The co-development of HedgeDATE, a public engagement and decision support tool for air pollution exposure mitigation by green infrastructure

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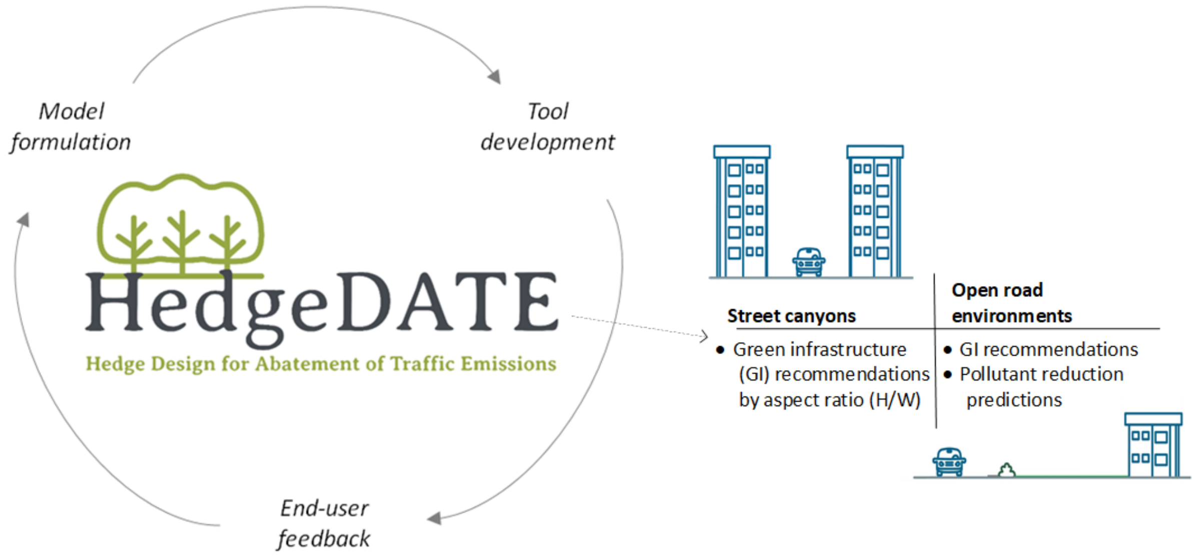
Graphical abstract



Abstract

There is a lack of clear guidance regarding the optimal configuration and plant composition of green infrastructure (GI) for improved air quality at local scale. This study aimed to co-develop (i.e. with feedback from end-users) a public engagement and decision support tool, to facilitate effective GI design and management for air pollution abatement. The underlying model uses user-directed input data (e.g. road type) to generate output recommendations (e.g. plant species) and pollution reduction projections. This model was computerised as a user-friendly tool named HedgeDATE (Hedge Design for Abatement of Traffic Emissions). A workshop generated feedback on HedgeDATE, which we also discuss. We found that data from the literature can be synthesised to predict air pollutant exposure and abatement in open road environments. However, further research is required to describe pollutant decay profiles under more diverse roadside scenarios (e.g. split-level terrain) and to strengthen projections.

Workshop findings validated the HedgeDATE concept and indicated scope for uptake. End-user feedback was generally positive, although potential improvements were identified. For HedgeDATE to be made relevant for practitioners and decision-makers, future iterations will require enhanced applicability and functionality. This work sets the foundation for the development of advanced GI design tools for reduced pollution exposure.

Keywords: Urban forestry and greening; Gardening; Land management; Passive control; Air quality; Built environment

1. Introduction

Air pollution is the most significant environmental hazard to human health, responsible for an estimated 6.5 million premature deaths annually worldwide (Landrigan et al., 2018). Poor air quality is of particular concern in urban areas, where transport emissions constitute an important source (Heal, Kumar, and Harrison, 2012; Kumar et al., 2013; Heydari et al., 2020). Traffic-related air pollution is characterised by a number of harmful pollutants, including particulate matter ≤2.5µm ($PM_{2.5}$), ultrafine particles (UFPs), nitrogen oxides (NO_x), carbon monoxide (CO), and black carbon (BC) (Patton et al., 2014; Li et al., 2016; Kumar et al., 2014). These are associated with excessive mortality and morbidity rates at global scale (World Health Organisation, 2016). In England, nearly 30% of preventable deaths are due to non-communicable diseases that are explicitly attributable to air pollution (NHS, 2019) and, in December 2020, a coroner has found for the first time that air pollution exposure was a significant contributory factor in the tragic death of a child in London (Record of Inquest, 2020). With 55% of the global human population residing in urban areas in 2018, projected to rise to 68% by 2050, the abatement of traffic emission exposure in urban areas is crucial (United Nations, 2018).

Targeted green infrastructure (GI; e.g. trees, hedges, green walls, green roofs) can form a cost-effective passive control system for air pollution (Abhijith et al., 2017; Hewitt, Ashworth, and MacKenzie, 2019; Tomson et al. 2021), particularly during peak times such as ‘rush hours’ or where concentrations occasionally exceed background levels (Riondato et al., 2020). This is primarily ascribable to the propensity of GI to remove, redirect and reduce air pollutants through the processes of dry deposition and atmospheric dispersion (Janhäll, 2015). GI is considered to be more effective for PM deposition than grey or non-porous infrastructure due to its comparatively high surface area, and due to biochemical interactions between healthy vegetation and the ambient air (for the removal of UFPs and gaseous pollutants) (Janhäll, 2015; Tiwari et al., 2019). For dispersion, GI can act as a physical obstacle affecting air flows (Abhijith and Kumar, 2019), thereby influencing the concentration and transportation of ambient pollutants (Tiwari et al., 2019; Tiwari and Kumar, 2020).

At local scale, vegetation barriers (trees, hedges or tree-hedge combinations) between traffic emissions and pedestrians or properties have been found to be effective (Abhijith and Kumar, 2019; Gallagher et al., 2015; Ottosen and Kumar, 2020). Such barriers effectively extend the path-length of the pollutant plume between source and receptor, reducing downwind concentrations and encouraging dilution via turbulence (Baldauf, 2017; Hewitt et al., 2019; Kumar et al., 2019). Air pollution dispersion often results in exponential reductions in concentrations as pollutants move away from their source, and thus the impact of extending this path-length by even 1m can be significant. Moreover, results from a remote sensing investigation suggest that roadside hedges can be implemented with minimal necessary alterations to existing UK urban infrastructure (Irfan et al., 2018). This highlights the potential impact of urban hedges as a passive control system proximate to pollutant sources, to reduce exposure in near-road environments such as private gardens, public spaces, and school and hospital grounds.

Beyond complementary ecosystem services, the use of vegetation, rather than solid or non-porous barriers, facilitates greater deposition, which may be further enhanced by appropriate plant choice and other elements of barrier design, including barrier porosity (a function of width and vegetation density) and dimensions (Barwise and Kumar, 2020; Chaudhary and Rathore, 2019). However, effective vegetation barrier design is highly contextual, with the relative significance of different plant-specific considerations (e.g. biogenic volatile organic compound (bVOC) emissions, pollen emissions, morphological characteristics) being variable according to each immediate environment as well as the spatial scale of the intervention (Barwise and Kumar, 2020; Hewitt et al., 2019). For example, plants with significant bVOC emissions, which are precursors of ground-level ozone, are primarily unsuitable for large-scale projects or where NO_x concentrations and sunlight levels are typically high; the significance of pollen emissions depends on site-specific factors, including proximity to vulnerable populations; and tall vegetation barriers are generally recommended in open road environments but can impede pollutant dispersion in some urban street canyons (Barwise and Kumar, 2020).

Cities across the world have set ambitious tree planting targets for the enhanced provision of ecosystem services including air pollution abatement. However, this assumption requires the right plant in the right place, and GI design is nuanced, with net positive or negative impacts on air quality depending on plant selection, configuration, and post-planting management (Barwise and Kumar, 2020; Hewitt et al., 2019; Tomson et al., 2021). Knowledge on interactions between vegetation and air quality is not sufficiently applied in urban planning processes (Badach et al., 2020), and there is a need for guidance that delineates context-specific design principles for effective vegetation barrier implementation (Barwise and Kumar, 2020; Kumar et al., 2019; Ortolani and Vitale, 2016). Despite the apparent increase in relevant resources over recent years (see Supplementary Information (SI) Table S1), such resources to date have provided generic recommendations, which may lead to inappropriate or, in some cases, detrimental GI design under specific circumstances (Abhijith et al., 2017; Barwise and Kumar, 2020; Isakov et al., 2018). This underlines the importance of applications and tools that can assist people in making data-informed decisions based on real-world scenarios, which are clearly needed but currently unavailable. The novelty and primary scientific contribution of the present study lies in its objective to address this problem; i.e. to contribute to the development of tools that facilitate appropriate decision-making for improved air quality at local scale.

We co-designed and co-developed a decision support tool (HedgeDATE: Hedge Design for the Abatement of Traffic Emissions) with potential end-users (Section 2.3). This prototype offers site-specific recommendations regarding GI design for air pollution abatement and comprises a template upon which future work may build. The tool also serves as a mechanism for public engagement on air pollution, the advantages of which include the potential for collaborative innovation, improved public knowledge and trust, and expedited implementation of research findings in practice (Cohen et al., 2008; Mahajan et al., 2020).

HedgeDATE is initially intended for the general public, as an engagement and educational resource. However, it may be refined in future iterations to offer more comprehensive guidance for practitioners and policy-makers. The prototype discussed in this paper focuses on plant species selection and pollutant exposure reduction in open road and street canyon environments but does not model individual scenarios in detail (Sections 2 and 2.1). Thus, the aims of this paper are to: present the development process of the HedgeDATE tool; present and discuss results from a public demonstration and workshop, which generated feedback from end-users on the interface, utility and potential uptake of the tool; describe prospects for further development; and provide recommendations for relevant research.

2. Methodology

A series of public engagement events were held via the Guildford Living Lab platform (GLL, 2016; Mahajan et al., 2020). These events highlighted a popular desire among attendees for straightforward and engaging guidance on plant selection and management for reduced air pollution exposure. HedgeDATE was conceptualised in 2018 to meet this demand, and a project to develop it was later formalised by the University of Surrey's Urban Living Award (ULA, 2019). Initial decisions regarding the concept included that the prototype would be presented as a web-based application whose logic and content would be developed from findings from the existing scientific literature, with a long-term ambition to refine said prototype via bespoke research. This application would generate projections and recommendations as outputs according to user-directed input data (Figure 1). For the prototype, such outputs would be specific to the user's urban context (street canyon (and type of street canyon) vs open road) and physical environment (e.g. distance to road), but not to their individual scenario in terms of meteorology, elevation, soil type and quality, etc. The prototype would finally be subject to end-user feedback as part of the validation process. This study's methodology is therefore categorised below as that which concerns the formulation of the underlying model (Section 2.1), the formulation of the web-based tool (Section 2.2), and the feedback on the tool (Section 2.3).

2.1. Model Formulation

From the landing page, the underlying model begins by establishing the urban context that best describes the user's area of concern (AoC; e.g. the user's home), as shown in Figure 2a. If the user selects the 'Street canyon' button, they are taken to a page that estimates the aspect ratio of their street canyon (SI Figure S1), and from there to a relevant page that contains generic recommendations (Section 2.2.1) regarding GI design according to the indicated street canyon type (SI Figures S2-S4). Users that select the 'Open road' button are instead taken to a page that contains an expanded image of the open road environment, along with a series of input boxes (Figure 2b). This area of the tool requires input data on four parameters: width of road; distance between road edge (pollutant source) and planting site; width of available planting space (perpendicular to road direction); and distance between planting site and AoC. The model then uses this input data to generate a predicted percentage reduction in pollutant concentration as compared to a GI-free scenario and as a result of the optimal GI intervention (Figure 2c). Section 3.1 discusses the formulation of this section of the model (i.e. the 'Model calculations' as indicated in Figure 1) in detail, which is intertwined with outcomes of the model formulation process.

2.2. Tool formulation

2.2.1. User interface, content and recommendations

The model is presented as a web-based application, which utilises user-directed input data to generate output projections and recommendations (Sections 2.1 and 3.1). For clarity and ease of use, the tool includes images wherever possible and offers the user choices as simple buttons beneath the images (Section 2.2.2). Generic recommendations and links to further information on, for example, plant management (SI Figure S6), are provided at various end-points of the model. Content regarding street canyon environments was drawn and summarised from Kumar et al. (2019) and GLA (2019) (street canyon classification by aspect ratio) and Abhijith et al. (2017) (flow characterisation and GI implementation). Recommendations for street canyons are minimal (SI Figures S2-S4) for several reasons: (i) because reliable, specific recommendations regarding GI in street canyons may not be made without pilot modelling studies due to unpredictable influences of complex canyon geometry on air flows (Abhijith et al., 2017); (ii) because trees, hedges and vegetation barriers are generally not recommended in street canyons in any case; (iii) because the majority of viable planting space exists in open road environments; and (iv) because GI implementation in street canyons typically requires backing by businesses and/or local authorities, rather than the sole permissions of members of the public at which the prototype is aimed. General recommendations regarding GI for transport-related pollution exposure mitigation in open road environments are summarised by Table 1.

Although some site-specific factors are noted, Table 1 includes factors and recommendations explicitly regarding air pollution exposure reduction. Table 1 does not include other management considerations, such as road safety and additional ecosystem services (e.g. carbon sequestration, biodiversity) or disservices (e.g. invasiveness, toxicity), although such considerations are highlighted at relevant points in the HedgeDATE tool.

A minimum height of 2m is recommended because this height offers exposure reduction for roughly a few metres beyond the barrier, but greater height is necessary with greater distances from the road as well as with greater distances of the AoC from the barrier (GLL, 2019). Recommended plant species (SI Table S2) were extracted from Hirons and Sjöman (2018) for two reasons: (i) the source was created by investigating species that are currently used in temperate urban forestry, as well as species whose ecoregion is similar in constraints to those of typical urban planting environments; and (ii) it contains internally consistent, species-specific information on several factors that are significant in air pollution mitigation (Barwise and Kumar, 2020). Species were selected for inclusion if they had demonstrated suitability for hedging in the UK or some tolerance of air pollution and/or salt. Species known to be high emitters of bVOCs were excluded in order to avoid recommending such species for hedging at large scales or at many different sites within a neighbourhood, due to the minimal range of species included in the prototype. A caveat regarding the importance of site-specific species selection (e.g. considering environmental conditions) was also added as a pop-up box to the tool (SI Figure S6).

2.2.2. Technical description

The HedgeDATE application was developed using NetBeans 8.1 (https://netbeans.org/downloads/old/8.0/), which uses the Apache server (https://www.apachefriends.org/download.html), and requires JDK 1.8.0 (https://www.java.com/en/download/) or a later version to run the encoded model formulation (Section 3.1). The model formulation is encoded into the University of Surrey's server using PHP and HTML languages. PHP is an open-source scripting language, which was used to create dynamic contents of the application, such as input values, a counter for number of visitors, and output results. HTML was used as a markup language that helps users to move around on the different landing pages by clicking on hyperlinks. The HedgeDATE tool's web link (https://hedgedate.eps.surrey.ac.uk/HedgeDATELandingPage.php) directs users to the main landing page, which presents a brief description of the tool and number of visitors (users) to date, and allows the user to navigate to other pages as mentioned in Section 2.1. Users whose AoC embodies an open road environment enter their input values (Figure 2b), and the relevant calculations are performed on the server-side based on the formulation encoded in PHP. Results (exposure projections and GI recommendations) are thereby instantaneously provided using the HTML-encoded markup page on the user browser (Figure 2c). The authors chose the above-mentioned server and encoding languages because they are available as open source and commonly used in web development and in many successful web tools.

2.3. Feedback on the tool

Following a series of informal, internal verification procedures (e.g. repeated runs on different systems to verify consistent input-output results), we sought independent feedback on the HedgeDATE prototype from prospective end-users. A public workshop was held in July 2019 at the University of Surrey, lasting approximately two hours. A brief presentation on urban air pollution was followed by an introduction to the HedgeDATE concept. Participants (Section 2.3.1) were then split into three randomly mixed focus groups of roughly equal numbers, including one facilitator per group. A facilitator demonstrated the tool to each group and supported each participant to use the tool. Each focus group was asked to discuss two questions: (Q1) 'What are the limitations or drawbacks of the HedgeDATE tool?'; and (Q2) 'What additional content or functions would you include?'

Significant points from the group discussions were noted by each group for later analysis (Section 3.2). A rapporteur also worked between all groups and noted individual opinions and statements on an ad hoc basis. After discussions and feedback from each group, a questionnaire (SI Section S2) was completed by each individual participant.

2.3.1. Participant profile

The target population for the workshop comprised intended end-users of HedgeDATE (i.e. the general public, as discussed in Section 1). The workshop was advertised in the local community (Guildford and surrounding areas, UK) via social media channels, posters, newsletters from the University of Surrey and partners, and direct correspondence with local community groups via the Guildford Living Lab (GLL, 2016). Ethical approval was sought, and consent forms were completed by all workshop participants (*n* = 14). As the data from the completed questionnaires (SI Table S3) indicates, this sample included participants of different age groups, ranging from '26-35' (50%) to 'Over 65' (14%). 43% of the participants were male, and 57% were female. 79% did not have an employment or educational background involving plants, plant health, plant management, or green space management. The highest level of completed formal education among participants ranged from 'Further education (pre-university)' (one participant) to 'Undergraduate' (four participants) and 'Postgraduate' (nine participants, including two participants that had ticked the 'Other' box and specified "PhD" in the adjacent space). The majority of participants were university-educated, which may be seen as a limitation of the sample used in our study. There were several other commonalities between participants, including that all but one participant owned or had access to a garden. However, motivation for attending was found to vary between participants (Section 3.3.1).

2.3.2. Materials

The primary aim of the workshop was to collect feedback from potential users on the utility, functionality, and interface of the prototype. The focus group questions (Section 2.3) were designed to collect qualitative data on these three factors for thematic analysis. The questionnaire that followed the group sessions (SI Section S2) was also designed to address these factors and collect related open-response (qualitative) and rating scale (quantitative) data. However, an additional aim of the workshop was to refine the questionnaire for future implementation (Section 5). Therefore, the workshop was also an opportunity to pilot test the questionnaire.

The questionnaire (SI Section S2) contained 14 questions, which combined to serve the overall objective; i.e. to indicate participant behaviour and the likelihood of uptake by HedgeDATE users, as discussed in Section 1. Initial questions requested information on each participant's background and motivation, in order to understand the participant profile (Section 2.3.1). This included participants' age range, gender, employment status, highest level of education, knowledge of green infrastructure or greening, ownership of or access to relevant garden space, how they knew of the workshop, and their reason for involvement.

Quantitative data was obtained via several Likert scales embedded in the questionnaire. Following the Theory of Planned Behaviour (Ajzen, 1991), we examined participants' attitudes, social norms (perceived social approval), and perceived behavioural control regarding gardening or greening and air pollution issues. We asked participants to rate different statements on a scale of agreement from 1 (strongly disagree) to 5 (strongly agree). Such statements included: 'My neighbours enjoy gardening'; 'I do not enjoy gardening'; 'My friends and family are concerned about air pollution'; and 'I know how to limit my contribution to air pollution'. However, as the focus of this paper is the viability of the HedgeDATE prototype (rather than related, broader themes), we will primarily present and discuss results pertinent to this focus. Another question constituted an individual evaluation of the prototype explicitly, with four targeted statements for participants to rate their agreement with (on the same 1-5 scale), such as: 'The layout and images in the prototype are generally clear'. Similarly, to assess behavioural intention and willingness to pay regarding the prototype and related concepts, participants were asked to rate their agreement with each statement on a scale of 1 (definitely will not do this) to 5 (definitely will do this). Statements included, for example: 'Alter your garden to improve your local air quality'; 'Use the HedgeDATE tool'; and 'Recommend the HedgeDATE tool to others'.

Finally, participants were asked whether or not they were aware of any similar tools, resources, or apps, with adjacent space for further information if 'yes'. This question was intended to investigate the novelty of the tool and lend an understanding of the scope for uptake.

3. Results and discussion

3.1. Model formulation and outcomes

As mentioned in Section 2.1, HedgeDATE follows a process of establishing the user's AoC and thereby providing targeted recommendations regarding GI. Users whose AoC comprises a street canyon environment are directed to recommendations categorised by canyon aspect ratio, for reasons outlined in Section 2.2. For open road environments, users are additionally provided with a predicted percentage reduction (*PPR*) in pollutant concentration at their AoC if GI is implemented and managed as recommended. The model estimates this *PPR* using Eq. (1).

$$PPR\ (\%) = \left(\frac{C_{NoGI} - C_{WGI}}{C_{WGI}}\right) \times 100 \qquad (1)$$

Where *PPR* is predicted percentage reduction (-), C_{NoGI} is pollutant concentration (µg/m^3) at AoC in the absence of GI, and C_{WGI} is pollutant concentration (µg/m^3) at AoC in the presence of GI. However, spatial pollutant concentration gradients near roadways depend on many factors, such as traffic volume, meteorological conditions, and pollutant type. The presence of GI near roadways can make estimations of such gradients even more complex (Tiwari et al., 2019). Advanced approaches (Baldwin et al., 2015; Chang et al., 2015; Richmond-Bryant et al., 2018) for characterising pollutant concentration gradients near roadways require detailed input inventories and expertise in using dispersion models. Therefore, to minimise user input (as shown in Figure 2b), we used the exponential function described in Eq. (2) to predict the pollutant concentration (C_{NoGI}) at specific distances from the roadway (Nayeb Yazdi, Delavarrafiee, and Arhami, 2015; Richmond-Bryant et al., 2018; Richmond-Bryant et al., 2017).

$$C_{NoGI} = C_b + C_0 e^{(-d \times x)} \quad (2)$$

After mixing, pollutant concentrations reach a constant value that is also known as the background concentration (C_b). C_0 represents pollutant concentration on the traffic lane, *d* is rate of decay, and *x* is distance from the roadway at which C_{NoGI} is estimated. The effect of GI presence on the pollutant decay profile is included in HedgeDATE by a GI reduction factor ($\alpha e^{-\beta \times LAD}$) as a function of the LAD (leaf area density; m^2/m^3) of GI. Here, we have assumed that the concentration decay profile before and after the GI intervention will remain the same (Figure 3). If the distances from source to GI and GI to AoC are *y* and *z*, respectively, then the pollutant concentration would reduce to ($C_b + C_0\, e^{(-d \times y)}$) before passing through the hedge, at which point it would further decrease by a reduction factor ($\alpha e^{-\beta \times LAD}$) due to the presence of GI. This reduced pollutant concentration (($C_0\, e^{(-d \times y)}$) $\times$ ($\alpha e^{-\beta \times LAD}$)) would then be subject to further pollutant decay until it reaches the background concentration. Thus, the pollutant concentration at AoC with the presence of GI (C_{WGI}) is estimated by Eq. (3).

$$C_{WGI} = \left(\left(C_0 e^{(-d\times y)}\right) \times \left(\alpha e^{-\beta\times LAD}\right) \times e^{-d\times z}\right) + C_b \tag{3}$$

where α and β are factors that depend on pollutant type and interaction between pollutant and plant species (-), y is the distance (m) between source and GI location, and z is the distance (m) between GI location and AoC. After incorporating Eq. (2) and Eq. (3) in Eq. (1), the predicted percentage reduction (PPR) can be written as follows (Eq. (4)).

$$PPR = \left(1 - \frac{\left(\left(\left(C_o e^{(-d\times y)}\right)\times\left(\alpha e^{-\beta\times LAD}\right)\times e^{(-d\times z)}\right)+C_b\right)}{C_b + C_o e^{(-d\times x)}}\right)\times 100 \tag{4}$$

It is worth noting that the values of C_0, C_b, d, α and β vary from site to site, according to pollutant type, traffic characteristics, and the immediate physical environment (Table 2). In the HedgeDATE prototype, we adopted CO as a proxy for the decay profile of other pollutants because it is inert and can avoid the effect of change in pollutant concentration due to atmospheric chemical reactions (Kumar et al., 2019). However, by adopting relevant values for the above parameters for different pollutants from Table 2, or from relevant sources elsewhere, similar estimates can be made for other pollutants to expand the capability of the tool in future. Thus, we have used C_b = 0.51 μg/m^3, C_0 = 4.28 μg/m^3, and d = 0.04 /m, based on measurements and a best-fitting exponential decay curve (R^2 = 0.99; here R^2 is the Goodness of Fit for an exponential decay profile, where R^2 = 1 indicates a perfect fit of the regression model to the data) from a study by Nayeb Yazdi et al. (2015). The authors of this study measured CO and PM near a busy highway in Tehran (Iran), on flat terrain and where the effects of buildings, GI and other emission sources on pollutant decay were negligible (Nayeb Yazdi et al., 2015). Nayeb Yazdi et al. (2015) also validated the exponential decay profile results with the operational CALINE4 dispersion model, which requires traffic volume, meteorological parameters, surface roughness, background concentration, and emission factors to predict pollutant decay profile. The GI-induced reduction factors that we used (α = 1.29 and β = 0.105; SI Figure S7) were estimated from a CFD study by (Ghasemian et al., 2017) for inert gas, which is similar to CO in terms of dispersion characteristics. In this study, the normalised average pollutant concentration reduction with a GI barrier on a flat terrain was simulated under various LADs (Ghasemian et al., 2017). The reduction factors are therefore only valid where the GI intervention is taken to be a hedge of at least 2m in height, beginning at ground level, and consisting of species that exhibit the necessary LAD according to the barrier width (width of available planting space, which is limited to 2m in HedgeDATE to represent the practical constraints of a solitary hedge). We have encoded a LAD range of 1.5 to 5 m^2/m^3 (based on an exponential function derived from Ghasemian et al. (2017), as illustrated in SI Figure S7), where values from 1.5 to 2.5 entail a negative result (signalling 'insufficient width of hedge' to the user, and not progressing to plant species options) and from 2.5 to 5 entail a positive result (with plant species options offered to the user). Figure 4 illustrates that LAD and barrier width (width of hedge) are the most significant parameters in terms of impacts on PPR, when compared with the other, site-specific parameters, such as width of road, width of footpath, and distance between hedge and receptor (AoC). The length of the hedge is assumed to be absolute, and so scenarios with shorter planting spaces (i.e. where the length of the user's hedge does not surround or completely shield their AoC) may be subject to unaccounted impacts of flow around each end of the hedge or in gaps. This point was highlighted during the workshop (see Representation under Section 3.2.1).

Changes in pollutant concentrations due to the presence of GI depend on many different GI characteristics, including physiological traits that influence deposition, such as leaf micromorphology (Barwise and Kumar, 2020). However, in the present tool, we have primarily focused on GI-induced aerodynamic effects, whereby spatial pollutant concentration distributions are altered due to physical characteristics of GI (e.g. configuration, width, height, LAD). These parameters influence local turbulence and pollutant dispersion patterns, which are dominant mechanisms of concentration change when compared to deposition effects induced by a single hedge near a roadway (Tiwari et al., 2019).

The *PPR* is therefore valid under the following assumptions: (i) the pollutant concentration decay profile is applicable from traffic lanes and across level ground or an even terrain; (ii) the effect of wind speed and direction is not considered in the decay profile; (iii) the modelled pollutant is a non-reactive tracer; (iv) there is no change in the pollutant concentration decay profile before and after the GI location; (v) the traffic volume is an average annual daily flow, with no seasonal and daily variation; and (vi) deposition is independent of leaf characteristics and type of pollutant.

For practicality, we elected to streamline the production of this rudimentary prototype, which may be adjusted and refined over time, rather than strive for a holistic model at the outset. This necessitated a number of acknowledged limitations. For example, the *PPR* may be overestimated where available planting space does not extend across the entire boundary length (parallel to road) of the AoC. Limitations of the prototype are addressed in subsequent iterations of HedgeDATE, as discussed in Section 3.5.

3.2. Focus group results

We isolated verbatim responses from the workshop posters according to their relevance to Q1 or Q2 (Section 2.3). Any additional responses were not included in the following analysis. The rapporteur's notes were consulted where there was any ambiguity in meaning.

3.2.1. Q1: What are the limitations or drawbacks of the HedgeDATE tool?

Themes were identified by deductive reasoning, following two well-established methods of theme identification: (i) repetition, where words or phrases were consistently mentioned; and (ii) indigenous categorisation, where we identified words or phrases specific to the situation (Ryan and Bernard, 2003). Four themes were identified during the analysis of responses to this question: education; language; presentation; and representation.

Education: We defined this theme as: Phrases related to mechanisms or content, either existing or suggested, that convey educational information or guidance regarding plant species, air pollution, land management, or any other concept-specific topic. Due to technical difficulties, plant species recommendations were not available on the day of the workshop. Participants indicated that the HedgeDATE prototype would have limited utility without this educational aspect. One group encapsulated their discussion on this point by noting, "What species?"

Language: We defined this theme as: Phrases related to language used by the prototype, including word choice, phrasing, and grammar. Participants noted that the content of the tool was too verbose and recommended that we "avoid long paragraphs." It was suggested that the language should be more specific, including instructions such as "where in the road the measurements should be taken from (edge? centre?)." There was also a voiced preference for the prototype to use British English rather than American English (i.e. 'metre' rather than 'meter'; Figure 2b).

Presentation: We defined this theme as: Phrases related to the clarity, formatting, or style of the interface, including ease of use. All three groups noted that elements of presentation were limitations or drawbacks of the prototype. For example, the user instructions, images, and the links between the two should be clearer, particularly in terms of where to click to progress through the application. Some participants also suggested that a mobile application for smartphones would be easier to use and of greater utility.

Representation: We defined this theme as: Phrases related to the verisimilitude of the prototype's interface content, including images and scenarios. Participants highlighted that image elements (such as a hedge or a car) were not internally consistent in terms of scale. It was also suggested that the "diagram should accurately depict the numbers entered into the form"; i.e. that the relative dimensions of the four parameters on the open road input screen (Figure 2b), for example, should appear to reflect the user's input data. Furthermore, participants noted that the length of the hedge, which is treated by the model as absolute (Section 3.1), should be explicitly discussed with relevant guidance.

3.2.2. Q2: What additional content or functions would you include?

Using the same methods as for Q1 (Section 3.2.1), five themes were identified during the analysis of responses to this question: education; presentation; input functionality; visualisation; and context. Education and presentation were recurring themes from Q1.

Education: All groups indicated that additional educational content would be advantageous. Participants suggested a video introduction at the start of the tool, to welcome users and briefly explain the concept. It was also suggested that references and links to relevant guidance documents, reports or publications should be provided at appropriate points. Similarly, participants asked for "photos of case studies," to demonstrate the impact of GI implementation. One group suggested guidance-related additional content or functions regarding: the impacts of climate change on recommended GI; the "carbon footprint" of recommended GI; novel plant species; the cost, management, maintenance and other pertinent aspects of each species; and gardening considerations.

Presentation: Participants suggested several potential improvements to the prototype's presentation, including: colour formatting of image elements to distinguish 'positive' elements ("hedges/trees – bright green in colour") from 'negative' elements ("cars in red"); the use of photographs, either to supplement or replace existing figures, to demonstrate differences between street canyons with divergent aspect ratios; and the use of pop-up images where relevant, such as to show a bird's eye perspective of air flows (see *Visualisation*, below).

Input functionality: We defined this theme as: Phrases related to the functionality of selectable or editable items, either existing or suggested, including icons, buttons, and text entry boxes or fields. Participants suggested that HedgeDATE should include "adjustable bars" rather than text entry boxes (see Figure 2b) and that it should offer a "comment box" or boxes where appropriate.

Visualisation: We defined this theme as: Phrases related to mechanisms or content, either existing or suggested, that support the user's visualisation of a process, scenario, GI intervention or impact. One group suggested that the user should be able to "see the results instantly;" i.e. that the potential impact of an intervention (or lack thereof) should be evident as the user makes changes to input data, rather than the results of all combined input data be presented on a separate 'output screen' (Figure 2c). This group also suggested: the use of three-dimensional figures; a more explicit indication of wind direction in figures; and an indication of the personal "Exposure height" of any pedestrians, which may offer an opportunity to highlight that children are typically exposed to higher concentrations near roadsides due to lower breathing heights. Another group suggested that "photos of case studies" (see *Education*, above), if included, should illustrate scenarios "before & after" GI implementation.

Context: We defined this theme as: Phrases related to mechanisms or content, either existing or suggested, that are intended to reflect the regional or local spatial context of different users. Participants suggested that HedgeDATE should include a broader range of scenarios, to reflect instances where the building, GI and adjacent road are not on level terrain, and that citizen science may be utilised to inform future iterations of the model in this respect. One group suggested that the focus of HedgeDATE "should be city & town centre urban environments (not leafy suburban or open park areas).” This group also suggested that HedgeDATE should take local traffic hotspots or road layouts into consideration.

3.3. Questionnaire results

3.3.1. Participants’ individual backgrounds, interests and qualitative feedback

As mentioned, initial questions were intended to gather information on the participant profile (Section 2.3.1). Most participants had learned of the workshop via social media or email . A variety of reasons were given for attending, although an interest in GI and/or air pollution was a dominant factor. Several participants also indicated that concern for their family’s health influenced their participation: “I live in the town centre and my children attend [*redacted*] Primary School. I would love to improve the air quality & increase the level of greenery at school & locally.” Only one participant indicated that their motivation for attending was to “find out more about the HedgeDATE project.” All 13 participants indicated that they were not aware of any similar tools, resources or applications.

When offered to provide any additional comments, seven participants spontaneously provided positive feedback. Comments were unanimously positive about the event and about the HedgeDATE prototype or concept: “An extremely informative workshop. Thank you for taking the time to inform us, and creating a tool that will make a huge difference to many lives. I would happily have a sensor in my garden to help, and definitely plan to use the app.” One participant used this ‘further comments’ space to provide an additional recommendation regarding the tool’s functionality, which had not been noted in response to Q2 of the group session (Section 3.2.2): “I think running this as a plug in tool for 3D software would be really useful for urban designers/architects/landscape designers.”

3.3.2. Individual ratings of HedgeDATE and behavioural intention

Not all participants answered every question, but the overall consensus was very positive. For example, one participant responded only to the final item, simply indicating that they definitely will recommend the HedgeDATE tool to others. Participants agreed (or strongly agreed) that HedgeDATE was relevant to them, and that the recommendations, language and layout were generally clear. Some participants also left additional handwritten comments. Several participants reiterated points made during the group discussions (Section 3.2), such as that the language “could be more specific about the placement of measurements” and that images “could be to scale.” One participant defended their ‘Disagree’ response by noting that “More parameters are required” for the input options and output recommendations to be generally relevant or applicable to them.

When asked about the likelihood of HedgeDATE having had an impact on their behaviour, participants’ responses were more varied. Participants stated they were likely (or definitely will) recommend the tool, use it themselves, and would buy a plant or build a hedgerow to improve air quality. One participant qualified their ‘Unlikely’ response by writing that they were “not able to” to alter their garden. Another participant indicated that they were likely to plant a hedgerow to improve air quality but added: “not at my property though.” One participant also left a qualificatory remark below their ‘Not sure’ response: “I would like to [use the tool] but I think it's limited to mainly suburban areas where it's easy to plant a hedge. Where I live I'd love to plant hedges along the road, but will need the council on board for this.”

3.4. The functionality and utility of the prototype

The backgrounds of most of the questionnaire participants did not involve plants, plant health, plant management, or green space management, and yet all but one participant owned or had access to a garden (Section 2.3.1). Given the variation in motivation for attending, this commonality may indicate that there is scope for local uptake and application of the

HedgeDATE tool. This is further supported by agreement across all participants that, to the best of their knowledge, no similar tools or resources currently exist.

Feedback on the tool itself was generally positive, with a consensus on the relevance, utility, and clarity of the HedgeDATE prototype (Figure 6a). Furthermore, excluding the participant that indicated that they could not use the tool where they live, all participants indicated either that they likely will or definitely will use the HedgeDATE tool and recommend it to others (Figure 6b). However, several areas for improvement were identified.

Some recommendations from the focus group discussions would, if implemented, cover a number of themes (Section 3.2). For example, Group 2's request for "photos of case studies" to show "Before & after" GI implementation would satisfy a general desire for Education (3.2.1) and Visualisation (3.2.2). Ideas between different groups also overlapped or recurred. For example, Group 2's suggestion that the "diagram should accurately depict the numbers entered into the form" is similar to Group 1's suggestion to "use adjustable bars and see results instantly." We may therefore infer that such suggested changes or additions to the tool would satisfy the requirements of prospective end-users rather than the inclinations of an individual.

Group 1's suggestion that we use adjustable bars rather than numerical input boxes may support functionality, such as by indirectly guiding users towards appropriate responses. Adjustable bars may also make the tool easier to use if it is developed as a mobile application, as suggested by Group 3. Many ideas from the workshop participants were similarly complementary, with the potential implementation of one idea often supporting another. Comment boxes, as suggested by Group 3, may provide a valuable mechanism to collect user feedback over time, potentially regarding several iterations of HedgeDATE.

Each group indicated that education should be a central aspect of HedgeDATE and that enhanced educational content may increase the tool's relevance and/or utility. Groups 1 and 3 both highlighted the importance of plant species recommendations. The range of species included in the prototype (SI Table S2) will therefore be extended and refined to ensure that: a number of suitable options are offered for any given context; they do not contain any significant drawbacks (Table 1); and a greater number of evergreen and coniferous species are included. Additional information and links to relevant guidance (e.g. regarding viability under projected climate change) will also be provided with each species recommendation, where possible, as suggested by Groups 1 and 3.

Suggestions under the ‘Presentation’ theme (Section 3.2.1) were made by all groups and in answer to both questions from the focus group session. We will therefore review the design of the interface for subsequent iterations of HedgeDATE. Indeed, a majority of suggestions made during the group discussions will, if feasible, be implemented (Section 3.5).

As mentioned in Section 2.3.2, the focus of this paper (i.e. the viability of the HedgeDATE prototype) means that a discussion on broader, related themes, such as attitudes towards air pollution and urban greening, would be superfluous. Moreover, significant conclusions on social norms, attitudes and behaviours regarding such themes, based on data from such a small sample size, would have been unfeasible. However, average responses (including standard deviations) to relevant constructs regarding greening and air pollution issues, are provided in SI Table S9. Ongoing implementation of the questionnaire alongside the online tool (Section 5) will support future research in this area.

It is interesting to note that two individuals did not respond to all items of question 13 (Section 3.3.2). Given the short length of the questionnaire (i.e. excluding boredom or time constraints as potential factors), and that this is the only Likert scale that was not completed by every participant, we may infer that the structure and/or language of question 13 should be revised. Similarly, the mean response (‘Not sure’) to the fourth item of question 13 (‘Avoid buying plants that are not aesthetically pleasing[...]') may indicate some confusion on behalf of the participants and that this item should be reworded for clarity or replaced. However, 11 of the 13 participants to the third item of question 13 confirmed that they likely will or definitely will buy a plant thought to improve air quality, even if it is more expensive than other available plants. This suggests a willingness to pay amongst end-users, which matches the aforementioned intentions to use or recommend HedgeDATE.

3.5. Refining the prototype

The current prototype is a basic, flowchart-based tool to identify GI recommendations (plant species, organised by crown density) and provide projections (pollutant concentration reductions if the recommended GI is implemented), based on user-orientated input data (road type, distance from road to home, available planting space, distance from planting area to road). This prototype tool was targeted at private garden owners, and feedback from the workshop will be implemented in HedgeDATE. Indeed, some of this feedback has already been implemented, such as amendments to language used and input functionality. Although the current version of HedgeDATE is primarily a vehicle for public engagement on GI for air pollution exposure abatement, refining and expanding the tool with future iterations will also improve its relevance for and potential uptake by GI practitioners (e.g. urban planners, landscape architects, garden designers, urban foresters). Development of a version of HedgeDATE for use by professionals will include expanding the tool's applicability (e.g. include a broader range of urban scenarios), capabilities (e.g. include a broader range of species and a more complex underlying model), functionality (e.g. create an app version for mobile use) and interface (e.g. improve the style and quality of content, including figures). We would also like to make the tool map-based (i.e. georeference each user's planting site), so that it may offer more bespoke projections and recommendations (e.g. according to the user's climate, soil type, elevation), as well as to automate some of the input data (e.g. road type) and offer unique visualisations.

Enhancing the complexity of the underlying model (Section 3.1) may include developing procedures to: 'orientate' the model to account for variation in barrier length; incorporate barrier height recommendations (e.g. a (3xheight) – 3 rule to describe adequate barrier height (in metres) according to distance of AoC from road (GLA, 2019)); utilise map-based input data to offer nuanced plant species recommendations (e.g. to avoid recommending high pollen-emitting species where primary schools or hospitals are present within a certain radius of the AoC); and indicate acceptable plant species substitutions (e.g. where contractors can't or won't plant a particular species). Bespoke field research, including investigations into plant species, will allow us to address assumptions in the model (Section 3.1) and improve the validity of output projections and recommendations.

4. Summary, conclusions and future work

This study explored the development of a decision support tool for improved vegetation barrier design and management in the UK, with a focus on plant species selection and air pollutant exposure reduction in open road and street canyon environments. The developed prototype was aimed at the general public, and private garden owners in particular, as an engagement tool and educational resource. We collected feedback on this prototype in order to establish the viability of the concept and the functionality of the tool. The following conclusions were drawn:

- Freely available scientific and technological resources enable the development of tools for enhanced public engagement in science and improved decision-making.
- There is a wealth of valuable data and findings from previous studies that can be successfully synthesised to predict air pollutant exposure and abatement in open road

environments. However, further research is required in order to describe pollutant decay profiles under more diverse urban roadside scenarios (e.g. split-level terrain) and, crucially, to validate projections made by models that utilise such decay profiles.

- The adoption of relevant values for parameters used in our model, from previous work or from targeted research, will enable estimations of concentration reductions for different air pollutants by vegetation barriers in open road environments.
- Findings from the workshop validated the HedgeDATE concept and suggested that there is scope, at least in the UK, for uptake of a decision support tool for vegetation barrier design.
- End-user feedback on the tool was generally positive, with a consensus among workshop participants on the relevance, utility and clarity of the HedgeDATE prototype. However, potential improvements were identified, including opportunities for additional educational content, enhanced graphics, and improved input formulation. Where feasible, these improvements will be implemented in future iterations of HedgeDATE and the web-based application (Section 5) will be periodically updated.
- The HedgeDATE questionnaire retrieved useful data on the novelty, quality and utility of the tool, as well as participant awareness, attitudes, social norms and perceived behavioural control regarding gardening or greening and air pollution. However, a number of problems with the questionnaire and/or its delivery have been noted and will be addressed before posting the questionnaire alongside the web-based application (Section 5).
- A greater sample size (to confer statistical power) would have enabled us to draw stronger conclusions regarding public awareness of air pollution issues, impacts of green infrastructure, and other relevant themes. However, this will be achieved via ongoing research.

For the HedgeDATE tool to be relevant for GI practitioners and decision-makers, future iterations will require broader applicability, enhanced capabilities and functionality, and a much-improved user interface. The model and associated predictions will also require validation via targeted field research. However, the co-development of the prototype discussed in this paper illustrates a gap between research findings on the relationship between GI and air pollution and public awareness or application of such findings. This work sets the foundation for future research into the development of advanced GI design tools for reduced exposure to air pollution, towards the implementation of research outcomes in practice.

5. Availability and further information

The HedgeDATE prototype is accessible at: https://hedgedate.eps.surrey.ac.uk/HedgeDATELandingPage.php. Future iterations in the near- to medium-term will also be maintained at this address. Visitors of this address will be prompted to complete an updated version of the questionnaire (SI Section S2) on the utility, functionality and interface of HedgeDATE, as discussed in Section 2.3.2, in order to collect ongoing feedback on different iterations of the tool and support continued development (Section 3.5). Relevant information and progress regarding the HedgeDATE project and any future events are maintained at: https://www.surrey.ac.uk/global-centre-clean-air-research/projects/hedge-design-abatement-traffic-emissions. The main developers of HedgeDATE can be contacted at: gcare@surrey.ac.uk.

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List of Tables

Table 1. General principles regarding effective vegetation barrier design for air pollution abatement in open road environments, extracted from Barwise and Kumar (2020).

Factors	**Recommendations**
Configuration	Vegetation barrier (hedge, stand of trees, or hedge-tree combination) should be aligned parallel and proximate to the road
Height	Minimum height of 2m, although height should increase with distance of barrier from road and/or distance of area of concern from barrier
Thickness/width	Thickness/width should maximise available planting space
Length	Length should extend beyond the area of concern, with no gaps
Canopy characteristics	High barrier density (low porosity); minimum LAD of ~4 m^2/m^3, particularly for narrow barriers (e.g. solitary hedges); continuous leaf cover from ground level
Leaf properties	Evergreen > deciduous; coniferous > broadleaf; small/complex leaves (high specific leaf area) > larger/simpler leaves; rough, hairy, waxy leaves
Site-specific	Air pollution tolerance (all immediate roadsides); salt tolerance (some immediate roadsides); tolerance for other site-specific stressors (e.g. drought, compaction, waterlogging, shade); low pollen emissions (particularly near vulnerable populations)
Large-scale projects	Low bVOC emissions; high species diversity

LAD: leaf area density; bVOC: biogenic volatile organic compound

Table 2. Estimated best-fit exponential functions from different field studies for different pollutant concentration decay profiles near traffic lanes with no obstructions to air flow. PNC refers to particle number concentrations in the ultrafine particle size range, which are measured as number of particles per cm^3.

Pollutant type	Background concentration (C_b; $\mu g/m^3$)	Decay rate (d; /m)	Pollutant concentration at source (C_0; $\mu g/m^3$)	Goodness of fit (R^2)	Author (year)
CO	0.19-0.33	0.033-0.055	4.26-4.54	0.99	Zhu et al. (2002)
CO	0.51-0.64	0.04–0.08	3.75-4.28	0.99	Nayeb Yazdi et al. (2015)
PM_{10}	32 - 34	0.013–0.02	62-67	0.96	Nayeb Yazdi et al. (2015)
NO_2	5.75	0.0281	38.1	0.74	Clements et al. (2009)
NO_2	0.5-0.6	0.004-0.008	23-36	0.91	Richmond-Bryant et al. (2017)
NO	2.30	0.0337	32.0	0.76	Clements et al. (2009)
NO	3-5	0.012-0.022	13-15	0.52	Baldwin et al. (2015)
PNC (6-100 nm)	1952-5952	0.001-0.0016	7910-16564	0.43	Baldwin et al. (2015)
PNC (6-300 nm)	207-13000	0.16-0.17	1.4-25 x 10^4	0.86	Zhu et al. (2009)
BC	0.45-1.61	0.005-0.011	0.38-2.48	0.3	Baldwin et al. (2015)

List of Figures

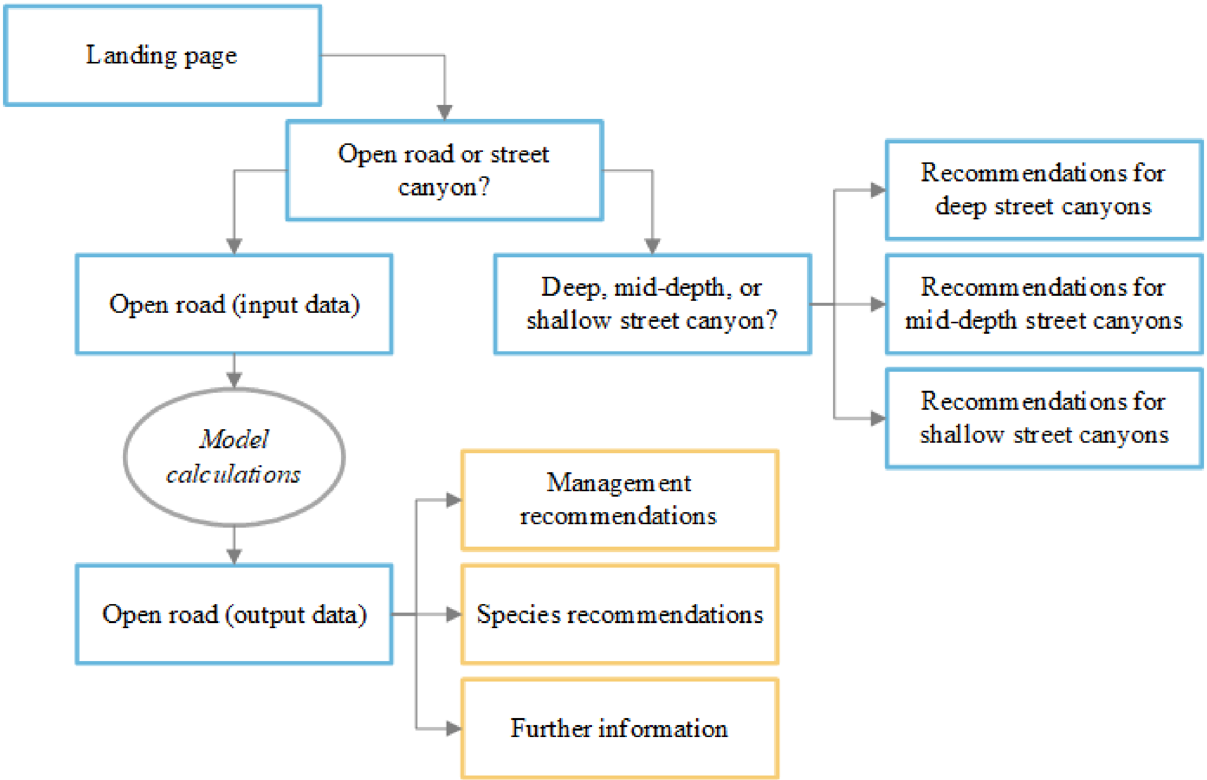

Figure 1. A schematic diagram of the HedgeDATE model. Blue rectangles represent different screens of the user interface; orange rectangles represent pop-up boxes. Street canyons are classified as deep (height/width (H/W) ≥2), mid-depth (0.5< H/W <2), or shallow (H/W ≤0.5).

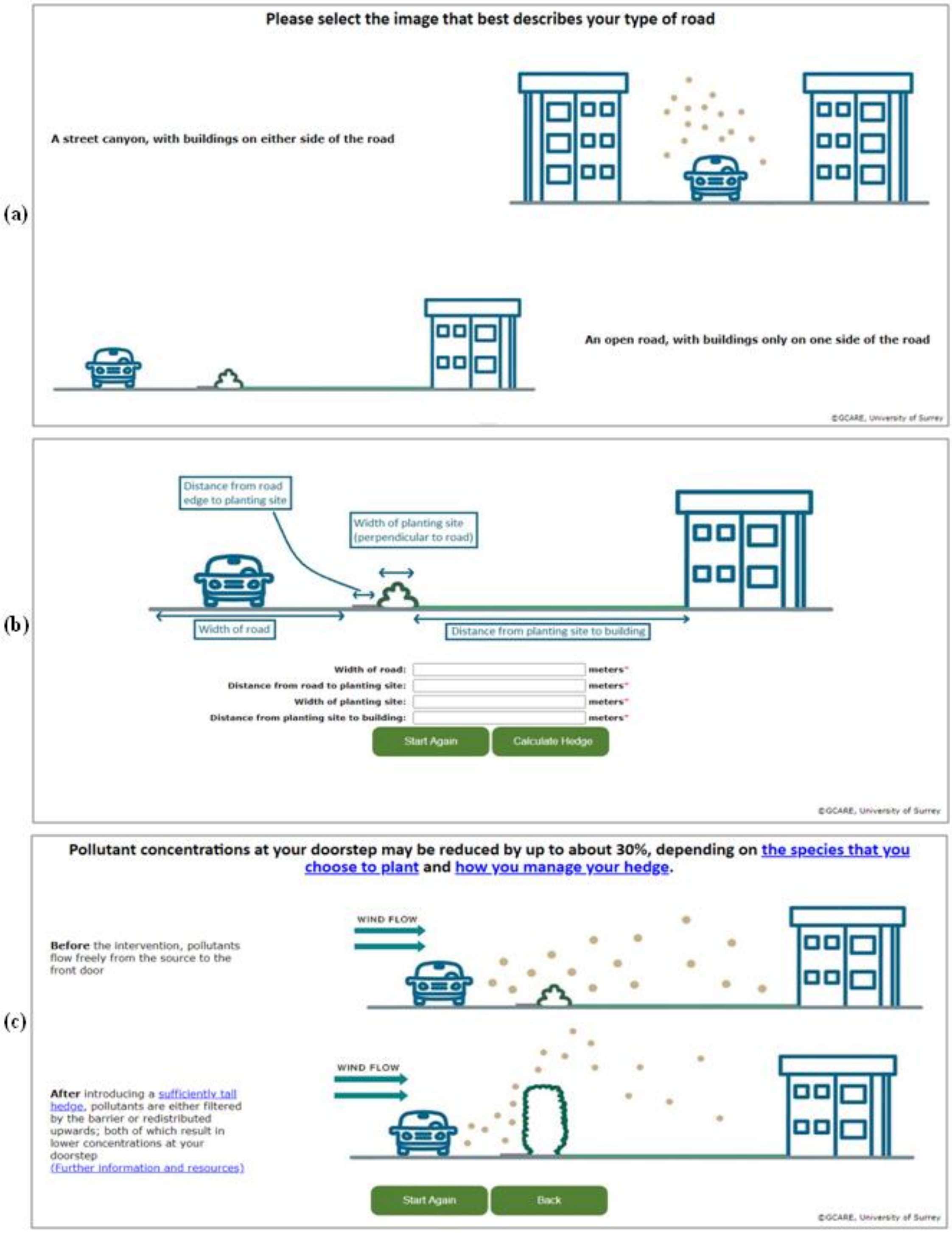

Figure 2. (a) the 'street canyon vs open road' screen of the HedgeDATE prototype, (b) the 'open road (input)' screen of the HedgeDATE prototype, and (c) the 'open road (output)' screen of the HedgeDATE prototype.

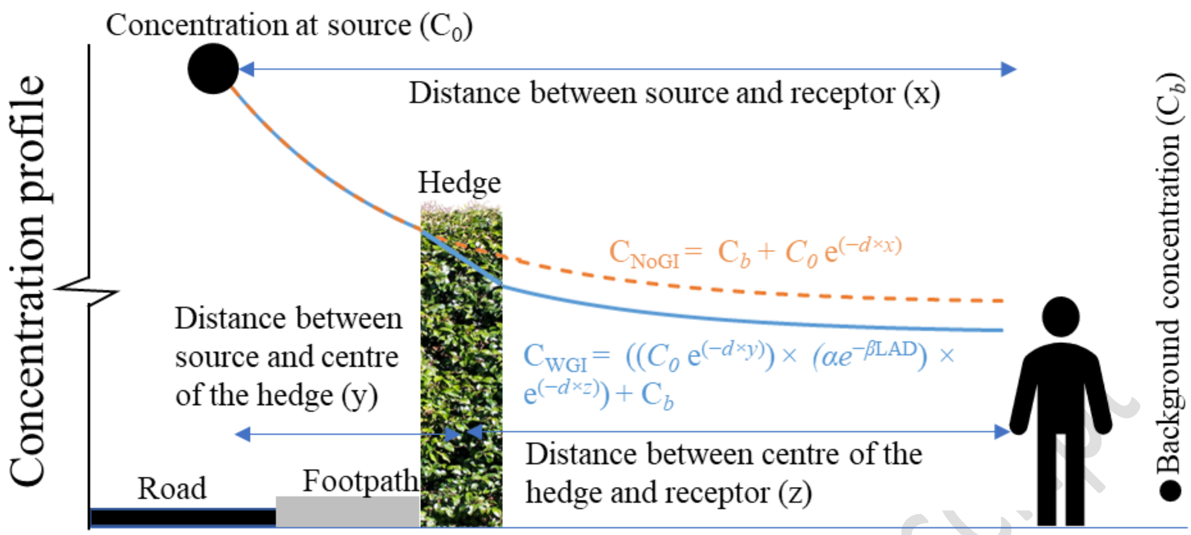

Figure 3. A schematic diagram of the ambient pollutant concentration profile and associated impact of a hedge in open road environments, as estimated by the HedgeDATE model (the reduction in pollutant concentration inside the hedge is assumed to be linear for purposes of representation).

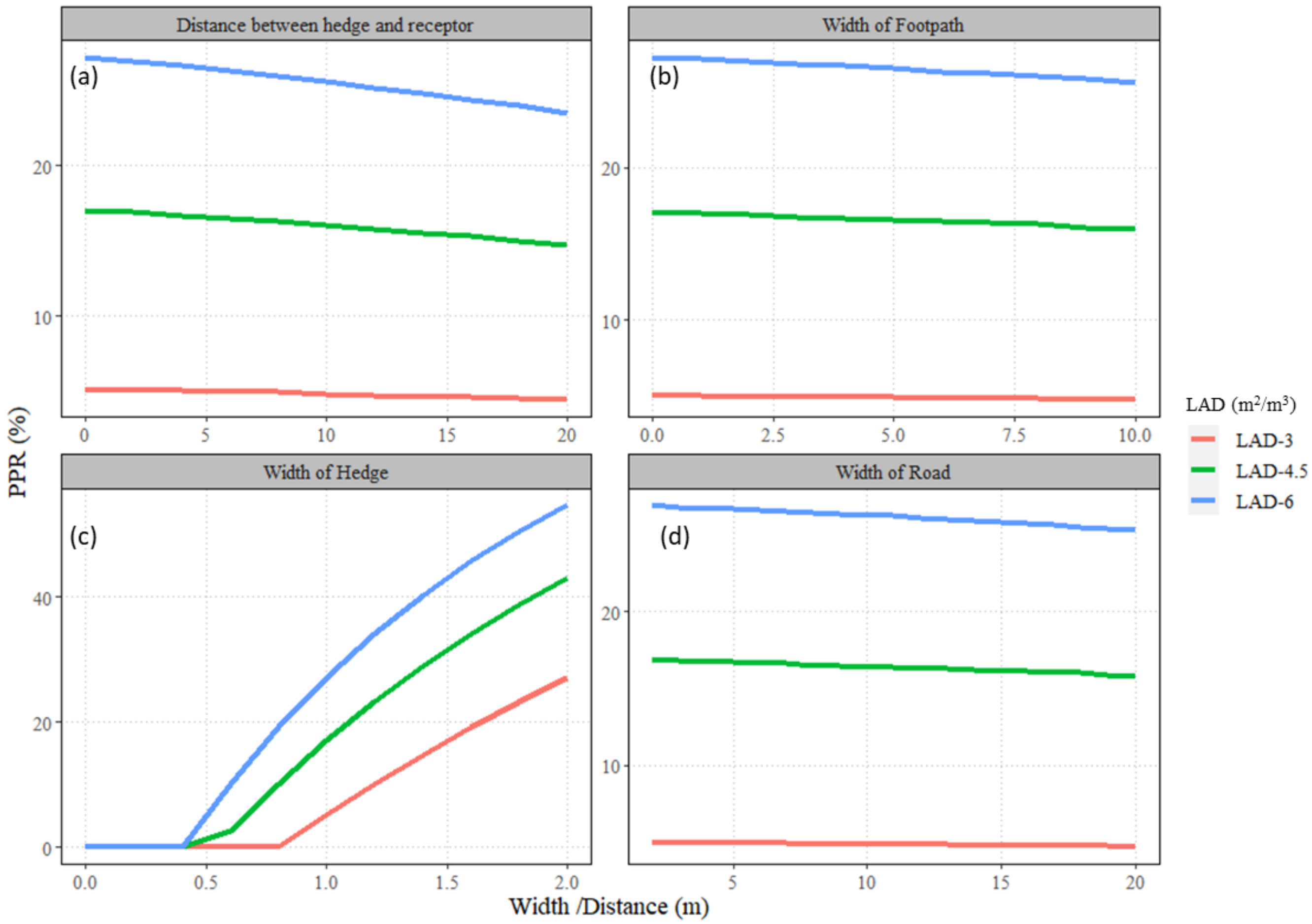

Figure 4. Impacts on the predicted percentage reduction (*PPR*) in CO concentrations for three leaf area densities (LAD; low (3), medium (4.5), and high (6)), as estimated by the HedgeDATE model, with changes in: (a) distance between hedge and receptor; (b) width of footpath; (c) width of hedge; and (d) width of road.

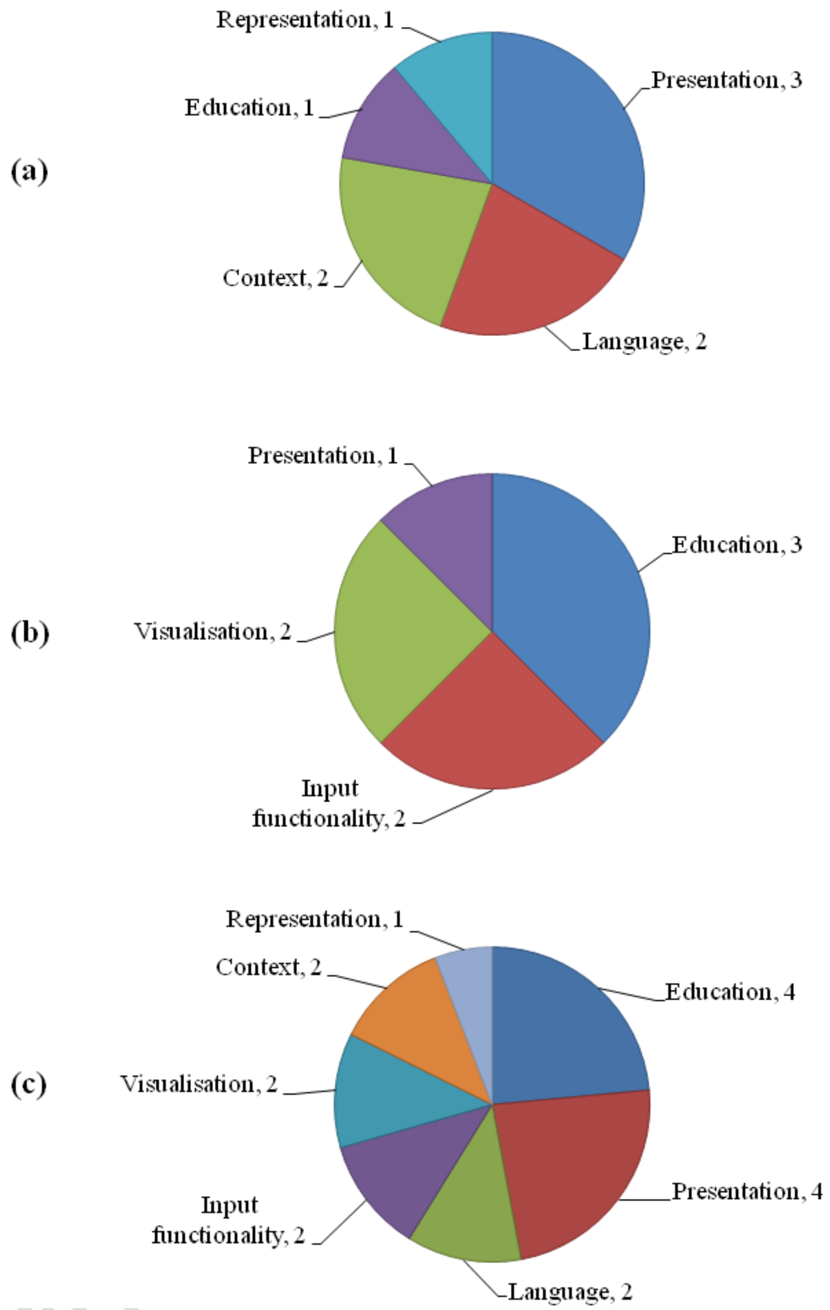

Figure 5. A summary of findings from content analysis of responses to the focus group questions, showing: (a) the occurrence frequency of each identified theme, across all groups, in response to Q1 (‘What are the limitations or drawbacks of the HedgeDATE tool?’); (b) the occurrence frequency of each identified theme, across all groups, in response to Q2 (‘What additional content or functions would you include?’); and (c) the total occurrence frequency of all identified themes, across all groups and in response to both questions.

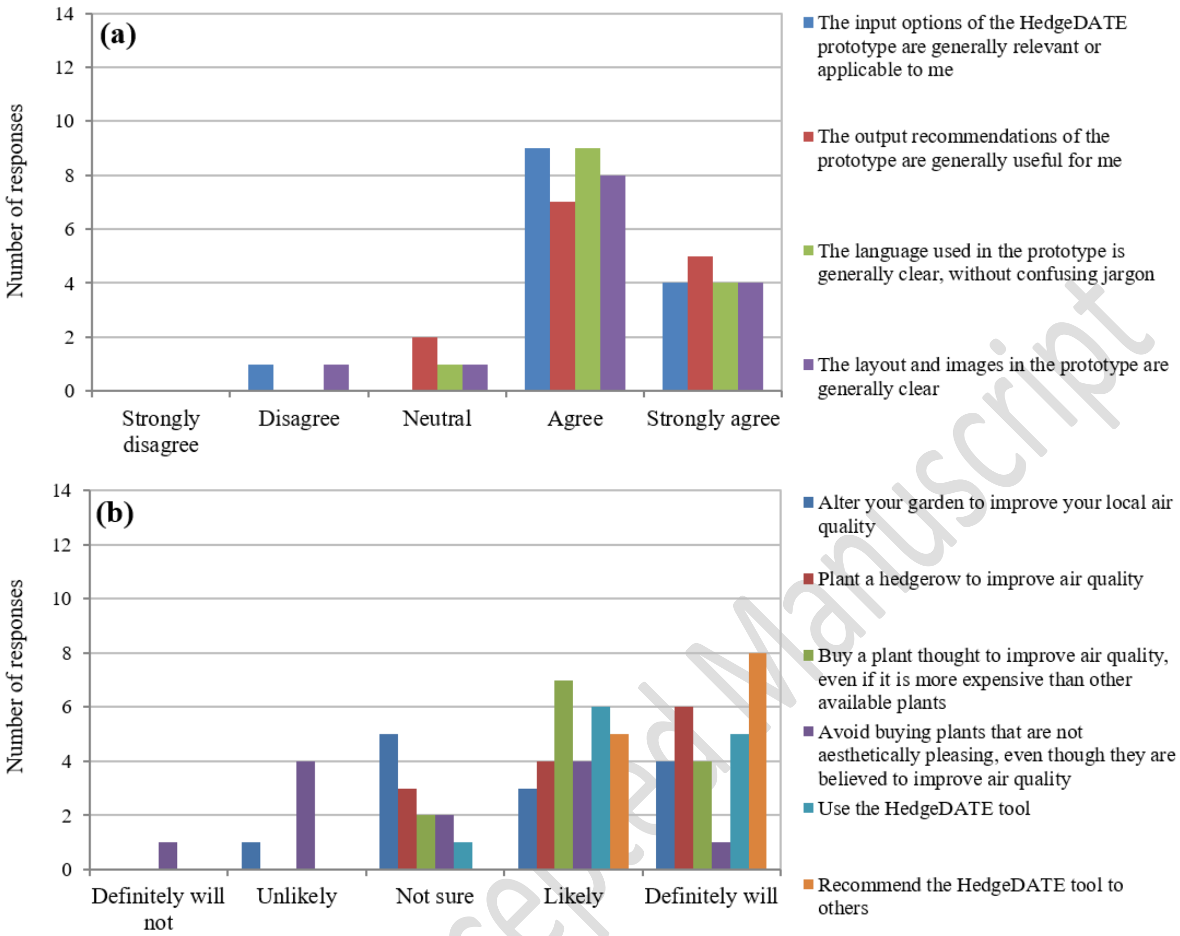

Figure 6. (a) Levels of agreement among participants regarding statements about the HedgeDATE tool, and (b) their likelihood of changing their behaviour as a result of the tool.