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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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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.

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).

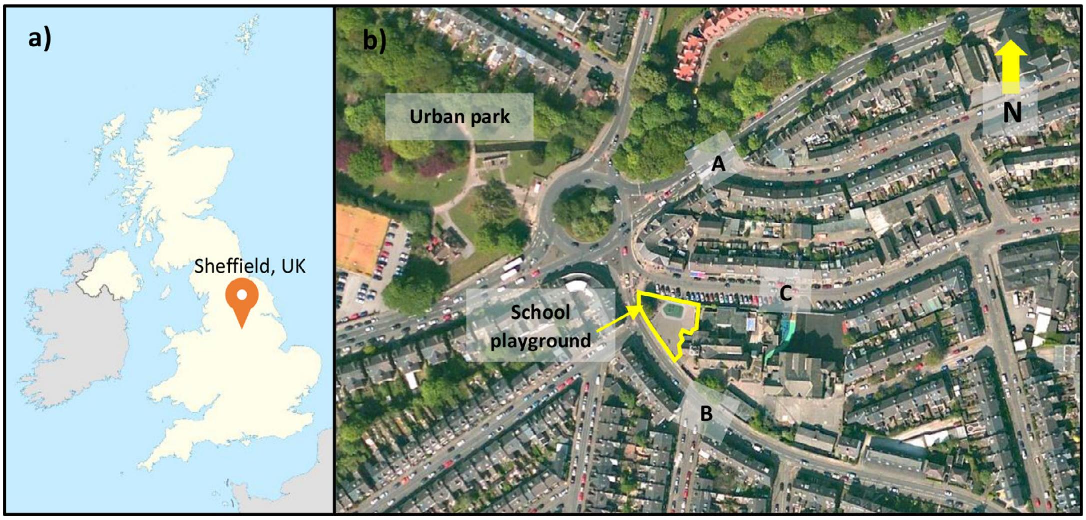

Fig. 2. School playground location (a) in the UK, and (b) in urban layout.

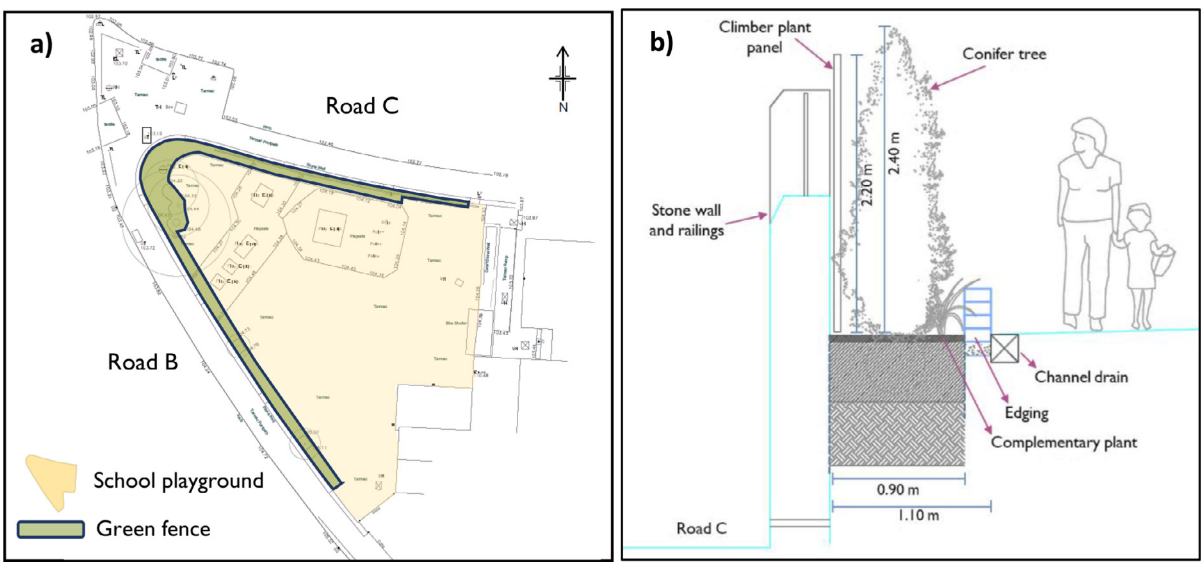

Fig. 3. Layout of (a) green fence in case study school playground, and (b)* illustrative detail of green fence section. *Modified from Urban Wilderness section drawings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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).

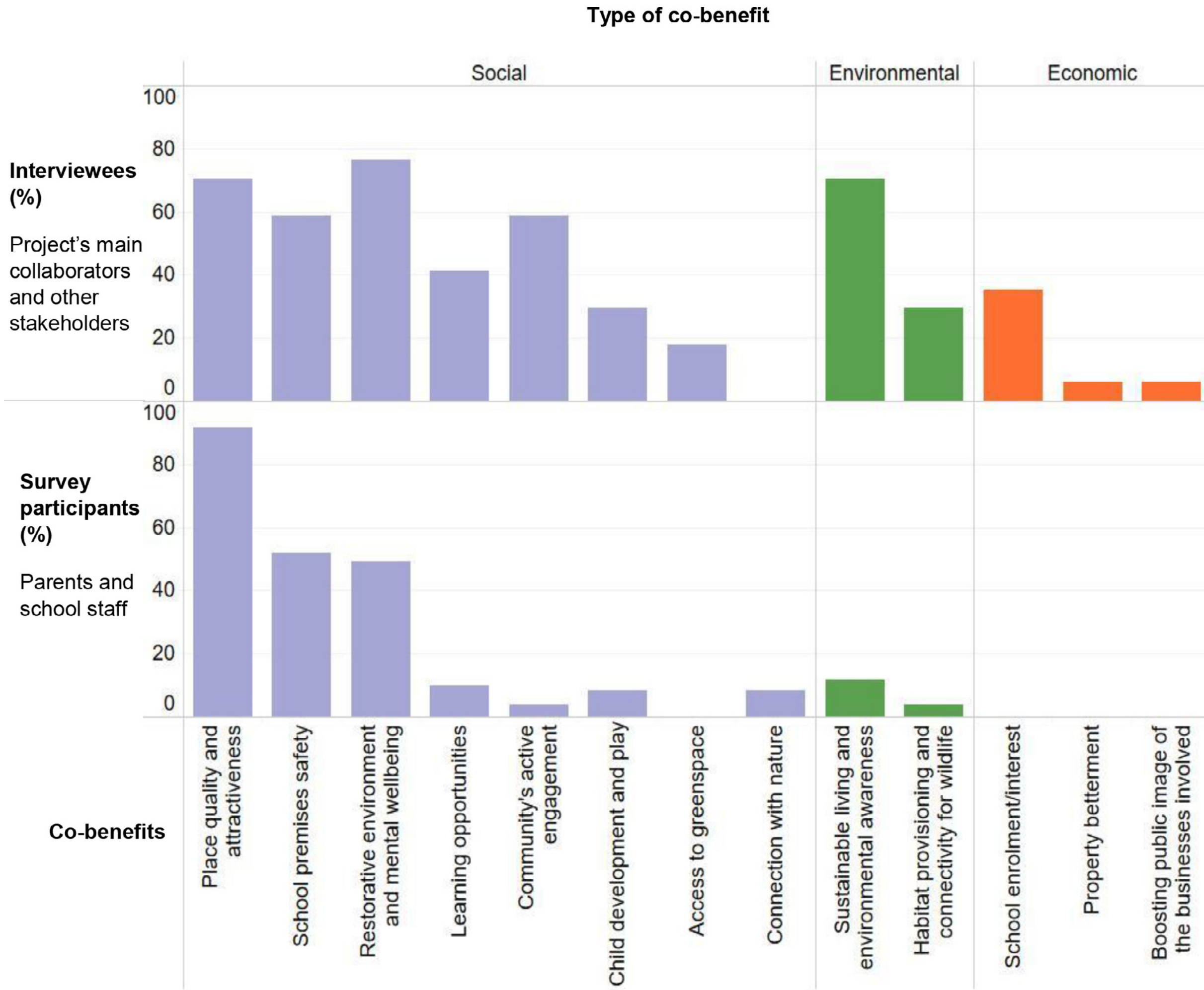

Fig. 5. Perceived co-benefits of GI4AQ+ in the case study school with the percentages of interviewees or survey participants that mentioned them. The co-benefits are depicted according to the 'tripartite model' of sustainability: social pillar, environmental pillar, and economic pillar [38,39].

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

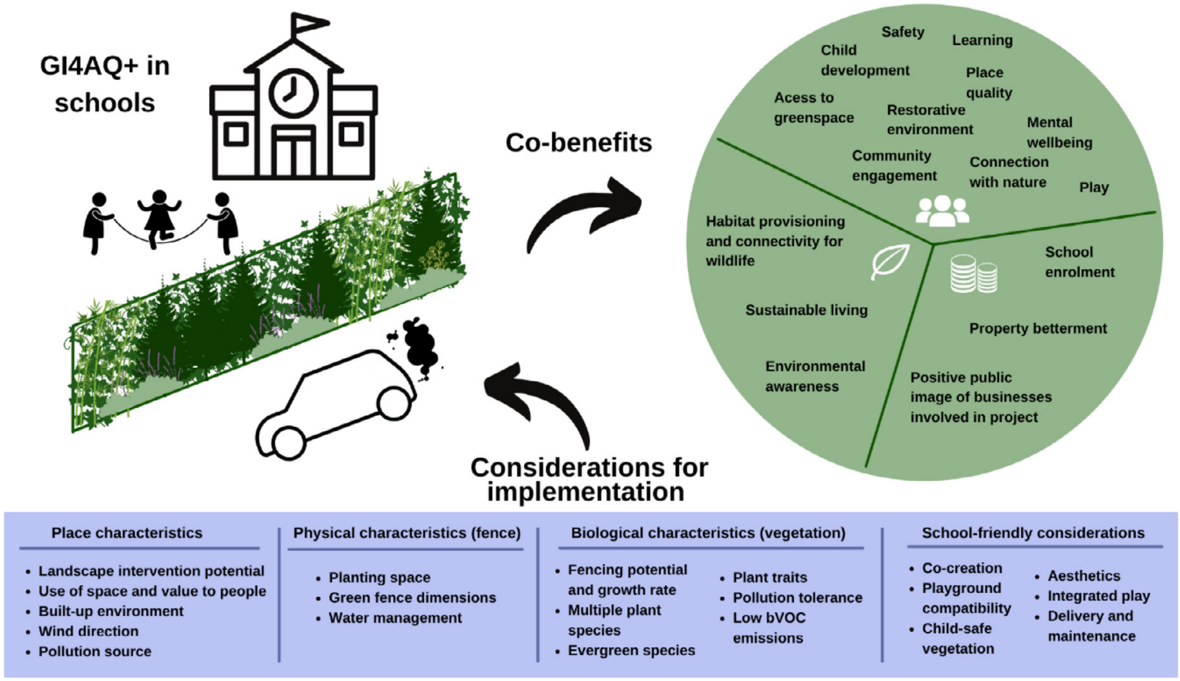

Fig. 7. GI4AQ+ dimensions for implementation in schools and their derived perceived co-benefits beyond air quality provisioning.

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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