Sheffield case study school. Starting from MCRB's left: parent governor, landscape architect, headteacher, three representatives from a construction firm, school caretaker, and civil engineer.

Summary of research findings

This PhD study explored the use of green barriers in school playgrounds as a tool to reduce air pollution. It also aimed at understanding the broader impacts of green barriers in school communities, and the hurdles and challenges to developing such GI. The study's strategy involved action research in two case study schools (in Sheffield, UK and Buenos Aires, Argentina) as the overarching primary research approach. Action research was carried out through a collaborative process of green barrier implementation in each case study school playground, which included the involvement of stakeholders in designing the intervention, planting the vegetation, and monitoring the impacts. Additionally, the study relied on other research methods from the fields of climate science, materials engineering, geography, and landscape architecture. The multidisciplinary research aims at each case study differ, therefore, social science methods were used to study the Buenos Aires case study; whilst scientific and social science methods were adopted at the Sheffield case study. A summary of the key findings and their link to the research aims is shown below in Table D1. The research outcomes, presented in the three previous chapters, effectively fulfilled the proposed research aims.

The following section matches the outcomes of this study with the prior established knowledge gaps of GI4AQ+, positioned accordingly to the NbS knowledge gaps identified by Kabisch et al., (2016). It also pairs the outcomes to the research aims and questions that were achieved and answered in this study.

Table D1. Summary of research findings and their link to the research aims.

Chap.	Knowledge gap	Research aims	Research questions	Case study	Research findings
3	*Technical knowledge concerning green barriers is scarce in real life applications – design gap* *Methods to effectively monitor impacts on air and vegetation can be expanded – design gap*	1. Assess the air pollution mitigation potential of green barriers in school playgrounds, considering the air pollution-vegetation interaction.	Air component ● Can a multi-species thin green barrier provide enough protection against NO_2 and PM air pollution for a school in Sheffield, UK? ● What is ambient PM around such UK inner-city school made of? ● What has a larger influence on school air quality: a multi-species thin green barrier implementation or low-vehicle traffic (due to covid-19 lockdown) in Sheffield, UK? Vegetation component ● Do the micromorphological mechanisms of PM capture differ within the plants of a green barrier in Sheffield, UK? ● Under similar exposure conditions, does PM density differ within those green barrier plants?	Sheffield	Air component ● This study suggests that the site-specific and multi-species thin green barrier built in a UK school playground reduced air pollution. The reduction in pollutants concentration was significant for NO_2 (between 13% to 23%) and slight for PM (about 2%). ● Composition of PM deposited on the green barrier plants from the UK case study suggests PM of natural and anthropogenic origin. The latter include catalytic converters from motorised vehicles. ● Low-vehicle traffic and low-citizen mobility (lockdown) seem to have significantly reduced NO_2; such reduction exceeds the effects of the green barrier. These mobility restrictions do not seem to significantly reduce PM pollution in the UK case study, most likely because meteorological patterns and conditions have a stronger influence on PM than traffic levels.

Chap.	Knowledge gap	Research aims	Research questions	Case study	Research findings

			• Does leaf surface roughness correspond to higher particle capture for those green barrier plants?		Vegetation component
					• The study suggests that the multiple green barrier plants from the UK case study enabled several PM capture mechanisms at different PM sizes, as follows:
					  • <u>*T. occidentalis*</u>: Highest PM density most likely because of wax layer presence.
					  • <u>*H. helix*</u>: Second highest PM density. It seems to have frequent deep/narrow grooves best suited to capture $PM_{2.5}$ and PM_1.
					  • <u>*P. nigra*</u>: Lowest PM density. It showed significant PM_1 adherence, of almost the same magnitude as *H. helix*.
					• The surface roughness method used was not optimal to predict PM capture due to certain localised foliar structures.

4	*Co-benefits, trade-offs, and disservices of green barriers are unknown for school communities - effectiveness and social relations gaps*	2. Identify the co-benefits, trade-offs and disbenefits of green barrier implementation for school communities.	What are the perceived co-benefits of implementing GI4AQ+ in a Sheffield, UK school according to its school community?	Sheffield	• The research outcomes from the UK school suggest that its community perceived the green barrier as providing benefits beyond air quality provisioning. These entailed eight social, two environmental, and three economic benefits, as listed below:
					  • <u>Social</u>: school premises safety, place quality and attractiveness, restorative environment and mental wellbeing, learning opportunities, connection with nature, access to greenspace, child development and play, and community's active engagement.
					  • <u>Environmental</u>: habitat provisioning and connectivity for wildlife, and sustainable living and environmental awareness.
					  • <u>Economic</u>: school subscription/interest, property betterment and local area's visual enhancement, positive public image of businesses involved in barrier sponsorship.
					• Additionally, the playground was transformed into an enclosed space by the greenery, which stopped the interaction of pupils with the outside, considered a trade-off by some school teachers and a disservice by a few parents.

	Green barrier implementation in schools is unclear – design, and implementation gaps	3. Understand the implementation process and practicalities of	Which critical dimensions need to be considered to implement GI4AQ+ in UK schools?		• The research outcomes suggest considering four design dimensions when implementing green barriers, to have a positive impact on school air quality. These dimensions are: place characteristics (school premises and context), adequate

Chap.	Knowledge gap	Research aims	Research questions	Case study	Research findings
		green barriers in school playgrounds.			physical (dimensions) and biological (vegetation) green barrier characteristics, and school-friendly considerations. ● The study suggests that multifunctionality and co-benefits for school communities could also be achieved by taking into account such considerations during the green barrier design process, resulting in green infrastructure for air quality 'plus' (GI4AQ+).
5	*Green barrier implementation remains unexplored in low- and middle-income countries – implementation, effectiveness, and social relations gaps*	4. Identify barriers and solutions to green barrier implementation in school playgrounds in a Latin American context.	What are the barriers and solutions to GI4AQ+ implementation in a Buenos Aires, Argentina school?	Buenos Aires	● Green barrier implementation in a Buenos Aires school faced five additional hurdles to those known for the European context. These seem to be related to a socio-cultural, financial, and institutional lack of engagement with air quality as a health and environmental issue. Unclear governmental pathways and unclear horticultural logistics seem to also hinder green barriers implementation. ● The research outcomes suggest that to overcome such hurdles, the GI project relied on three of its attributes: its transnational collaboration, the commitment to urban nature and to society by the diverse participants, and having experimentation and innovation at the core of the project.

Chap. = chapter.

In short, multi-species thin green barriers (1.00-2.20 m) have the potential to reduce air pollution in school playgrounds when properly designed and implemented. This study's quantifiable example found air quality improvements to be significant for NO_2, but marginal for PM. However, there is evidence of the capture of PM by the green barrier plants, which is maximised by plant biodiversity. Additionally, a diligent green barrier design could provide other benefits highly valued by the school community. Finally, their implementation process faces multiple barriers, more so in countries without robust GI frameworks.

Contribution to knowledge and real-world impact

This research has contributed to closing knowledge gaps in the field of NbS and air quality, supporting, in turn, new approaches to addressing real-life problems.

Green barriers as a nature-based solution

The research findings mentioned above advance the nature-based solutions agenda. Firstly, this study suggests that a site-specific green barrier had a positive impact on air quality, specifically a reduction of NO_2 by 13% and of $PM_{2.5}$ by 2%. The air quality findings indicate that green barriers have tangible impacts that, in turn, could improve human health (physical and mental health). Evidencing the air quality impacts fosters validation of green barriers as a nature-based solution, worth studying and implementing in other contexts. Nevertheless, NbS aim for transformative change at the social, environmental, and economic levels. The 'Breathe' research set an early foundation for understanding the further impact of green barriers on those three elements. Specifically, the school community from the UK case study perceived the green barrier as providing eight social, two environmental, and three economic benefits to them and to the school. These findings foster an understanding of the wide reach of benefits that green barriers can have, and the importance of further studying and developing green interventions in schools.

Moreover, this study sets the design base for green barrier implementation. Nature-based solutions are increasingly recognised as tools for nature and community regeneration and resilience in cities. However, technical knowledge on NbS design and implementation has extensive gaps, which hinder the accomplishment of urban NbS interventions. This study presents four areas for consideration (place characteristics, physical and biological green barrier characteristics, and school-friendly considerations) to design functional green barriers in schools. This contribution to knowledge can foster the uptake of green barriers because it serves as a how-to guide for other schools. This transferable knowledge should be considered to create green barriers that foster air quality and prevent trapping polluted air. On the other hand, when implementing green barriers, the local context matters. As seen in the Buenos Aires case study, five additional hurdles (additional to the American and European literature) emerged during the green barrier implementation project in the school; however, they were overcome by key attributes of the project: transnational collaboration, experimentation and innovation, and a high commitment to urban nature and to society. Understanding the Buenos Aires local context and making the best of the project attributes led to the successful green barrier implementation. Therefore, technical green barrier knowledge is key, but so is understanding the local context. Together, these findings advance the knowledge of NbS implementation, with a relevant addition to knowledge from another region of the world, Buenos Aires, which is afflicted by air pollution.

This study has also advanced knowledge of relevant and useful methods to measure NbS impacts. Monitoring and measuring impacts are critical to understanding the effectiveness of NbS and supporting decisions on implementation and up-scaling. The 'Breathe' research used two methods to observe pollution capture and reduction. Besides air pollutants being measured via different air quality monitors, this study also assessed PM capture by the green barrier plants using SEM. These methods provided a wider picture of pollution mitigation by plants, and through which mechanisms. In fact, the SEM analysis suggests that the multiple green barrier plant species from the UK case study enabled several PM capture mechanisms at different PM sizes. Using both methods simultaneously to monitor air pollution mitigation by green barriers and other NbS supports a more robust impact assessment.

GI4AQ+ as a school and city greening strategy

GI4AQ+ can support the goal of greening schools to provide pupils with healthier playing and learning environments. Its measurable positive impact on air quality is an attractive selling point for schools and governments to adopt for children's health reasons and air pollution targets compliance.

Moreover, policy to reduce and mitigate the effects of air pollution is on the rise, for instance, the Mayor of London has already supported 29 schools in the UK's capital via the 'school air quality greening grant' (Greater London Authority, 2019). Therefore, green barriers are likely to be supported for their air pollution mitigation potential in the first instance. However, the gains for the school extend to mental health, connection to nature, safety, and outdoor learning, among others, as found in this study.

If governments adopted green barriers in schools as part of their policy via the 'excuse/motivation' of air pollution reduction, that could, in turn, become a city greening strategy. The design of green barriers could be done in such a way as to maximise co-benefits and foster ecosystem services. For instance, a network of pocket GI via green barriers in schools could serve as green stepping stones for wildlife through the urban matrix and provide it with habitats within the fragmented urban landscape. Iojă et al. (2014) support this idea and found that Bucharest's structural connectivity increases when considering green areas in schools, and argues that these could support species flow. Moreover, greening playgrounds could have a positive impact on pupils' health and wellbeing. Evidence suggests that pupil's attention is restored after spending time in a green schoolyard (Amicone et al., 2018; van Dijk-wesselius et al., 2018; Kelz et al., 2015); that positive social interactions increase (Bates et al., 2018; Brussoni et al., 2017), and that physical activity increases for girls (Raney et al., 2019; van Dijk-wesselius et al., 2018). Green spaces also offer opportunities for outdoor education and connectedness with nature (Garip et al., 2021). Such is the principle of 'Forest Schools' in the UK (Forest Schools, 2019). These added benefits might be even more important for schools than the air quality dimension. Green barriers can be multifunctional for the school environment, and their implementation in schools can be incentivised primarily via an air pollution mitigation motivation but supported by all the other co-benefits they provide.

Although improved air quality is the most engaging impact of GI4AQ+ and most likely the reason for schools and governments to explore the use of green barriers, it is important to acknowledge that the AQ benefits may be smaller than the co-benefits they provide. Besides, we cannot expect green barriers to having the same mitigation efficiency all year long for two reasons: 1) plants follow natural cycles and are more active/dormant during certain seasons, and 2) wind and humidity, which influence pollutants' dispersion, change across the year. Besides these two factors, width also affects green barrier performance, with thicker green barriers being better at reducing air pollutants. That said, it is important to account for and communicate the co-benefits of implementing green barriers in schools, as they could encourage school communities and stakeholders to consider this NbS.

Overall, the knowledge created by this research is a stepping stone into a more ambitious school and city greening strategy using GI4AQ+. It is worth noting that the strategy might focus on different GI impacts depending on the importance and awareness of air pollution in each country. For instance, focusing on the air quality impact seems to be the best option in the UK; whilst in Argentina, focusing on the co-benefits seems to attract governmental support. The GI4AQ+ approach is suggested as one option for NbS mainstreaming and urban green infrastructure expansion. Although more research and pilot projects are needed to understand whether the strategy will succeed, it is at least worth considering such new approaches.

Accounting for co-benefits, trade-offs and disservices of NbS

As mentioned above, accounting for the co-benefits offered by green barriers is a key means of encouraging GI4AQ+ adoption, and this research provides a glance into school communities' gains. Although the co-benefits found here relate to the school community's 'perception', this approach is a valid initial way to understand the broader impacts of green barriers. Other studies have also used subjective measures to document the benefits of GI, such as Navarrete-Hernandez and Laffan (2019), who used ten-point subjective wellbeing (SBW) and safety scales. In the Sheffield case study, some of the highest-ranked perceived co-benefits were safety and restoration. Sheffield participants' responses regarding the safety of school premises reflect aspects of the prospect-refuge theory by Appleton (1984), which argues that people are psychologically predisposed to liking places where they can see without being seen, the perfect prospect-refuge combination. Moreover, participants' use of language also shows alignment with Kaplan's (1996) four components of restorative environments:

- Being away: the playground was described as calming for both children and adults, a 'magical' and 'cosy' place 'away from the outside world' that you easily forget is next to a busy road.
- Fascination: the green barrier was described as fascinating to look at; it was satisfying for children to watch it grow and notice colour changes. Teachers mentioned that children were 'enamoured' and 'excited' by the plants and insects.
- Extent: the playground was described as not only being away from the intrusive urban activities like vehicle traffic and passing commuters and shoppers, but also feeling like a 'park' in its own right and interconnected to other nearby urban nature.
- Compatibility: the participants found the transformed playground to be compatible with children's play and relaxation.

Likewise, it is important to understand the trade-offs and disservices of GI4AQ+. This study highlighted its importance, presenting contrasting perspectives between teachers (trade-off) and parents (disservice) about the space enclosure caused by the green barrier.

Broadly speaking, it is common to design GI that aims to achieve a particular ecosystem service (air quality, flood alleviation, temperature regulation, improved biodiversity, improved wellbeing, among others), which is a sensible approach to tackle a pressing issue. Nevertheless, it is important to consider all other potential impacts to account for any trade-offs or disservices, and to maximise the co-benefits of the GI design. In this sense, following a more holistic way of thinking about using nature to solve socio-ecological problems could help to break down institutional fragmentation or siloed thinking – as highlighted by Sarabi et al. (2019) – and the challenges that these present. But to achieve holistic urban greening, we need to move past the anthropocentric perspective of assessing ecosystem services or co-benefits for society, as these approaches, although useful and measurable, seem to cause a bias towards valuing nature only for the good it can provide to humans. An alternative is the so-called 'nature-based thinking' model, which suggests considering the ecological, community, and economic dimensions of NbS, and their interlinkages, to better achieve urban greening (Randrup et al., 2020). Moreover, adopting other emerging concepts, such as 'biocultural diversity' (interconnection between biological and cultural diversity, unlike the unidirectional ecosystem services approach) (Buizer et al., 2016) could help account for the positives and negatives of developing a NbS in a particular place, and contribute to truly integrative and multifunctional interventions.

It is acknowledged that this research assessed green barrier co-benefits from a primarily anthropocentric approach. This is due to limited time during the PhD and the decision to allocate resources to meaningful outcomes that would benefit the school community. However, taking into account the principles for designing impact frameworks for NbS developed by Dumitru et al. (2020), I would encourage schools, city planners, local councils, and landscape practitioners leading future GI4AQ+ projects to ask themselves: What are the gains and losses to nature/people/economy acquired from the project/process? Are there any disservices or trade-offs between and within them? And how are the goals and impacts going to be communicated? Reflecting on these questions may help to design holistic and multifunctional green barriers.

Using GI4AQ+ where it is most needed

Air pollution disproportionally impacts low- and middle-income countries, where 91% of global premature deaths occur (WHO, 2018). Studying green barriers as a protection measure for children's health in Argentina was highly valuable to expand the knowledge on air pollution mitigation and its application where it is more needed. The Buenos Aires case study evidenced that although GI4AQ+ is a global solution, it must be adapted to the local context (climatic, environmental, social, and political). In my opinion, expanding GI4AQ+ research to other regions needing cleaner air and outside the European context, which benefits from a more established understanding of GI, is crucial.

Green barriers are a tangible empowerment tool for school communities to provide healthier environments for children; especially as the rate policy is moving does not seem to match the urgency of the health-related impacts of air pollution. For instance, 2019 air pollution levels caused 15,000 premature deaths per year in the UK and 13,800 in Argentina (Health Effects Institute, 2020); nevertheless, their governments have not committed to the recommended WHO air pollutant limits. WHO guidance was updated in 2021 to reflect the growing evidence on the link between air pollution and declining health. Therefore, although policy and behavioural changes to reduce air pollution come first, there is a place for green barriers from a grassroots approach to complement top-down strategies against air pollution. This is what happened at Sheffield's case study school, where school interest in improving playground air quality initiated the first collaborations for this research. Besides, green barriers in schools can be a visual message of air pollution problems and solutions when their aim is adequately communicated to the stakeholders. Under those circumstances, green barriers can become a tool to raise awareness, and even a form of activism - a call for change. As seen in the Buenos Aires case study, awareness-raising is crucial to developing solutions to air pollution.

Greening schools through GI4AQ+ can also help combat lack of access to high quality green space for urban children. In cities like Buenos Aires, where the recommended $10m^2$ of green space per capita is not met (Asuntos del Sur, 2020), children will benefit from being in contact with nature at school. Shoari et al. (2021) show that pupils in the UK also need this type of GI, as about 60% of pupils in London attend schools with less green space per pupil than recommended. The GI4AQ+ green strategy can play a role to change these realities.

Whether for air quality improvement or green space access, GI4AQ+ can have a real impact on people's lives. On a less scientific and more human note, green barriers in the Sheffield and Buenos Aires schools have had a largely positive impact on their communities. In Sheffield, the school community has totally appropriated the green barrier and now calls it 'the green hug'. Interest and engagement have grown across the city. For example, the business association (Sheffield Business Together) that provided in-kind work for the case study is planning to support similar projects in the future, and the landscape architecture firm that collaborated in the case study (Urban Wilderness) has already supported two other schools to install a green barrier on their premises. In Buenos Aires, the British Academy is supporting the development of green barriers in two additional schools. Furthermore, multiple stakeholders want to learn more about GI4AQ+. In the past years, numerous schools, NGOs, and representatives from the private and public sectors have contacted the research team to enquire about this research, including City of Trees, IDEA, Kids Plant Trees, Steel City Schools Partnership, Eco-Schools Sheffield, Meristem Design, Natural England, Department for Education, Brent Council, Rotherham Council, Chesterfield Borough Council, and Hackney Borough Council, among others.

Implications for practice

Landscape architecture is a discipline that can advance knowledge through one of its primary activities: design; which is called 'research by design' (Lenzholzer et al., 2013; Milburn and Brown, 2003). This type of research intends to design, assess, and create new landscape typologies based on current needs, and overall find solutions to socio-environmental and spatial problems at different scales. For this study's site-specific green barrier creation, the whole process was based on iterative research by design, which was documented via action research. This approach generated innovative outcomes as it was responding to the real-life situations the project encountered during its development. The research outcomes can serve as a model for other green barrier projects, advancing the knowledge of landscape architects on technical generalisations but site-specific contextualisation. Using the research by design approach was highly relevant to expand the knowledge of Landscape Architecture, and its specific implications are discussed below.

On a practical level, this research has established key technical considerations for designing green barriers that deliver air quality improvements and co-benefits for schools. The green barrier considerations expand the knowledge of GI and NbS research and practice, and pragmatically support the development of more projects that will better cope with the challenges and adaptations needed to implement green barriers in school facilities. This new knowledge offers landscape architects, horticultural practitioners, and other built environment professionals the right tools to create multifunctional green barriers and, most importantly, to prevent the creation of less than optimal GI that traps air pollutants or that limit the co-benefits due to shortcomings in design (e.g., poor plant selection). Additionally, although not all urban greening is aimed at improving air quality, designers should always consider it as AQ can easily be worsened if GI is placed in unfavourable locations. This awareness is crucial as air pollution remains a prevalent challenge in the urban landscape.

Moreover, the research outcomes exhort to defy the current one species hedge/fence approach that has been followed by commercial 'green solutions' suppliers like Hedera Screens or Mobiliane in the UK. They tend to use a simplified monoculture of ivy (*Hedera helix*), and are missing opportunities for making schoolyards better places for people and wildlife. At the same time, their fence design leads the market as it is one of the few options readily available for installation and it has been used, for example, at most schools where the Mayor of London funded added greenery for improving air quality (Mayor of London Press Office, 2019). On the other hand, this study suggests using a mix of plants to create green barriers, as each plant has its own mechanism for PM capture that favours a certain particle size; therefore, using more species fosters removing PM from the air in more ways. Adding more species can also allow the green barrier design to create a nicer environment for children; where colours, textures, layers, and scents enhance co-benefits such as restoration, safety, learning, and play opportunities. In this sense, the ready-made ivy fences from commercial suppliers can make a useful contribution to a more diverse planting strategy, being one of the multiple species making up green barriers. Such was the case of the green barrier in the Sheffield case study, which used five key fence-forming plants (including ivy) and 27 additional species.

Studying the whole process of green barrier implementation in schools has led to a deep understanding of what is required for a successful intervention, and co-creation is one of those elements. Even though the term co-creation is becoming a 'buzz' word (e.g. attracting grant awards and funding), involving stakeholders from the start of a project has an essential role to play. In this research, each case study collaborator contributed with specific expertise, motivations, resources and sometimes decision power to make the green barrier projects possible. Without the concurrence of all these experts and stakeholders, it would have been quite difficult to overcome the multiple hurdles that it takes to implement NbS in real life. But most importantly, these collaborations allowed knowledge exchange and provided a space for sharing ambitions and motivations that, in turn, helped with the projects' buy-in. It was clear that the involvement of the school community and other stakeholders is critical to the long-term success of the projects, as has been highlighted by other researchers (Deely et al., 2020; Sarabi et al., 2020; Kabisch et al., 2016). For instance, the school community is key for supporting plant maintenance, and an engaged community will find ways to make it work: volunteering events, establishing a gardening group, including it as part of a module where children participate, fundraising to buy irrigation equipment or to hire a professional gardener, among other strategies. Moreover, involving the school community (place users) is vitally important and can help practitioners move away from only 'consulting' with them at the end of the design process. This study's outcomes help raise awareness amongst landscape architects and other practitioners of the benefits of early involvement of stakeholders.

All research outcomes mentioned above aim to establish principles for improved GI4AQ+ that will help landscape architects, engineers, and other practitioners to implement green barriers in schools. These principles are more likely to reach practitioners if presented as a friendly summary rather than as journal articles. Therefore, to make this information more accessible, the research outcomes were transformed into a 'Guidance on green barrier implementation for schools and landscape practices' (Supplementary Material). This guide reflects learnings acquired throughout the PhD by the Lead Researcher. It also integrates learning not only from the landscape firm and school involved in the UK case study, but also from other schools and landscape practices in Sheffield that are interested in installing green barriers. Knowledge exchange during two workshops with school representatives (headteachers, parent governors, and a school caretaker) and landscape architects, as well as continuous collaboration with Senior Researcher Ross Cameron and a landscape architect from Urban Wilderness, culminated in the guide presented here. The guide is a pragmatic resource to close the technical gaps in knowledge, and a tool to advocate for upscaling green barriers. It also supports the involvement of informed landscape architects in creating multifunctional GI designs. The guide will be disseminated to local councils, landscape architects, and schools in the UK.

Implications for policy

The study's research outcomes regarding the AQ impact of green barriers can have significant policy implications. This research has shown that green barriers are a useful tool to help protect schools from the impacts of air pollution; however, it also evidenced that reducing air pollutants at the source has a greater impact. This finding relates to the greater reduction in NO_2 during the first covid-19 lockdown in the UK, when concentrations in Sheffield decreased by about 25%, compared to a circa 13% decrease due to the green barrier two years after its installation (de-seasonalised data). In contrast, PM concentrations did not significantly decrease during lockdown, and only slightly decreased (2%) due to the green barrier. This illustrates the complexity involved in reducing PM pollution, especially due to its ability to be transported between regions by atmospheric and climatic effects. But it also highlighted that human behaviour influences the sources of pollution as, in Sheffield, the use of woodburning stoves and garden fires were a significant source of PM pollution during lockdown. These findings can support governments in making informed decisions and creating evidence-based strategies to protect children from air pollution.

Some of these policies might include systemic changes to support active travel (e.g., infrastructure for safe walking and cycling, reliable and economically accessible public transport, or car-sharing schemes), reducing car use which equals reducing NO_2. Moreover, fossil fuel cars' phasing-out and the introduction of electric vehicles (EV) offer an alternative for mobility that does not generate NO_2. However, EVs will continue to generate PM, as the other sources of traffic-related PM are road dust resuspension, and brake and tyre wear and tear (Gonet et al., 2021; Liati et al., 2019; Pant and Harrison, 2013). The latter contributes to 68-85% of magnetite PM, which has serious implications for the brain and cardiovascular system (Gonet et al., 2021).

'School streets' is another initiative that is gaining momentum in the UK to protect pupils' health. They involve temporarily closing roads outside schools during drop-off and pick-up times, banning the circulation of motorised vehicles and supporting active travel. The first school street trial in Sheffield was too short to elaborate scientific conclusions (Barnes and Val Martin, 2020), yet, based on this study's results, a reduction of NO2 is likely to happen in schools if traffic flow decreases. School streets trials in London (over 300) have already shown large support from their school communities (Transport for London, 2021).

Overall, this research indicates that improving air quality is complex, and policy should cover multiple fronts to have the greatest impact on children's health in the short- and long-term. Policy supporting pollution reduction at the source can be complemented by policies for air pollution mitigation, such as GI. AQ policy can capitalise on climate change and net-zero policies, as actions to reduce and mitigate air pollution often deliver carbon capture or greenhouse gases reduction. Alternatively, green barriers could also be supported by policy as a school greening strategy that enables multiple benefits for school communities.

Limitations

This study experienced some overarching limitations. Firstly, it is important to acknowledge that this research was carried out in a sensitive environment. Working in school playgrounds meant that any action had to be done safely to protect children and during the least disrupting times, and that proved to be challenging. At the Sheffield case study school, the air quality monitor had to be installed with aerial cables to prevent tripping hazards. That meant that we could not install the monitor in the middle of the playground, as desired, but in its elevated northeast section. The monitor location may influence the air quality results due to the distance from the roads where the emissions occur. Additionally, the size of the playground limited the green barrier's planting space (0.9-1.3 m wide), which constrained the AQ impacts, as wider green infrastructure has shown to yield higher pollutant reduction. However, those conditions reflect the constraints of the urban landscape, therefore, the results are representative of the AQ improvements that can be achieved in real-life schools, in contrast to modelling studies.

The study faced several limitations due to the disruption caused by the covid-19 pandemic and the governments' lockdown measures in response to it. The AQ baseline at the Sheffield and Buenos Aires schools was collected during pre-pandemic times, however, the covid-19 pandemic was present during the years that followed the green barrier installation. Simultaneously, lockdowns created unique conditions, i.e. low-vehicle traffic and low-citizen mobility, that gave a different insight into air pollution patterns.

In the UK, lockdowns disrupted data collection, forcing us to extend it to 2021, which was not planned. Fixed-monitor data was only comparable from July-October each year (2019, 2020 and 2021), and mobile device AQ monitoring was restricted to September-October 2020. Additionally, temporary closure and reduced availability of labs at The University of Sheffield caused elemental composition analysis to be carried out in January 2021 instead of July-October 2020, not matching the study period as desired. Overall, the pandemic disruption created real challenges to analysing the AQ data and retrieving meaningful conclusions, hence expert advice and support from a colleague were needed to analyse the data. Additionally, social distancing limited the green barrier maintenance activities, stakeholder interviews (which switched online), and interrupted a questionnaire to measure the impacts of the green barrier on children's wellbeing and nature connectedness. The questionnaire was conducted with Y1 children in 2019, with intended follow-up with the same year group in Y2. This approach was challenging due to the short attention span of 6-year-old pupils even with a simplified version of the questionnaire, and ultimately the efforts were dropped because of school closures and potential pandemic-related stress on pupils.

On the other hand, the Buenos Aires school saw an even longer school closure period due to the covid-19 pandemic. Technical and financial constraints forced us to conduct the air quality monitoring with a mobile device only, and the school closure meant that no one was allowed into the premises to conduct this activity post-green barrier installation. Therefore, the AQ monitoring approach in Buenos Aires changed at a very late stage (to diffusion tubes) and few data points are available to date. Additionally, the school community was not able to participate in the green barrier maintenance as desired. Fortunately, plant maintenance was carried out by the school caretaker (the only person allowed to enter the school), as an act of goodwill.

Finally, accurate and robust air quality monitoring is costly and requires constant maintenance. Such high expense was an important limiting factor in Buenos Aires, where only mobile air quality monitoring was possible. Whilst a fixed 'low-cost' monitor (~£3,500 compared to £50k-£80k in the case of the reference monitors used by the UK government) was installed at the Sheffield school, its maintenance costs were high, and repairs were needed twice during the duration of this study (costing an overall sum of £4,000). A malfunction of the air quality monitor in Sheffield caused some data loss, and its repair was delayed due to budget constraints. I consider the cost and technical and difficulties of AQ monitoring to be the largest limiting factor to developing this kind of research.

Further research

Further GI4AQ+ research is required in other world regions needing cleaner air. For example, expanding the knowledge of Argentine local plants with the potential to create efficient green barriers will benefit further trials. Plant knowledge is especially important to prevent reliance on fixed species lists/ blueprints, which could lead to losing the local specificity and biological diversity that supports the multiple co-benefits we seek. Research on GI4AQ+ governance is also recommended, as top-down and bottom-up governance approaches may look different in other contexts. Moreover, this study evidences the perceived co-benefits derived from green barriers in schools, which is subjective to the school community. Therefore, there are opportunities for researching and measuring other co-benefits in schools, such as energy conservation of buildings, urban heat island mitigation, noise mitigation, a healthier human microbiome, and positive affect, among others.

Additionally, finding ways to include children's opinions on green barrier design is suggested for future projects. Measuring impacts directly on pupils, such as wellbeing, attention restoration, or play is also recommended. It can be challenging to create age-appropriate activities that will have measurable outcomes, and to ensure children consent to the activities. However, pupils are the ultimate users and beneficiaries of green barriers in schools. Providing a platform for their voices to be heard could improve the design, make children feel appreciated, and create a sense of ownership.

Final reflection

Transitioning towards ensuring clean air environments for children is a challenge that requires all levels of society to be involved. From people's attitudes to mobility and energy generation, to systemic changes that provide effective infrastructure for low pollution/carbon day-to-day living activities, and policy that considers clean air as a human right. There is still much to do in relation to those three aspects for a just transition, however, it is crucial to keep pushing for changing the realities of those 300 million children that live in highly polluted areas. The nature-based and people-centred solution presented in this thesis contributes to preventing stories like Ella Kissi-Debrah's or mine from happening. In fact, it creates the opposite: healthy environments that support mental wellbeing, play, and learning, which inspire children and their families to live more sustainably. I envision green barriers research supporting policy, practice and activism, and hope that it can contribute to positioning GI and NbS as valuable options in the toolbox of solutions to urban challenges.

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Supplementary material

Material included in this section:

- Photolog of green barrier implementation in Sheffield and Buenos Aires
- Guidance on green barrier implementation for schools and landscape practices
- Supplementary material from publications
- Ethical approval
- Permission to include published material in thesis

Supplementary material

Photolog of green barrier implementation in Sheffield and Buenos Aires

Sheffield case study school

Groundworks: underground survey, soil and tarmac excavation, tree survey

Planting days with volunteers

Maintenance activities with volunteers

Green barrier launch event

Green barrier – final product

Air quality monitoring

Buenos Aires case study school

Planting days with volunteers

Green barrier – final product

Supplementary material

Guidance on green barrier implementation for schools and landscape practices

Clean air in schools using green barriers

Guidance for practitioners and schools

María del Carmen Redondo Bermúdez[1], Ross Cameron[1], Steve Frazer[2], Design by Liwen Zhang[1]. Co-developed with School communities in Sheffield, UK and landscape practitioners. With special support from Hunter's Bar Infant School and Rowan Hall[3]. 2022

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The University Of Sheffield.

URBAN WILDERNESS

Green (vegetated) barriers are a nature-based solution to air pollution, complementing other efforts to improve the quality of the air we breathe. This document provides a user-friendly guide to developing green barriers around school premises.

- Section 1 outlines what we mean by green barriers and some of the evidence around the benefits they provide. It also illustrates a case study in Sheffield, UK.
- Section 2 outlines how school communities can effectively navigate the process of implementing a green barrier.
- Section 3 supports landscape architects and horticulturalists to provide robust advice on green barrier design and plant selection.

Ideally, practitioners and school communities (including for some aspects - the pupils) should adopt a genuinely collaborative approach (co-production) to developing the green barrier, as this provides a range of additional benefits and functions.

1. Green barriers and air quality

Poor air quality is one of the most relevant challenges of modern cities. It is estimated that 99% of the world's population breathe unhealthy air, with levels that exceed World Health Organization (WHO) limits[1]. Air pollution is associated with diseases and organ damage across the body. Although pollutants usually reach our lungs first, causing respiratory diseases and asthma exacerbation[2], they travel to other parts of the body through our bloodstream. That is why heart attacks, cognitive dysfunction and different types of cancers are associated with air pollution[3].

Children are most at risk. They have smaller bodies and inhale more air per unit of body weight, and their bodies and lungs are immature and need a clean environment that supports their development[4]. Moreover, children are more likely to play and spend greater time outdoors[4]. These aspects influence the correlations between air pollution and children's health, such as decreased lung function, low attention span and concentration, increased allergies[5], metabolic changes related to anaemia or obesity, and eczema exacerbation[3].

Protecting children from air pollution is urgent and imperative. In 2016 the law firm ClientEarth sued the UK Government over its failure to secure healthy air for its citizens[6]. Awareness is growing and attitudes against air pollution hardening. For example, a Sustrans' poll reveals that children across the UK are concerned about air pollution and want to take action to reduce its impact[7]; and the community group 'Mums for Lungs' have campaigned since 2017 for cleaner air around schools. The priority is to reduce the sources of pollution around schools in the first place, for example, transitioning to cleaner energy production (e.g. avoid woodburning stoves - wood burner alert tool) or use cleaner forms of transport (cycling / walking to school) – Modeshift STARS, Living Streets, and Global Action Plan have useful tips in this respect).

Complementary to reducing the sources, we can use plants to prevent air pollutants from reaching school facilities and green barriers are a practical way to achieve it. Green barriers are a type of Green Infrastructure (GI) consisting of rows of different types of vegetation, which together create a physical and biological obstacle for air pollutants to reach a sensitive zone, such as a school playground[8]. They act by blocking, depositing, and absorbing air pollutants (Figure 1). Plants effectively disperse and deflect the wind that carries air pollution[9]. Plants also absorb gas pollutants – e.g., nitrogen dioxide emitted from car exhausts – through the stomatal pores on the underside of their leaves[8]. Additionally, their leaves and bark can also capture smuts (small particulate matter, also named 'PM' pollution)[8]. These tend to come from various sources including vehicles' brake and tyre wear, dust from construction sites, and woodburning stoves. Also, the microbiota that live on plants and within the soil can degrade or transform air pollutants[8] into innocuous forms.

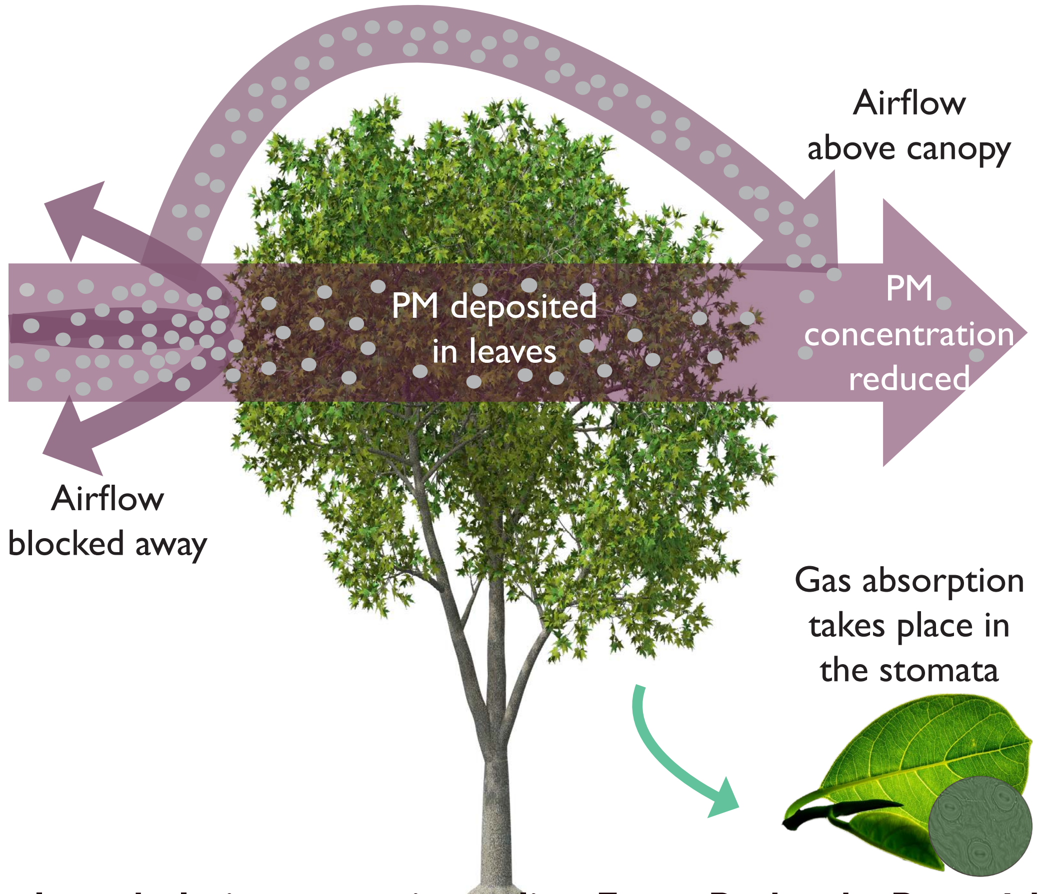


Figure 1. How plants help improve air quality. From Redondo-Bermúdez, 2020[8].

1.1 A green barrier in a school in Sheffield, UK

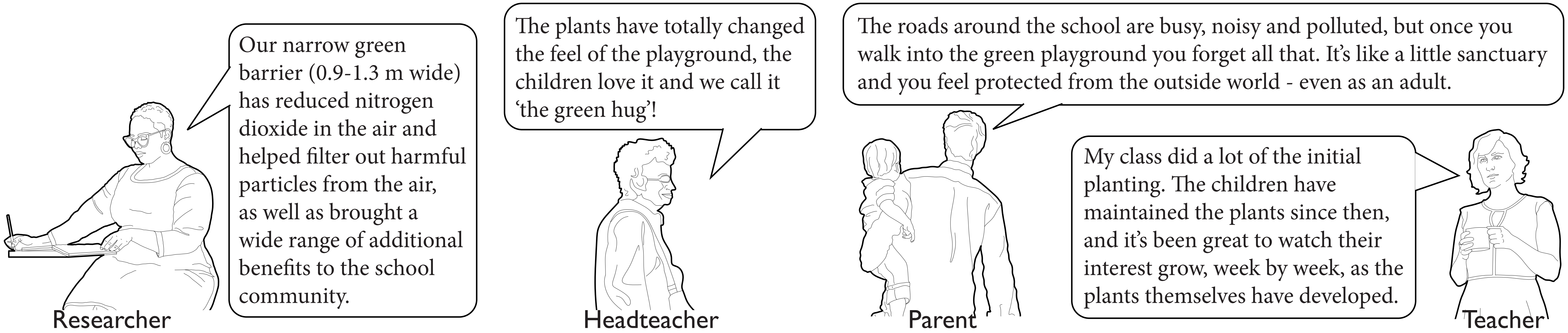
A green barrier was planted in Hunter's Bar Infant school in October 2019. The green barrier design and project development was a collaboration between the school community, local businesses, the city council, and The University of Sheffield. It was funded by the school community and supported by in-kind services from local business, who where mobilised via the school's #GoGoGreen Campaign.

The new green barrier helps shield approx. 270 pupils from pollution sourced from primarily vehicle traffic and domestic/commercial burning activities (e.g., the use of woodburning stoves). Five plant types were included to provide a pollution screening function:

- *Hedera helix* 'Woerner'
- *Phyllostachys nigra*
- *Thuja occidentalis* 'Smaragd'
- *Chaemacyparisus lawsonia* 'Ivonne'
- *Juniperus scopulorum* 'Blue Arrow'

Another 25 plant species were added to provide sensory interest, including texture, scent, and colour, as well as provide support for wildlife.

What does the school community think of the green barrier?



Although the primary objective of installing the green barrier in Hunter's Bar Instant School was to improve air quality, the added greenery generated other benefits[10] (Figure 2). Plants make the visual appearance of the school more attractive, promote mental well-being and encourage pupils to relax[11,12]. Green barriers are a form of green space – access to which is especially important in cities – fostering connection with nature and promoting learning opportunities. They also create safer and more private places for children to play.

Schools may wish to consider these additional benefits when developing their green barrier project, and think of the plants and design that will help them achieve these co-benefits.

Figure 2. Green barriers can provide a wide range of benefits to the school community.
Adapted from Redondo-Bermúdez et. al., 2022[12].

The following sections outline the process for school communities to follow should they wish to develop a green barrier, and what sort of support landscape practitioners can provide.

2. Launching a green barrier project – Information for schools

The delivery of the green barrier involves several distinct project stages (Table 1). Throughout this process, the involvement of the school community is crucial to success, as schools will be ultimately responsible for the governance and maintenance of the green barrier in the long-term.

Table 1. Stages of a green barrier project.

Stage 1 Setting goals	Stage 2 Co-design	Stage 3 Survey and construction	Stage 4 Planting	Stage 5 Maintenance
				
What would you like to achieve with the green barrier (think of multifunctionality)? Who are the key collaborators for your project? How will you involve them in the project? What is your budget and how will you cover the costs?	What will the green barrier look like? Where and how will you implement a green barrier for your space?	Have you carried out a physical examination of the site? How are you going to prepare the space for planting? What is the schedule for the construction activities in your school?	Where are you procuring the plants from? Who will participate in the green barrier planting?	How will watering, pruning, and tidying of the green barrier be accomplished in the long-term? Do you have a contingency plan for watering during the summer break?

If your school is planning to undertake this project, we suggest paying particular attention to the following areas: governance, funding, maintenance, monitoring wind direction, and monitoring impact.

- **Green barrier governance.** We recommend appointing a representative who will be responsible for the creation and ongoing management of the green barrier. This can be an individual, or group of individuals, that will foresee activities throughout the project stages. It could be a member of staff or an external partner, as long as the individual can adequately represent the schools' interests and understands key needs and constraints.

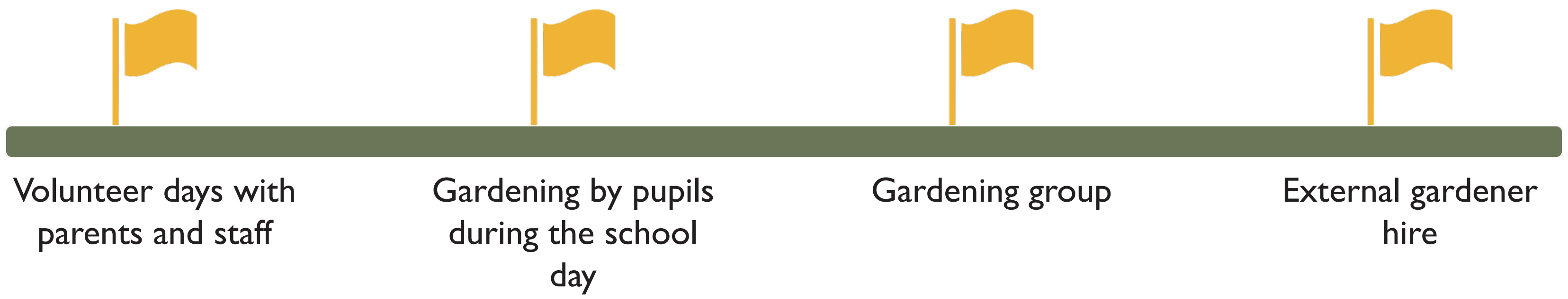
- **Funding.** The materials, labour, and time dedicated into each stage of the project imply a cost. Whether your project starts from the grassroots at the school or local community group, to having a 'top-down' approach supported by governmental bodies, funding is required and can be accessed through multiple means. Funds can be used to directly cover the costs of the project, for example buying plants, hiring a landscape architect, or paying for an underground site assessment, but these could also be provided through in-kind work and donations.

- **Maintenance.** Plants are living beings that require care and attention in order to thrive. Periodical maintenance activities including irrigation, pruning, soil enhancement, as well as care for hard infrastructures and surfaces are all necessary to support the long-term health of your green barrier. These activities can be undertaken by the school community or external support; either way, it's important to develop a maintenance plan that defines clear and feasible actions and nominates those responsible for carrying them out.

Suggestions for green barrier governance representatives:

Suggestions for funding processes:

Suggestions for green barrier maintenance:



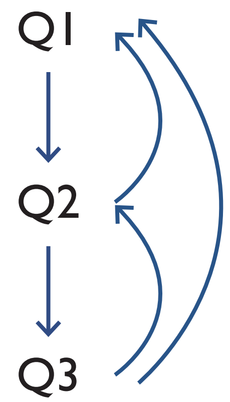
- **Monitoring wind direction.** Knowing the local wind direction is crucial to inform the green barrier design. Pollutants are carried in but also out of the playground by the wind and if the flow is restricted by the green barrier in erroneous places, they can get trapped in the playground. This can be prevented by managing the air flow, once knowledge of the local wind directions and frequency is obtained. Simple wind monitors (anemometers) can be installed in the playground for a couple of months to register the wind data. Technology brands have affordable and user-friendly anemometers/weather stations that record data.

- **Monitoring impact – air quality and co-benefits.** Monitoring air quality and evidencing any additional benefits is encouraged. Monitoring air pollution levels before and after the installation of the green barrier could help to understand and quantify its impacts. While this task can be challenging, a range of low-cost sensors are available (comprehensive information on sensors can be found at UK Air DEFRA and the US Environmental Protection Agency). Local councils may also provide support in accessing simple monitoring tools, such as diffusion tubes for NO_2. If done successfully, monitoring can add significant value to the project, allowing you to showcase the positive transformation you have achieved for the school community and the environment. This can also aid in fundraising, as government grants typically require robust evidence of impact.

3. Green barrier co-design - Information for landscape practitioners and horticulturalists

The green barrier co-design is an iterative process between landscape practitioners, school communities and other stakeholders relevant in the area (e.g., local councils or community groups), that entails gathering site information and trialling different approaches. It entails understanding the site, proposing vegetation types, and defining suitable dimensions and shapes of your green barrier. Each school is different and poses its own challenges. It's important to understand the context, especially the main potential sources of aerial pollutants and the predominant wind direction. You want the green barrier to block and disperse poor quality air, not act as a trap for it!

When designing a green barrier, consider asking the following questions. Remember: the more information you gather, the better prepared you will be to answer the questions and achieve the best design.



Q1 – Is the school suitable for planting new vegetation?
Q2 – Where exactly can we install the green barrier?
Q3 – What will the green barrier look like?

Q1 – Is the school suitable for planting new vegetation?

Q1 summary:
Determine whether the site is ready for planting or if you need to adapt it. Check the site's:
☐ Land rights ☐ Above- and under-ground structures ☐ Infrastructure to support plant development ☐ Health of existing plants

- Check **land ownership**. Identify who is the responsible body for managing the site and who will need to grant permissions (if applicable). Schools in England are usually owned and managed by either the Local Authority or Charitable Foundations. Permission to install a green barrier may include: permissions by landlord, permissions to work by the local City Council and Building Regulations Department approval.

- Check **site characteristics**.
  a. Assess **above- and underground structures** and **site size**. For example, identify surface and substrate materials: tarmac, bare soil, rubble; aboveground infrastructures: e.g. walls, railings, gates; and underground infrastructure: water pipes, gas pipes, network and power cables. The assessment could be supported by topographical surveys, site plans by City Council, safe dig plans from the National Grid, or subsurface scans by construction professionals. Determine the overall size of the site and the potential planting space size and depth.

  b. Assess existing infrastructure to support **plant growth and development**. Plants need sunlight, water and a free-draining soil (amended with organic growing medium if necessary) to survive. Assess if the location provides these requirements, and what modifications might be necessary. If the plants are to be housed in planting pits or raised beds/planters – how large do these need to be? (a simple 'rule of thumb' is root systems can often mirror the dimension of the plants top-growth - leaves and branches). So consider light, wind direction (is it too exposed a site?) and soil structure and whether the plants can rely on rainwater; or should artificial irrigation be supplied if the roots are likely to be restricted within a small volume.

  c. Assess the **health** of any existing plants onsite, including trees, hedges, and other plants. Some plants may need removal, whilst some others may benefit from pruning, structural strengthening or even more nutrition or organic matter applied to the soil. For large trees, such assessments can be made by the local authority Tree Officer and/or professional arboriculturists.

Be as comprehensive as you can when gathering information. This will inform the feasibility of any barrier intervention and the key modifications required. For example, school facilities may need tarmac removal and soil addition, a water tap installation to support the plants, or there may be areas where underground lines make planting not feasible. Answering this question will also inform budget estimates.

Q2 – Where exactly can we install the green barrier?

Q2 summary:
Conduct an air quality visualisation exercise of the site and decide where to locate the green barrier, based on the wind direction and air pollution sources.

Each school layout and location within its neighbourhood are different. Acknowledging these specifics moves us away from a one-size-fits-all approach: green barriers must always be tailored to the school. There are three critical elements to consider when deciding where to install a green barrier: the **built environment**, **sources of air pollution**, and **wind direction**. Gather information at a local level on these factors and carry out an air quality visualisation exercise.

Air quality visualisation exercise ⟶ Attentively observe the school and its vicinities. Draw a map of the area for protection inside the school (e.g. school playground) and its surroundings, identifying and marking the following:

- **Built environment**
  a. Site layout and supporting information from Q1
  b. Neighbourhood vicinities (about a 150 m circumference from the area of protection)
  c. Street types:
    i. open roads (roads with no buildings or with buildings on one side)
    ii. street canyons (roads with buildings on both sides. These range from sparse low-rise buildings e.g. streets with single or double storey houses, to tightly packed and high buildings e.g. central London streets)

- **Sources of air pollution** (location and intensity)
  d. Traffic (flow and vehicle type share)
  e. Domestic activities – e.g. wood burners
  f. Construction sites
  g. Waste burning facilities
  h. Commercial activities resulting in air pollution
  i. Any other particular activity to the site's surroundings

- **Wind direction**
  j. Prevailing wind
  k. Local wind (incl, channelled windflows)
  l. Seasonal changes

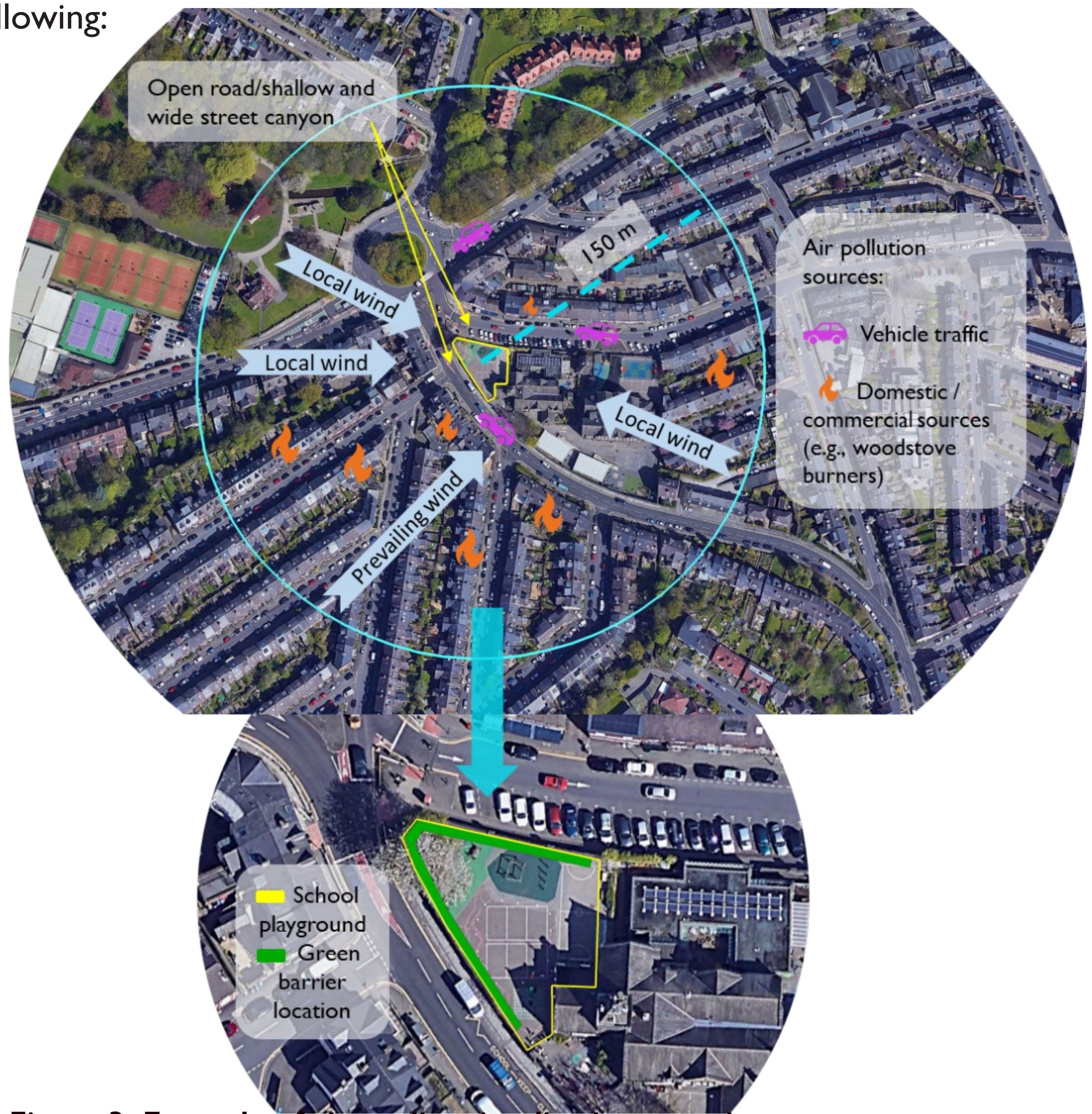


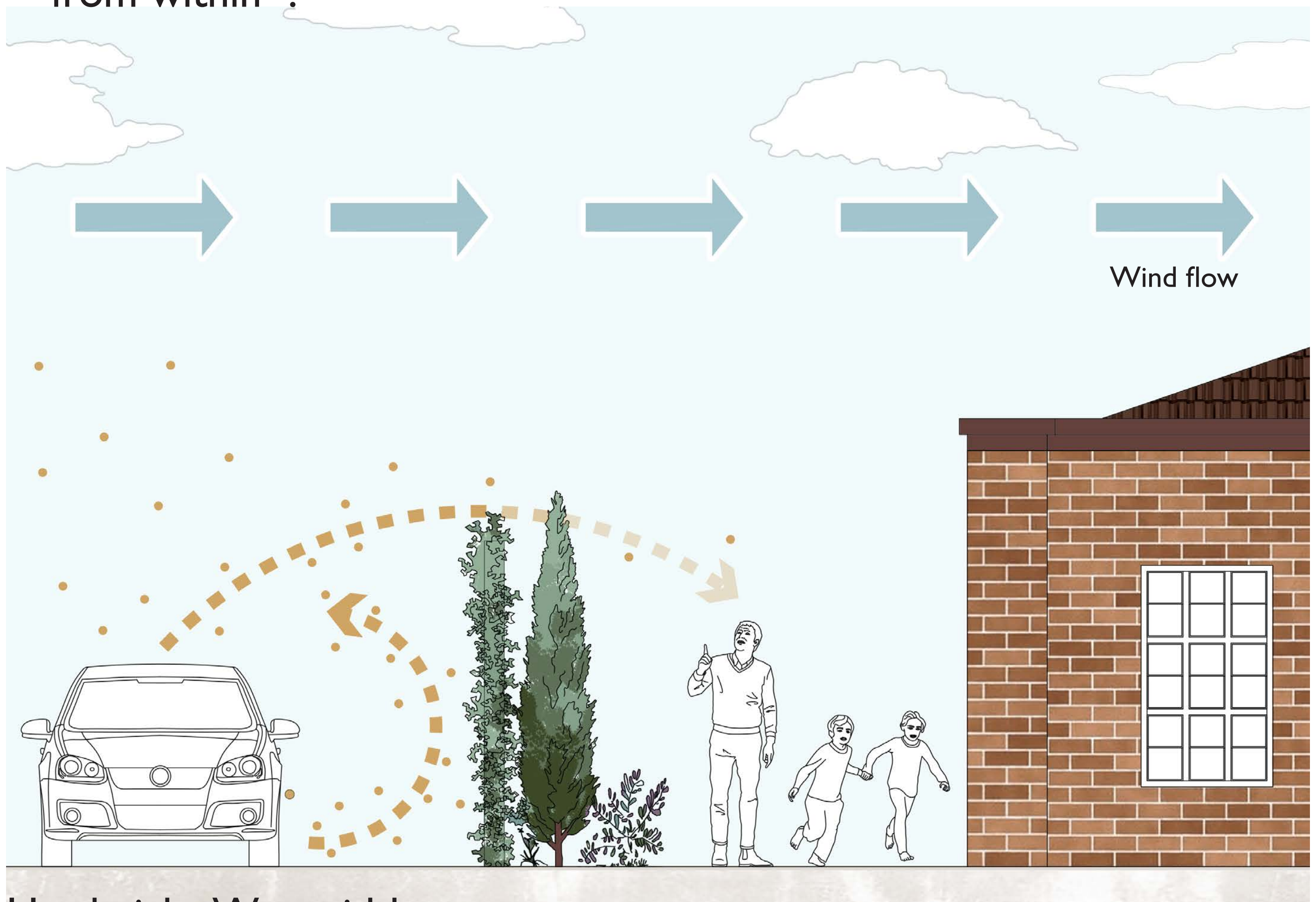
Figure 3. Example of air quality visualisation exercise

Support the air quality visualisation exercise with satellite maps exploration (e.g. Google Maps), governmental or open-source data of transport types, traffic flow volume and times, and wind direction. If wind data is not available, consider installing a wind station on-site (there are many low-cost options with data loggers) – this information is critical for the green barrier design! It is useful, but not essential, to have a record of local air pollution level, if data are available. Use public air pollution data sources (from community groups, research institutions, or government monitoring sources) or consider installing low-cost air pollution sensors.

Building on the air quality visualisation exercise, you can now map the ideal location and dimensions for your green barrier. Account for the various wind directions and pollution sources in relation to protecting the school. The green barrier needs to BLOCK pollutants from entering the school play areas, not trap them in. Consider the following depending on the street type (Table 2):

Table 2. Considerations for green barrier design and implementation according to street type.

Open road	Street canyon
- Locate the green barrier downwind, i.e. the area for protection is behind the barrier and the air flows perpendicular to the barrier from the road[13]. - Locate the green barrier close to the pollution source[14]. - Consider enclosing the area for protection with the green barrier to create a ‘green oasis’. Note that no sources of pollution should come from within[15].	- Locate the green barrier where its width would be perpendicular or parallel to the wind direction. Be aware of causing local air vortices, which may reduce or not, air pollution behind the barrier[16,17,18]. - Locate the green barrier close to the pollution source and note that very narrow street canyons (H/W ≥ 2) are not suited for green barriers[19].



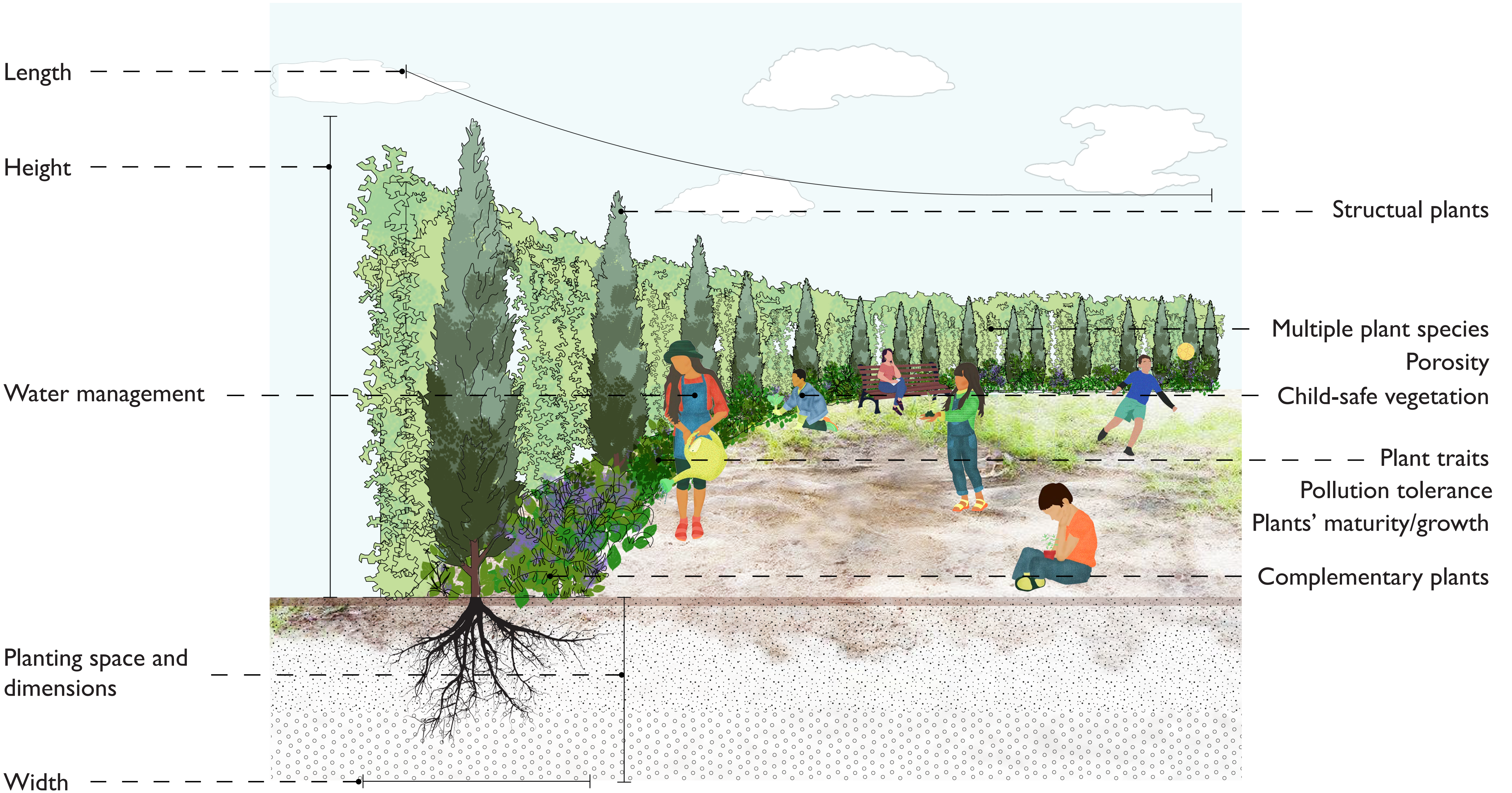
H = height; W = width

Make use of **modelling tools** to complement the air quality visualisation exercise. Tools such as i-Tree Eco[20] and the GI4RAQ platform[21] can model air pollution deposition and dispersion, helping to determine whether a green barrier is beneficial and where it should be located. These approaches may need to be re-run a number of times, to ensure a green barrier is appropriate and is located in the optimum location.

Q3 – What will the green barrier look like?

Q3 summary:
Select the height, width, and length of the green barrier. Select a plant composition beneficial for air quality and for creating co-benefits.

Physical characteristics **Biological characteristics**



Once the location of the green barrier has been determined, then thought can be given to its **dimensions** and **plant composition**.

- Select **dimensions**:
  a. Define green barrier dimensions (height, width, and length).
     i. **Height**: existing guidance suggests that the horizontal extent of protection behind the green barrier = '(3H) - 3 metres downwind under the right wind conditions[22]. Consider a minimum height of 2 metres, which will protect up to 3 m downwind (following the formula: 3*2 – 3 = 3 m)

     ii. **Width**: research recommends thick green barriers (sometimes of 10 m minimum)[23]. In urban landscapes where space is scarce, thinner green barriers (1-2.5 m) can still reduce air pollutants [18,22]. Consider utilising the most planting space you can, aiming for no less than a 1m width green barrier.

     iii. **Length**: green barriers should extend horizontally beyond the area of protection, if possible, to prevent polluted air entering at the barrier corners or edges.

  b. Define **type and dimensions of planting space**. Consider planting directly into the ground or using planters or raised beds. If you plant into the ground, a depth of 1 m will suit most planting schemes involving shrubs. Deeper root-zones may be required for large trees.

  c. Define **water management**. There are multiple possibilities based on budget, labour, and levels of engagement from the school. Approaches include manual irrigation by members of the school community, to installing automatic drip irrigation. Additionally, ensure a free-draining soil or make arrangements to allow it, such as weep holes or channel drains.

- Select **plant composition**:
  a. Define **structural functional plants**. The careful selection of these plants will help to achieve the desired green barrier dimensions (height, width, and length). While there is no precisely recommended number of plants species, there are several factors to consider when selecting the best plants for your school:

     i. Using **multiple plant species**. Each species of plant has different mechanisms to reduce air pollution (e.g. PM capture), therefore, using a range of complementary species will maximise the opportunities to capture, retain or deflect air pollutants[24]. Also, using species with different shapes and textures can add variety to the barrier, as well as improve the functionality. Evergreen species are preferred over deciduous to foster AQ impacts throughout the year.

ii. **Plant traits**. Certain plant traits foster PM capture or NO_2 absorption[25,26] (Table 3). Examples of species with these traits are shown in Table 4.

Table 3. Plants traits that favour air quality.

Plant traits	Particulate matter	Nitrogen dioxide
Macro-scale	- Conifer > broadleaved plants. - Small leaf size/high leaf complexity > large/simple leaves.	- Barrier forming plants, as dispersion by vegetation seems to be the main strategy to reduce the effects of gaseous pollutants.
Micro-scale	- High leaf roughness (for example with grooves or ridges) > smooth leaves - Presence of wax on leaves > low or no wax. - Presence of hairs on leaves > smooth leaves.	- Potentially high number of stomata on leaves (plants' gas exchange organs) with extensive opening periods – to foster gas absorption. For example, Populus spp. or Quercus spp. Note that evidence is not clear on which specific species are most effective at NO_2 absorption.

Table 4. Example of plants with air quality mitigation potential.

Climber	**Conifers**	**Other trees**	**Shrubs**	**Herbaceous**
- *Hedera helix L.* - *Trachelospermum jasminoides* - *Clematis armandii*	- *Juniperus virgininana* - *Juniperus chinensis* - *Chamaecyparis lawsoniana* - *Pinus sylvesteris* - *Pinus nigra* - *Cryptomeria japonica* - *Abies conconlor* - *Picea pugnens* - *Platycladus orientalis*	- *Ulmus pumila* - *Eucommia ulmoides* - *Carpinus betulus* - *Quercus ilex* - *Acer campestre* - *Catalpa speciosa* - *Phyllostachys spp.*	- *Photinia x frasieri* - *Elaeagnus × ebbingei* - *Viburnum tinus* - *Cercis chinensis* - *Sorbaria sorbifolia* - *Buxus sempervirens*	- *Spirea japonica* - *Lavandula angustifolia* - *Achillea millefolium* - *Heuchera spp* - *Buddleja spp.* - *Stachys byzantina*

iii. **Porosity**. Green barrier porosity (volume of gaps between plant structures) influences both wind deflection and wind crossing through the plants; the latter fosters PM deposition/NO_2 absorption. Plants that can create compact barriers with low porosity are preferred.

iv. **Plants' maturity/growth**. Once the green barrier dimensions and planting space are defined, you can select species that will thrive in that space and will not overgrow it. Find species that can keep to the desired size without requirement for frequent and excessive pruning (look for plants classed as moderate or slow growing).

v. **Pollution tolerance**. Plants themselves need to be tolerant to urban stress factors, and some themselves are susceptible to damage from atmospheric pollutants. Long needle pine species, for example, may be more susceptible to damage than their short-needle equivalents. Certainly, avoid species with limited tolerance to moderate drought, wind or compacted soils. Nursery catalogues and websites can help provide information here. Also observe plants growing in nearby gardens and parks, these are already often 'tried and tested' for local climatic conditions.

vi. **bVOCs and pollen**. Some plants are actually a cause of poor quality air, not a solution to it. Avoid species with a reputation of producing large amounts of allergenic pollen (some birch, Betula species for example); or choose female plants in dioecious (has separate male and female plants) species. Other, such as Eucalyptus, produce aromatic organic molecules (bVOCs or biogenic volatile organic compounds) which react in the atmosphere producing ozone (O_3) as a secondary air pollutant. Select species with low bVOCs emissions[15]; resources such as the bVOCs emission potential plant list[27] can inform your decision. Under 20°C bVOC emissions from most plant species are low[9] and overall emissions from small scale green barriers are likely to be insignificant.

i. **Child-safe vegetation**. Plants should not pose a risk to children who might interact with them, therefore, low-allergy, non-poisonous and non-spiky species are preferred. If in doubt, have a look at the checklist of harmful plants provided by the Royal Horticultural Society or The Horticultural Trade Association.

b. Define **complementary plants**. Once you have designed a green barrier that is optimal for air quality, then add plants that help maximise other benefits. For example, adding plants with a variety of colours and textures to either promote a relaxing or energising environment, and to increase place quality. Scent may also be useful here, with herbs and Mediterranean plant species providing strong attractive perfumes. Plants with simple, open flowers are usually useful for pollinating insects. Refer to your local council's Biodiversity Action Plan to align with the conservation/adaptation plans of your area and select complementary plants that enhance biodiversity.

Have you answered the three questions?

Collaboration between schools and practitioners is best to effectively deliver green barriers. School communities possess 'insider knowledge' which is invaluable to achieving the right design (Table 5). Moreover, schools can also define complementary objectives for the project. Revise the three questions taking into account the needs and wants of the school, and technical advice from landscape and horticultural practitioners. A directory of practices is available at the Landscape Institute webpage.

Most importantly co-creating green barriers with the intention to accommodate other school interests can maximise co-benefits. For example, think of adding different edging heights to support child development, or extend ground cover plants to create a garden - food and habitat for insects and birds. Make space for playful experimentation of the design to co-create a place of value for the school community!

Table 5. Examples of knowledge from the school community that can support answering the three questions for green barrier implementation.

Question	Q1	Q2	Q3
School input	• Land ownership • Playground compatibility and use • School delivery schedule and accessibility	• Pollution sources/patterns • Site layout • Specific site conditions (e.g, flooding)	• Maintenance capability • Aesthetics • Integrated play • Special interests to fit within the green barrier development (i.e., benches for outdoors learning space).

Conclusion

Green barriers are a tool to generate positive changes in schools. They can greatly add to the 'sense of place' around a school, and with understanding of the local environmental conditions, improve the air quality within the children's playing area. The design of a green barrier can be different from one school to the next, and will depend on the space available, the types of plants that are adapted to and function well within a given location, and what participants prefer. At the forefront of the mind though, is that the design should disperse or filter out pollution – not trap it. Successful design and implementation are best achieved when the school, landscape professionals and wider community come together early on to understand what is to be achieved by the barrier and what additional benefits might be gained. The barrier can be actively incorporated into the educational curriculum and become a resource for the school, raising awareness about wider environmental and sustainability issues.

Acknowledgements

We acknowledge support from the Impact Acceleration Account Grant, The University of Sheffield. MCRB acknowledges the support of the Grantham Centre for Sustainable Futures, The University of Sheffield for a PhD studentship.

Additional resources

Landscape practitioner directory:
- Landscape Institute directory. https://my.landscapeinstitute.org/directory

Plant selection resources:
- Royal Horticultural Society - guide to harmful plants. https://schoolgardening.rhs.org.uk/Resources/Info-Sheet/A-Checklist-of-Potentially-Harmful-Plants
- Sustrans. https://www.sustrans.org.uk/campaigns/air-quality/
- The Horticultural Trade Association - guide to harmful plants. https://hta.org.uk/poisonousplants
- bVOC emission plant list by Lancaster University and CEH. http://www.es.lancs.ac.uk/cnhgroup/iso-emissions.pdf

Modelling tools:
- GI4RAQ platform. https://www.gi4raq.ac.uk/pages/login
- i-Tree Eco software. https://www.itreetools.org/tools/i-tree-eco
- Global Action Plan. https://www.globalactionplan.org.uk/our-work

Air quality and wind monitoring:
- DEFRA - diffusion tubes overview. https://laqm.defra.gov.uk/air-quality/air-quality-assessment/diffusion-tubes-overview/
- UK Air DEFRA - air sensor guide. https://uk-air.defra.gov.uk/research/aqeg/pollution-sensors.php
- US EPA - air sensor guide. https://www.epa.gov/air-sensor-toolbox/how-use-air-sensors-air-sensor-guidebook#pane-1
- Weather station example. https://amzn.to/3b6MMQB

Air quality and schools:
- Client Earth news. https://www.clientearth.org/latest/latest-updates/news/clientearth-wins-air-pollution-case-in-high-court/
- Living Streets. https://www.livingstreets.org.uk/
- Modeshift Stars. https://www.modeshiftstars.org/
- Mums for lungs. https://www.mumsforlungs.org/
- Wood burner alert. https://sheffieldair.ac.uk/burneralert/

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Supplementary material from publications

From Chapter III

Publication (in peer-review process):
Redondo-Bermúdez, M.C., Chakraborty, R., Val Martin, M., Inkson, B.J., and Cameron R.W. A practical green infrastructure intervention to reduce air pollution in a UK school playground.

Figure S1 shows the partial dependencies – with Sch-GB site as an example – between $PM_{2.5}$, NO_2, and the weather covariates employed in the de-seasonalisation model. The model's performance was evaluated using tenfold cross-validation, and the resulting model fitting results are also displayed.

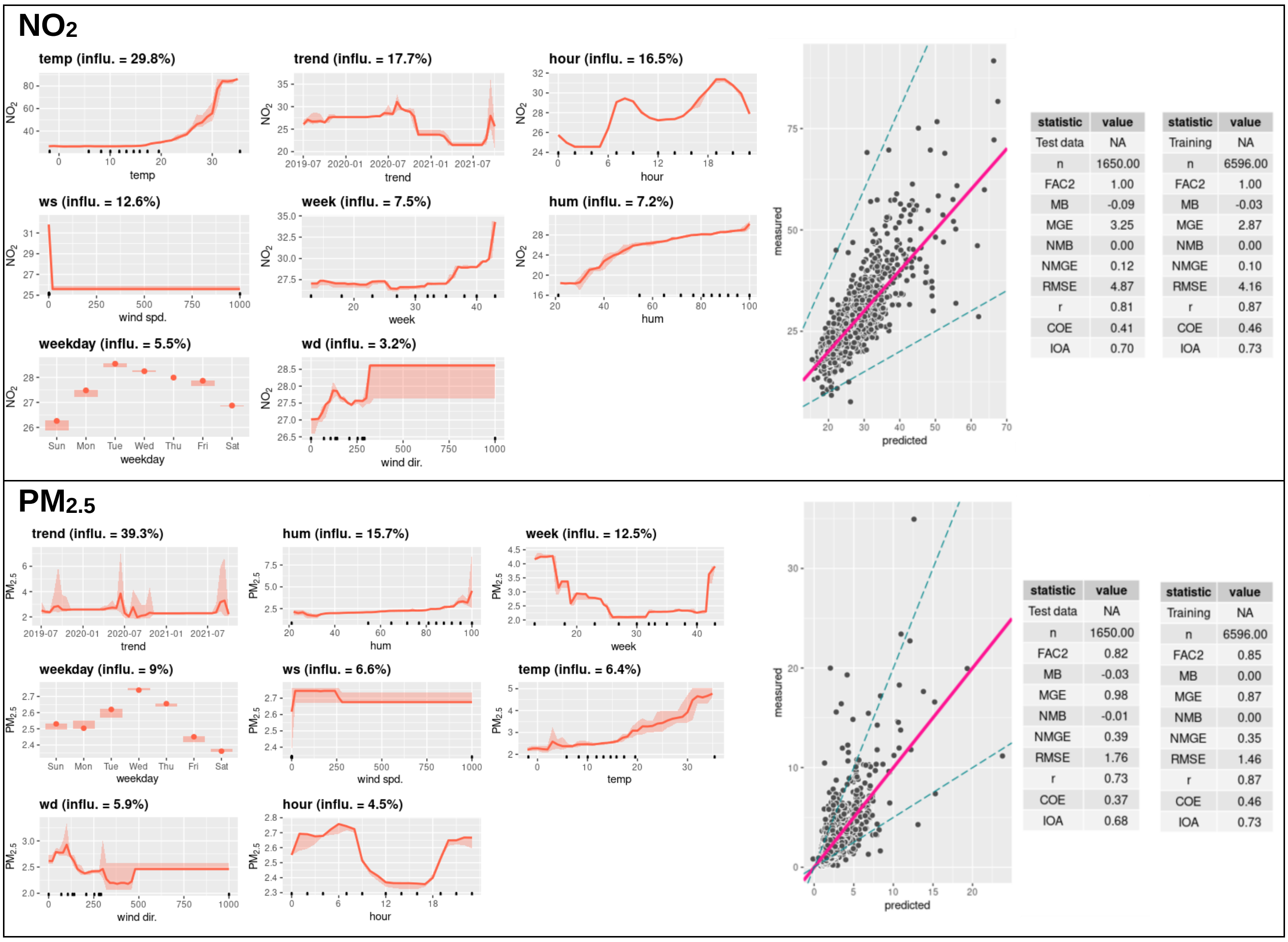

Figure S1. Model results and partial dependency of the covariates on $PM_{2.5}$ and NO_2 concentrations at Sch-GB from 2019 to 2021. Covariates: temp = temperature, hum = humidity, ws = wind speed, wd = wind direction, week = week of the year, hour = hour of the day, weekday, and trend.

A field co-location between low-cost mobile device (Aeroqual series 500) and the reference sensor MOBIUS (MOBIle Urban Sensing vehicle) from the Urban Flows Observatory, The University of Sheffield, was conducted to improve $PM_{2.5}$ data quality. The co-location lasted 11-hour in total in three separate events, and data were collected with 1-min resolution.

The measurements from the low-cost mobile device were calibrated against a reference-grade PALAS Fidas sensor built in the MOBIUS. A concentration range correction was applied based on the relationship between $PM_{2.5}$ concentration range and sensor performance. Accuracy of the low-cost monitor modelled data is shown in Figure S2.

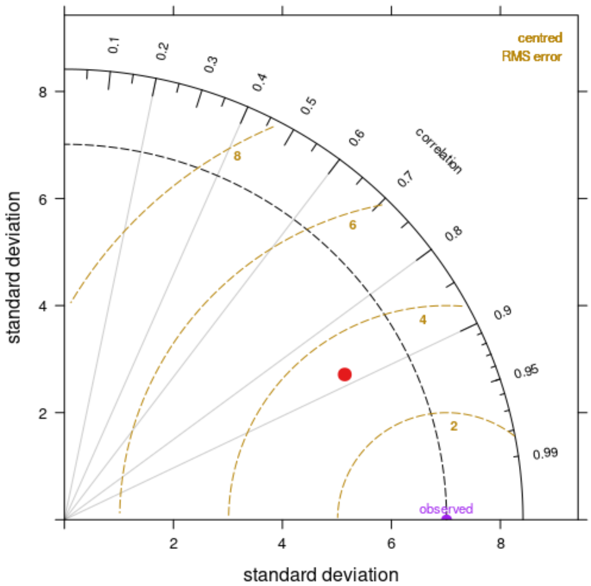

Figure S2. Taylor diagram comparing the modelled data (red dot) which is the corrected low-cost mobile device measurement to the reference data (observed). Correlation (R) - between 0.8-0.9; observed variability between 2-3 µg m^{-3} (through Standard Deviation); centred RMS error <4.

De-seasonalised data visualisations (boxplots) for each study period at all sites are presented below in figures S3 and S4.

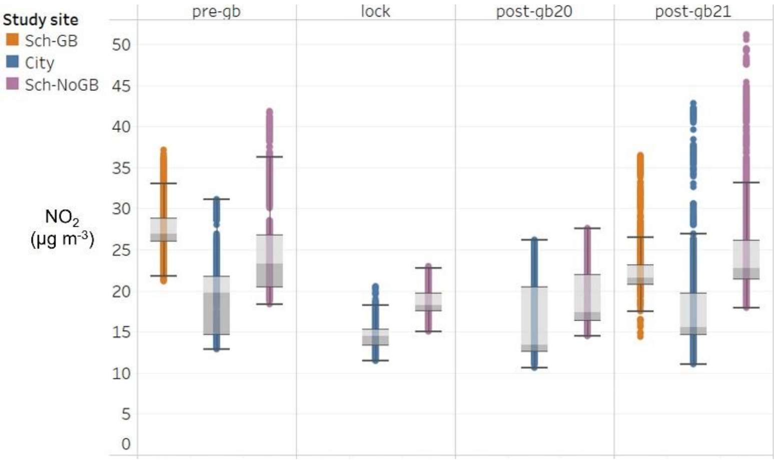

Figure S3. De-seasonalised NO_2 concentrations (µg m^{-3}) for each data collection period and study site. Colour change from light to dark grey within boxes represent the median NO_2 concentration, and whiskers extend to 1.5 the InterQuartile Range (IQR). *Figure in colour

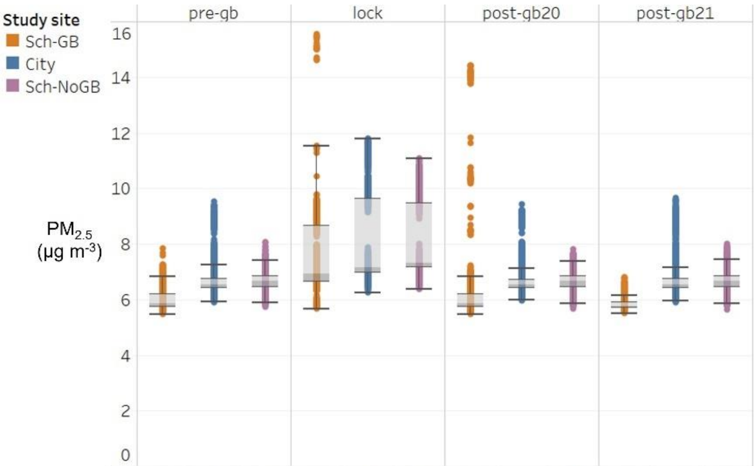

Figure S4. De-seasonalised $PM_{2.5}$ concentrations (µg m^{-3}) for each data collection period and study site. Colour change from light to dark grey within boxes represent the median $PM_{2.5}$ concentration, and whiskers extend to 1.5 the InterQuartile Range (IQR). *Figure in colour

Publication:

Redondo-Bermúdez, M.C., Gulenc, I.T., Cameron, R.W., Inkson, B.J., 2021. 'Green barriers' for air pollutant capture: Leaf micromorphology as a mechanism to explain plants capacity to capture particulate matter. Environ. Pollut. 288, 1–12. https://doi.org/10.1016/j.envpol.2021.117809

Table 1. Description of plant species characteristics at a macro scale.

Plant species	Common name	Species description
Hedera helix 'Woerner'	English ivy	Evergreen self-clinging climber. Three-lobed glossy leaves with repand margins.
Thuja occidentalis 'Smaragd'	White cedar	Evergreen conifer with a slow-growing conical shape. Tripinnate leaves with scale-like surface.
Phyllostachys nigra	Black bamboo	Evergreen bamboo with black arching canes. Ensiform leaves with entire margins.

Leaf description according to the Royal Botanic Gardens, Kew (Beentje, 2020).

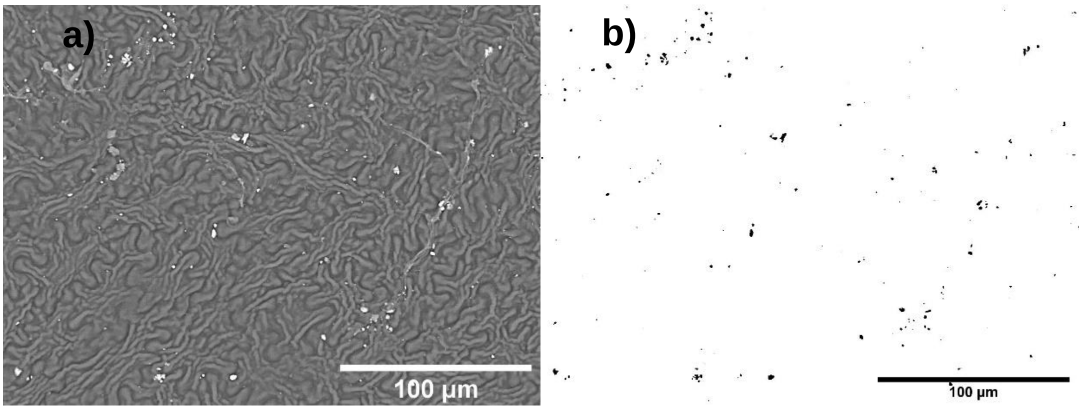

Figure 1. SEM BSE micrograph of *Hedera helix* adaxial leaf at 600x magnification, (a) original micrograph (b) after thresholding process to isolate particulate matter pollution.

References

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From Chapter IV

Publication:

Redondo-Bermúdez, M. del C., Jorgensen, A., Cameron, R.W., Val Martin, M., 2022. Green Infrastructure for Air Quality plus (GI4AQ+): defining critical dimensions for implementation in schools and the meaning of 'plus' in a UK context. Nature-Based Solut. 2, 2–13.
https://doi.org/10.1016/j.nbsj.2022.100017

Supplementary material

Sample of semi-structured interview questions

1. Name and occupation of the participant
2. What is your role/involvement in the project?
3. Why did you take part in this project?
4. Can you describe the process of the development and installation of the green barrier and the steps to come?
5. Why do you think that this project is happening now and not 5 or 10 years earlier?
6. Is the project relevant to you and/or your city?
7. Do you think that the green barrier will serve its purpose at the school?
8. What made the construction of the green barrier possible?
9. What do you think have been the strengths and positives of the project?
10. What are the challenges or barriers that you or others involved have faced during the development of the project? Can you say more about them? How were the challenges overcome?
11. Do you think that having the green barrier in the playground gives you/your children any other benefits?
12. Do you think there are any disadvantages or downsides to having the green barrier in the playground?
13. Do you think that the benefits outweigh the negatives or the other way round?
14. Have the ways that the playground is used changed since the barrier was installed?
15. Think of the last years when there was no green barrier, do you feel any different in the playground now? How?
16. Overall, do you feel satisfied or unsatisfied with the green barrier in the school playground?
17. Can you think of any positives or downsides to introducing the green barrier in the school playground for the school's or local community's economy?
18. Can you think of any positives or downsides to introducing the green barrier in the school playground for nature (plants, animal, insects)?
19. Would you change any aspect of the green barrier?
20. Would you recommend that this project be rolled out to other schools? What would be needed to roll It out?
21. Any extra comments or any experience that you want to share?

Sample of survey questions

1) What is your role in the school community?
- Staff
- Parent/carer

2) What is your gender?
- Female
- Male
- Other / Prefer not to say

3) Approximately how many years have you been a member of staff working at the school? Or, if you are a parent/carer, how many years have your children attended HBIS?
- __ number of years

4) Select the academic years that you have had children at the school or worked as staff in HBIS:
- 2016-2017
- 2017-2018
- 2018-2019
- 2019-2020

5) In October 2019, plants were introduced all along the school playground perimeter - a 'green barrier'. Do you know why it was added?
- Yes
- No

6) Please write your own understanding about why the green barrier was planted in the playground. Leave blank if you are not sure.

7) Some members of the school community were involved in the development of the green barrier. Were you involved in any of the stages of the development of the green barrier?
- Yes, I organised a fundraising event
- Yes, I attended a fundraising event
- Yes, I was in the management parent/staff team
- Yes, I facilitated services or contacts for its construction
- Yes, I made a financial or in-kind donation
- Yes, I attended a planting party
- Yes, I was involved in other ways
- No, I didn't actively participate

8) Have you told your friends or family about the transformation of the playground with the green barrier?
- Yes
- No

9)How many people have you share it with?

10) Some months ago the school playground looked different from how it looks now. Please choose the playground picture that you prefer, visually.

A	B	C
		

11)Why do you prefer this look of the playground?

12) Do you think that having a green barrier in the school playground has any particular benefits to you or to the children? Please list them here:

13) Is there anything that you don't like about the green barrier or problems associated with it?

14) Do you have any other comments you would like to add?

From Chapter V

Publication:

Redondo Bermúdez, M. del C., Kanai, J.M., Astbury, J., Fabio, V., Jorgensen, A., 2022. Green Fences for Buenos Aires: Implementing Green Infrastructure for (More than) Air Quality. Sustain. 14, 1–25. https://doi.org/10.3390/su14074129

Results from ongoing air quality monitoring in the pilot case study school are shown below in Table S1. They show monthly nitrogen dioxide concentrations inside the school in the green fence area and an unvegetated area, and outside on the adjacent street. A site plan illustrates the AQ sampling locations in Figure S1.

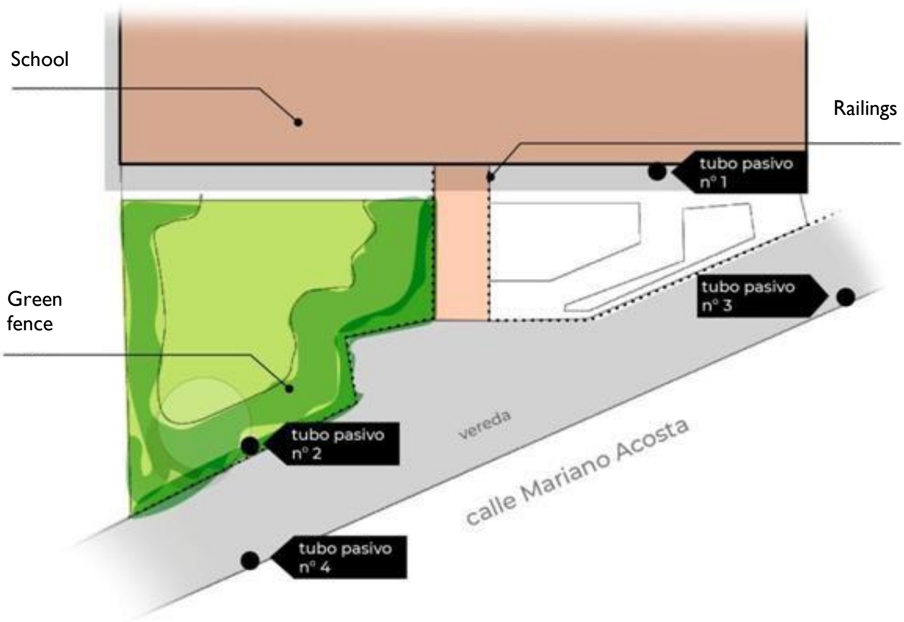

Figure S1. Location of NO_2 monitoring devices (diffusion tubes) in relation to the case study school and green fence.

Table S1. Results of monthly NO_2 concentration monitoring (diffusion tubes) in parts per billion (ppb).

Monitoring campaign	Temp (ºC)	Tube location	Average NO_2 concentrations (ppb)
1	17.9	Nº1	21
		Nº2	22
		Nº3	23
		Nº4	26
2	11.4	Nº1	21
		Nº2	22
		Nº3	33
		Nº4	24
3	9.2	Nº1	23
		Nº2	24
		Nº3	24
		Nº4	25

Supplementary material

Ethical approval

Downloaded: 06/11/2019
Approved: 31/10/2019

Maria del Carmen Redondo Bermudez
Registration number: 180229961
Landscape
Programme: Landscape (PhD/Landscape FT)

Dear Maria del Carmen

PROJECT TITLE: BREATHE: a feasibility study to air pollution mitigation in school playgrounds
APPLICATION: Reference Number 031003

On behalf of the University ethics reviewers who reviewed your project, I am pleased to inform you that on 31/10/2019 the above-named project was **approved** on ethics grounds, on the basis that you will adhere to the following documentation that you submitted for ethics review:

- University research ethics application form 031003 (form submission date: 16/10/2019); (expected project end date: 01/11/2020).
- Participant information sheet 1071287 version 2 (16/10/2019).
- Participant consent form 1071288 version 2 (16/10/2019).

The following optional amendments were suggested:

Ensure you carry a mobile phone with you at all times. The reviewers liked the visual nature of the information sheet. A comprehensive application.

If during the course of the project you need to deviate significantly from the above-approved documentation please inform me since written approval will be required.

Your responsibilities in delivering this research project are set out at the end of this letter.

Yours sincerely

Helen Woolley
Ethics Administrator
Landscape

Please note the following responsibilities of the researcher in delivering the research project:

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- The researcher is responsible for effectively managing the data collected both during and after the end of the project in line with best practice, and any relevant legislative, regulatory or contractual requirements.

Downloaded: 30/04/2020
Approved: 29/04/2020

Maria del Carmen Redondo Bermudez
Registration number: 180229961
Landscape
Programme: Landscape (PhD/Landscape FT)

Dear Maria del Carmen

PROJECT TITLE: BREATHE: a feasibility study to air pollution mitigation in school playgrounds - Social survey
APPLICATION: Reference Number 033846

On behalf of the University ethics reviewers who reviewed your project, I am pleased to inform you that on 29/04/2020 the above-named project was **approved** on ethics grounds, on the basis that you will adhere to the following documentation that you submitted for ethics review:

- University research ethics application form 033846 (form submission date: 07/04/2020); (expected project end date: 15/07/2021).
- Participant consent form 1077660 version 2 (07/04/2020).

If during the course of the project you need to deviate significantly from the above-approved documentation please inform me since written approval will be required.

Your responsibilities in delivering this research project are set out at the end of this letter.

Yours sincerely

Helen Woolley
Ethics Administrator
Landscape

Please note the following responsibilities of the researcher in delivering the research project:

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Sivadharshini Ananda Narayana
to Aldeena, me
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