RESEARCH ARTICLE

A survey on the perceived need and value of decision-support tools for joint mitigation of air pollution and climate change in cities

Erika von Schneidemesser*, Rebecca D. Kutzner* and Julia Schmale†

Decision-support tools are increasingly popular for informing policy decisions linked to environmental issues. For example, a number of decision-support tools on transport planning provide information on expected effects of different measures (actions, policies, or interventions) on air quality, often combined with information on noise pollution or mitigation costs. These tools range in complexity and scale of applicability, from city to international, and include one or several polluting sectors. However, evaluation of the need and utility of tools to support decisions on such linked issues is often lacking, especially for tools intended to support local authorities at the city scale. Here we assessed the need for and value of combining air pollution and climate change mitigation measures into one decision-support tool and the existing policy context in which such a tool might be used. We developed a prototype decision-support tool for evaluating measures for coordinated management of air quality and climate change; and administered a survey in which respondents used the prototype to answer questions about demand for such tools and requirements to make them useful. Additionally, the survey asked questions about participants' awareness of linkages between air pollution and climate change that are crucial for considering synergies and trade-offs among mitigation measures. Participants showed a high understanding of the linkages between air pollution and climate change, especially recognizing that emissions of greenhouse gases and air pollutants come from the same source. Survey participants were: European, predominantly German; employed across a range of governmental, non-governmental and research organizations; and responsible for a diversity of issues, primarily involving climate change, air pollution or environment. Survey results showed a lack of awareness of decision-support tools and little implementation or regular use. However, respondents expressed a general need for such tools while also recognizing barriers to their implementation, such as limited legal support or lack of time, finances, or manpower. The main barrier identified through this study is the mismatch between detailed information needed from such tools to make them useful at the local implementation scale and the coarser scale information readily available for developing such tools. Significant research efforts at the local scale would be needed to populate decision-support tools with salient mitigation alternatives at the location of implementation. Although global- or regional-scale information can motivate local action towards sustainability, effective on-the-ground implementation of coordinated measures requires knowledge of local circumstances and impacts, calling for active engagement of the local research communities.

Keywords: decision-support; policy; air quality; climate change; urban; decision-support tools

1. Introduction

Air quality and climate change are two of the foremost environmental issues of concern at the global, regional and local scales. Yearly, 2.6 million premature deaths globally result from air pollution (Lim et al., 2012), which are estimated to cost developed countries 2% and developing countries 5% of their annual GDP (UNEP, 2005). Adverse impacts of climate change are rising temperatures, more extreme weather events, and rising sea level, amongst others (IPCC, 2013). These two issues are connected, through their emissions sources, by their atmospheric properties and processes, and through mitigation measures (von Schneidemesser et al., 2015). In this paper, 'measures' refers to mitigation options, actions, policies, or interventions; for example, a measure to improve air quality could be the implementation of a low emissions zone. Ideally, making decisions among possible mitigation options would take into account advantages and disadvantages of coordinating measures to manage

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air quality and climate together, instead of managing only one of these areas. This could avoid trade-offs with adverse consequences. For example, to reduce carbon dioxide (CO_2) emissions, one option would be to support (e.g., through subsidies or otherwise) modern residential heating stoves that use biomass, such as pellets, which have lower net CO_2 emissions relative to heating provided by fossil fuel sources. Such stoves, however, often emit significant amounts of particulate matter, including black carbon, a short-lived climate-forcing pollutant with detrimental human health effects.

Cities are responsible for approximately 70% of global CO_2 emissions and contribute significantly to air pollutant emissions (Kennedy et al., 2009; UN-HABITAT, 2011). Emissions at the city level are inextricably linked to, for example, transport and traffic, building infrastructure and consumption patterns. Those activities are all connected to policy domains in which both environmental and socio-economic considerations play important roles. This makes cities critical players in tackling air pollution and climate change challenges. In addition, national policies often provide boundary conditions for systems supporting cities (e.g., provision of power and food), and influence policy options in cities (e.g., through nationally determined targets). These examples illustrate that policy decisions for air pollution and climate change are embedded in a variety of other policy domains. This complexity poses a challenge to policy makers. Socio-economic factors, synergies and trade-offs, feedback effects and the different spatial scales involved all need to be considered in the decision-making process.

To support the evaluation of policy options, researchers have developed a variety of decision-support tools (e.g., González et al., 2013; Sharifi and Murayama, 2013). The instruments developed to specifically support city-level administration aim at either climate change or air pollution, without integrating both issues.

Decision-support tools, also called decision support systems, exist in two main formats—as written documents and as software tools. Regulatory authorities maintain reports and written guidance as a means to follow a standardized, reproducible approach to facilitate consistent decision-making (Sullivan, 2002). Whereas, computer-based decision-support systems have substantially evolved since the 1970s as the second form (Shim et al., 2002). Different categories of decision-support systems have also been identified, including communication-driven, data-driven, document-driven, knowledge-driven and model-driven (Power et al., 2015). An important aspect of the tools is that they generally deliver either an output "of decision variables (e.g., cost or risk) or a direct comparison between alternative remedial strategies" (Sullivan, 2002). We summarize a number of examples below to elucidate the range in policy level, issue focus, and complexity that decision-support tools can provide.

The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model is a decision-support tool that provides cost-effective information regarding alternative emission control measures at national to international levels, and considers air pollution as well as greenhouse gases (Amann et al., 2011). A wide variety of assessments (e.g., UNEP/WMO 2011) have applied the GAINS model. However, the resolution, at 50 km × 50 km, is too coarse for sub-national or city-level decision makers, and is only helpful to them as a starting point or context in which to frame their decisions (Amann et al., 2011; Bizek et al., 2013). Furthermore, the GAINS model considers only urban areas with greater than 350,000 inhabitants (Gidhagen, 2013). In order to be useful at city-scale, the results would need to be incorporated into a downscaled model linked into a decision-support system. Researchers are currently testing a model version, GAINS-City, for the megacity of Delhi (Amann et al., 2017). A further example of sub-national application is the Regional Integrated Assessment modelling Tool (RIAT+; http://www.riatplus.eu/html/eng/home.html) which was developed to support policy makers at a sub-national level in the context of the OPERA project (Operational Procedure for Emission Reduction Assessment, OPERA, n.d.). Using RIAT+ requires a basic understanding of modeling functionalities, as well as substantial, region-specific, detailed input data. A limitation of the applicability of the results to regional policy is that some of the suggested measures are often linked to national or European-level policy and would need to be carried out at a higher level than those at which the RIAT+ user would be operating (Carnevale et al., 2014).

A much simpler to implement decision-support tool was developed during the 5 year project, JOAQUIN (Joint Air Quality Initiative), focused on air quality in Northwest Europe (joaquin.eu). The tool incorporates different emissions reduction measures and provides evaluation of the measures through a ranking of practice, including low, moderate and good practice, in a searchable database. The JOAQUIN tool addresses air quality and implications for human health but does not include implications for climate change strategies in any detail.

The RIAT+ and JOAQUIN tools support local- to regional-level decision-makers and focus on air quality. Another tool, the 'Stadtklimalotse' (English: city climate pilot) addresses a similar decision-making level, but focuses on climate change mitigation and adaptation (http://www.stadtklimalotse.net/). It provides a catalogue of measures with information on their synergies and conflicts, as well as cost estimates. As with many of these tools, much of the information provided is qualitative and based on previous experience and best-practices.

A number of other tools exist, ranging from simple, searchable, catalogues of measures to more complex model-based platforms. These aim at scales ranging from city to national level and higher. The more complex tools allow for the input of context-specific information, require greater time investment for use, but often produce more detailed, tailored results (e.g., EC Catalogue of Air Quality Measures (Version 2014.01.21) (https://luft.umweltbundesamt.at/measures/); Knowledgebase on Sustainable Urban Land use and Transport (KonSULT) (http://www.konsult.leeds.ac.uk/pg/01/); IEA Policies and Measures Database (http://www.iea.org/policiesandmeasures/); Climate & Clean Air Coalition SNAP initiative and toolkit (http://www.ccacoalition.org/fr/initiatives/snap); Urban Transport Roadmaps (http://urban-transport-roadmaps.eu/)). While a wide variety of decision-support tools are available in the general areas of air quality and climate change, the vast majority, including the tools mentioned above, focus on one issue, e.g., traffic planning, air quality plans, or energy-related policies. Furthermore, while these tools were often created with a specific end-user group in mind, and sometimes in consultation with end-users, little information exists on their actual use beyond a proof of concept (e.g., Carnevale et al., 2014; Miranda et al., 2016; Vlachokostas et al., 2009), specifically for use at local to regional scales. For example, Sullivan (2002) evaluates decision-support tools but for contaminated land management. In the area of air quality and climate change, Miranda et al. (2013) reviews air quality and health assessment methods but focuses more on source apportionment or other modelling techniques, which are not the same sort of decision-support tools as discussed here. While Halsnæs et al. (2007) reviews decision-support tools, their focus is more on the methodological approaches and not on specific tools themselves.

Here, we explored the need for and value of combining air pollution and climate change mitigation measures into one decision-support tool. A secondary aim was to understand the context in which such a tool might be used and by whom, informed by an understanding of the level of awareness and action on air pollution and climate change and the connections between them. We developed a prototype decision-support tool and administered a survey that used this prototype. The survey addressed two main areas: (1) participants' understanding and awareness of air pollution and climate change, including perceptions of their institutions' environmental priorities, and (2) evaluation of the prototype decision-support tool for measures mitigating air pollution and climate change. In this paper, we describe the development of the decision-support tool prototype and the survey that evaluated the tool, followed by results and a discussion of our findings.

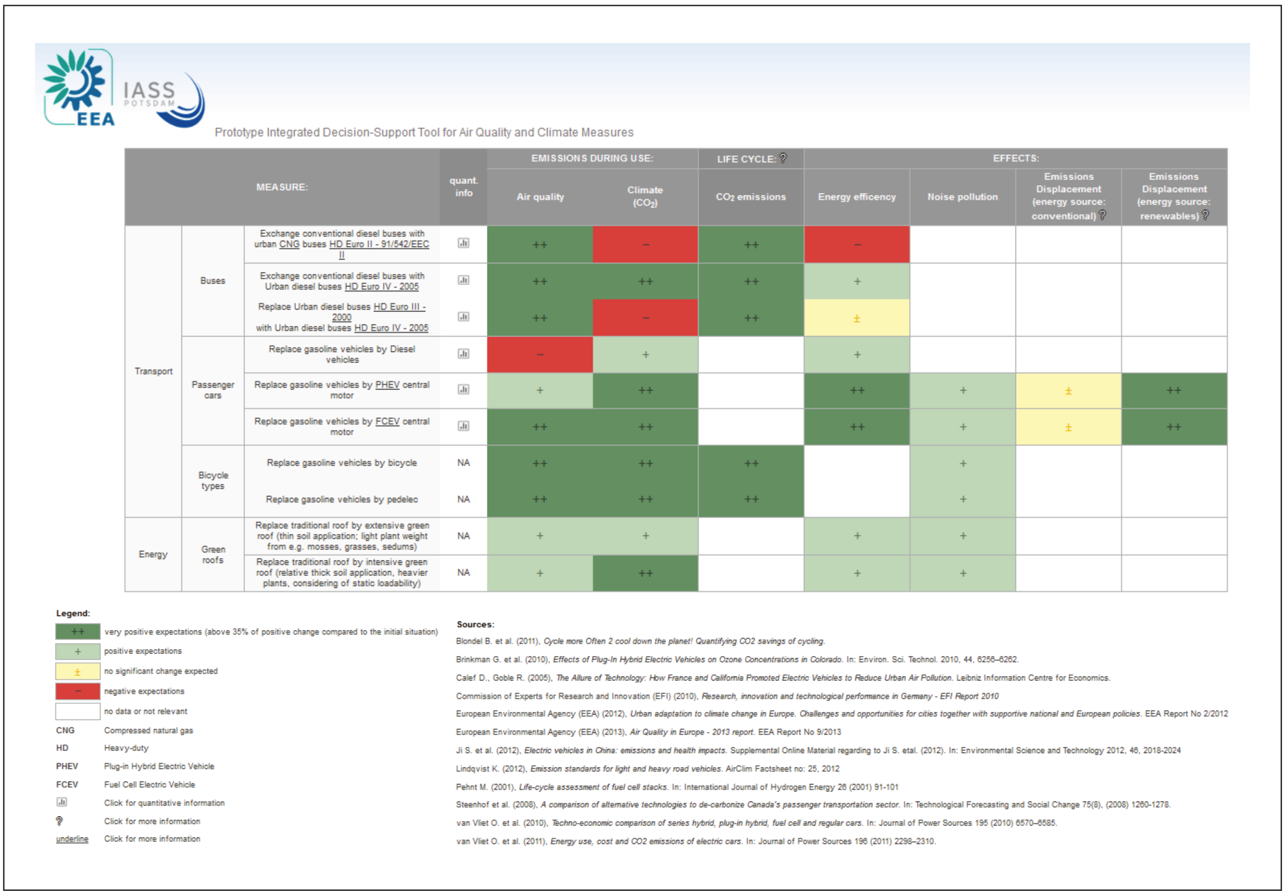
Here, a 'coordinated approach' refers to recognition of the connections between air quality and climate change, for example, when decision makers evaluate a potential air quality measure for its effects on climate change and vice versa. This serves the purpose of taking advantage of synergies and avoiding trade-offs. The primary target audience for the decision-support tool and survey was decision-makers in governments and NGOs.

2. Methods

2.1. Development of the prototype decision-support tool

We created a prototype decision-support tool in order to give survey participants a specific example of such a tool addressing air pollution and climate change in a coordinated way, and as a reference point to explore and critique decision-support tools (http://idst.iass-potsdam.de/ and shown in **Figure 1**). The prototype included integrated information on air quality and climate change to facilitate planning and a comparison of the expected effects of measures prior to implementation. This was a crucial point behind the development of the prototype tool, since the linkages between air pollutants and greenhouse gases have been shown to result in potential benefits, but also imply trade-offs that depend on the measures implemented (Williams, 2012). The prototype tool was developed for use in the survey, with survey participants asked to view the tool and answer questions about it. It is a draft tool, not a finalized product, and will not be developed further at this point by either the Institute for Advanced Sustainability Studies (IASS) or the European Environment Agency (EEA).

We conducted a literature review to collect comparable emissions data for the prototype decision-support tool, including measures from: the transportation sector including buses, passenger cars, and bikes (Blondel et al., 2011; Brinkman et al., 2010; Calef and Goble, 2007; EFI, 2010; Ji et al., 2012; Pehnt, 2001; Steenhof and McInnis, 2008; Van Vliet et al., 2011; van Vliet et al., 2010), and residential energy use including green roofs (Li and Babcock, 2014; Pandey et al., 2013; Speak et al., 2012). The tool includes a limited number of measures to limit the complexity and time needed to develop it, given that we wanted the tool to serve as a prototype for assessment. The decision-support tool includes effects of the measures on the following areas: air quality, climate (life cycle CO_2), energy efficiency, noise pollution, and emissions (including power derived from conventional sources vs renewable sources). Data collection focused on comparable data for the different categories within each group of similar measures. Those were organized in the tool similar to a decision matrix: rows containing measures and columns containing the categories of impact evaluated for these measures, similar to Gebhardt et al. (2012), combining qualitative and quantitative information. The air quality category included emissions from the following substances: carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC), ammonia (NH_3), lead (Pb), and particulate matter with a diameter smaller than 2.5 µm ($PM_{2.5}$). CO_2 emissions and a life cycle analysis represented the climate change effects. These climate metrics apply only to those measures related to transportation options and included emissions from production (energy and material inputs required to manufacture the vehicle), maintenance (energy and material inputs required to keep the vehicle in good working order) and operation (fuel production and utilization). It did not include infrastructure (impact and lifespan of roads and bicycle paths) or disposal (impact of waste material from standard practice reuse and/or recycling) (Blondel et al., 2011). For energy efficiency, we gathered data on energy consumption (mega joules per kilometer) for vehicles and reports of energy saved in buildings due to green roofs (Li and Babcock, 2014). Noise pollution effects were extracted from a technical report (EFI, 2010). Finally, a category for emissions displacement was included. This captured the possibility that overall emissions did not decrease, but were simply emitted at a different location. If, however, emissions were moved from a city center to a less populated area, this could still be of benefit overall – electric cars being one example.



MEASURE:			quant. info	EMISSIONS DURING USE: Air quality	EMISSIONS DURING USE: Climate (CO_2)	LIFE CYCLE: CO_2 emissions	EFFECTS: Energy efficency	EFFECTS: Noise pollution	EFFECTS: Emissions Displacement (energy source: conventional)	EFFECTS: Emissions Displacement (energy source: renewables)
Transport	Buses	Exchange conventional diesel buses with urban CNG buses HD Euro II - 91/542/EEC II		++	–	++	–			
		Exchange conventional diesel buses with Urban diesel buses HD Euro IV - 2005		++	++	++	+			
		Replace Urban diesel buses HD Euro III - 2000 with Urban diesel buses HD Euro IV - 2005		++	–	++	±			
	Passenger cars	Replace gasoline vehicles by Diesel vehicles		–	+		+			
		Replace gasoline vehicles by PHEV central motor		+	++		++	+	±	++
		Replace gasoline vehicles by FCEV central motor		++	++		++	+	±	++
	Bicycle types	Replace gasoline vehicles by bicycle	NA	++	++	++		+		
		Replace gasoline vehicles by pedelec	NA	++	++	++		+		
Energy	Green roofs	Replace traditional roof by extensive green roof (thin soil application; light plant weight from e.g. mosses, grasses, sedums)	NA	+	+		+	+		
		Replace traditional roof by intensive green roof (relative thick soil application, heavier plants, considering of static loadability)	NA	+	++		+	+		

Figure 1: Image of the prototype decision-support tool for air quality and climate measures. The interactive, online, prototype decision-support tool (top), including the legend (bottom left) explaining the color codes and abbreviations used, and references (bottom right) on which the support tool was based. DOI: https://doi.org/10.1525/elementa.126.f1

Data from the peer-reviewed literature are not necessarily comparable, because researchers have not standardized methods for generating emission values (e.g., g/km vs g/amount of fuel) nor decided which processes should or should not be considered (e.g., emissions generated during production through use vs emissions from use only). This resulted in incomparable units from different papers or comparable units but for noncomparable car classes or emissions. Therefore, we used emissions predominantly from one source/paper for as many different measures per impact category as possible: for example, the source for CO_2 and energy data for vehicle measures was Van Vliet et al., (2011) and Van Vliet et al. (2010), while Brinkman et al., (2010) was the source for VOC and NOx emissions for the vehicle measures. In some cases this led to missing data and in others to different units for different substances/components. Nonetheless, to place all substances within one category, we calculated the percent reduction relative to the technology being replaced or improved instead of using absolute units.

The data matrix in the decision-support tool (**Figure 1**) qualitatively compared the measures using an intuitive red-green color code and plus or minus signs. For example, each row represents one measure (described in the first column), such as replacing conventional buses with CNG buses. All columns to the right of the measure are the categories for estimation of impacts of this measure, such as the expected effect on air quality or climate. Green colors and a plus sign indicate a positive or beneficial effect; red color and a minus sign indicate negative or adverse effects. By visually following one row across for a measure, the user can see if effects for all categories are largely positive (green), negative (red), or involve trade-offs – a mix of both positive (green) and negative (red) effects. The tool provides supplemental quantitative data (the percent reduction for specific substances/components) by pop-up graphs accessed by an additional click (**Figure 2**). These data provided information on the percent change in emissions expected for individual air pollutants and greenhouse gases, as well as energy consumption. Users can see pop-up information on the percent change by holding the cursor over the bar for any of the pollutants, shown in **Figure 2** for CO. If the net change was zero, a break in the grey line at the y-axis' zero value was present, (as for NH_3 in **Figure 2**). Where no quantitative data were available, the category was left blank (there was no break in the gray zero line, as for N_2O in **Figure 2**) and no value would be provided when the user held the cursor over that space. Finally, the prototype tool included additional explanatory information via other pop-up windows that users could access, as indicated by underlined text or a question mark. A legend provided explanations of

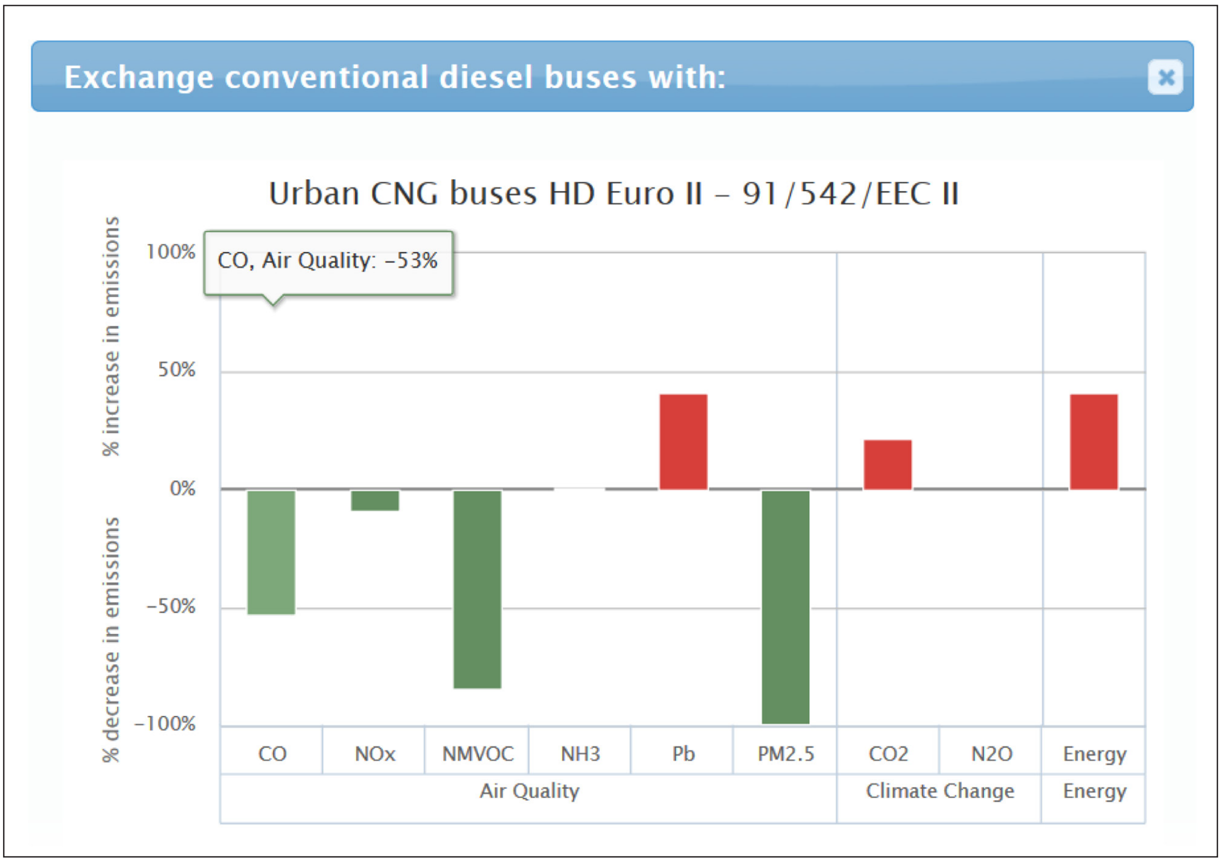


Figure 2: Pop-up graphic providing quantitative information associated with exchanging diesel buses with CNG buses. For each measure included in the decision-support tool (see Figure 1), a pop-up graphic provided quantitative information when a user clicked on the icon in the column 'quant. info.' These graphics provided greater detail than was possible to provide on the main page of the decision-support tool, in this case shown for the measure – exchanging conventional diesel buses with CNG buses. DOI: https://doi.org/10.1525/elementa.126.f2

acronyms and the color codes used in the qualitative assessment. References were also included below the tool and legend for completeness. Interested readers can explore the tool online at http://idst.iass-potsdam.de/.

2.2. Development and administering of the survey

We developed the survey questions according to the guidelines of Bortz and Döring (2006). We used closed questions to explore one of our main goals: to gain insight about the participants' awareness of linkages between climate change and air pollution considering their type of professional affiliation. 'Closed question' means that the answer was based on multiple-choice options or required a simple 'yes/no' or level of agreement, e.g., 'strongly agree', 'agree', 'disagree', etc. The second part of the survey addressed our second main goal, asking participants to evaluate the prototype decision-support tool, using both closed and open questions. An 'open question' required an explanatory answer for which participants wrote into a textbox. The survey was distributed in German and English.

We developed the questions around these goals and refined them through two rounds of testing and revision of survey drafts. Furthermore, five people external to the IASS and EEA who were representative of the target audience, e.g., city governments and NGOs, tested a pre-final version of the survey. The German and English versions of the survey were identical with the exception of one error identified later, that is, the German version lacked the 'low priority' option for the question on perceived prioritization of environmental issues at the participant's place of employment. Given our grouping of 'low priority' and 'very low priority' answers, this should not have a significant effect on the outcome. A copy of the survey in English appears in the Supplemental Material to this article (Text S1).

We sent the survey to more than 1200 people via an initial email and one reminder email. Specifically, we contacted people: (a) working on air quality or climate change at different levels of government from the municipal to the regional/European Commission level, (b) working in environmental protection agencies or environmental ministries, (c) working in NGOs engaged in influencing policy decisions related to air quality and climate change, and (d) working at research institutions, especially those providing data relevant to such tools or other decision-support. The survey was completed by 137 participants within four months. The survey focused geographically in Europe and topically on people working on environmental issues in a variety of institutions. 70% of respondents were from Germany (reflecting the network of contacts of the authors), followed by 7% from Belgium, 5% from U.K, 3% Norway and 2% each from Denmark, the Netherlands, and Ireland. Countries representing less than 1% of the participants (equivalent to only one person) were Austria, France, Iceland, Italy, Poland, Sweden, South Africa, USA, India and 4% of the participants did not provide a country. Three surveys completed by people from outside Europe were removed to allow us to assess results against the more coherent policy context of Europe, leaving 134 responses. From this point forward we will only discuss the 134 survey responses. The evaluation was also conducted according to the guidelines Bortz and Döring (2006) as well as (Crawford, 1997).

The survey instrument provided the participants with a link to the prototype decision-support tool and informed them that it was a prototype, representing an excerpt of what could be a more complete tool (in terms of the variety and amount of measures included). Participants were asked to explore the tool and then provide feedback through a series of closed and open questions.

In one question, multiple statements aimed at the same outcome were included to assess consistency in the respondents' answers, regarding the amount of coordinated or integrated decision-making for air quality and climate change already taking place in their institutions. Consistency was assessed with the following four statements:

(1) Climate change mitigation measures are only evaluated for climate change impacts.
(2) The impact on air pollution is considered for climate change mitigation.
(3) Air pollution mitigation measures are only evaluated for air pollution impacts.
(4) The impact on climate change is considered for air pollution mitigation measures.

If a respondent *(strongly) agreed* or *(strongly) disagreed* with statement one, then the person should have answered the reverse for statement two. That is, if climate change mitigation measures are only evaluated for climate change impacts, they are not evaluated for impacts in any other areas, including air pollution. Agreeing to the second statement would contradict the previous one. However, the reverse is not necessarily the case. For example, if the respondent disagreed with the statement – climate change mitigation measures are only evaluated for climate change impacts – this does not mean that the measures are necessarily evaluated for their impact on air pollution, but rather that the measures are evaluated for other effects such as on noise mitigation or mobility. This would similarly be the case for statements three and four. For all statements, a *neither agree nor disagree* answer was also possible.

To facilitate presentation and analysis of the results from the answers to the open questions, we created categories based on the responses. The responses were then evaluated by three individuals independently, classifying the responses into the different categories. Then, we compared this categorization of responses and accepted those for which at least two of the three people agreed upon the categorization. For example, in answers to the open question requesting initial thoughts about the presented tool, 'this is a wonderful tool' and 'looks handy' were both categorized as 'positive'. Examples of other categories included comments indicating that the tool was 'too general', or that 'cost information' would be necessary. Further description of the categories developed for each question and the responses appears below in the discussion of results.

Interested parties may contact the authors to view survey responses, in accordance with proper protection of the human subjects surveyed.

3. Results

The majority (>80%) of respondents had some degree of higher education (Masters degree or higher). 80% of respondents were in the 30–59 year age range. Of the respondents, 28% were female and 65% were male. We note in the text below if less than 90% (120 of the 134 European participants) provided an answer to any one question.

The type of affiliation cited by the respondents is shown in **Figure 3**. Of the 12 responses that were 'other', we reassigned eight to existing categories, which is reflected in the figure. For example, two of the responses listed 'university' as the type of institution under 'other'; these were reallocated to 'research institution'. We considered the following participants to be 'policy-makers': persons working in a governmental institution or state agency, city administration, or transnational institution, as well

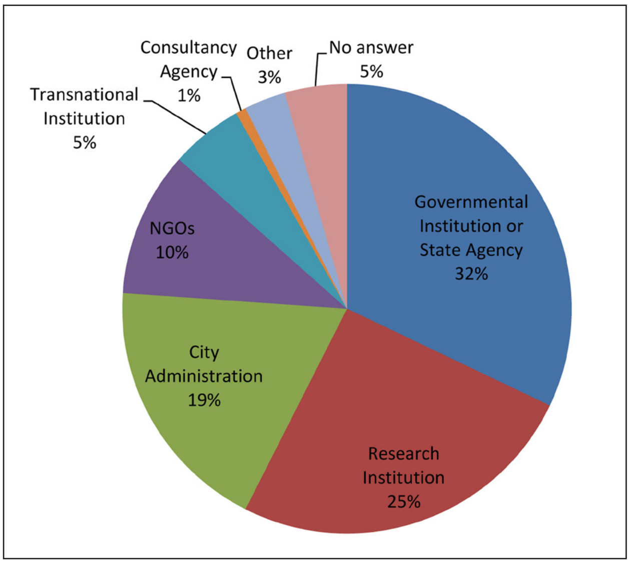


Figure 3: Distribution of institution type for survey participants. Transnational institutions are defined here as international, governmental or non-governmental organizations that operate at higher levels than nation-states and influence policy decisions, such as the European Commission. Governmental institutions include federal ministries, state ministries, national governments and similar institutions of authority at the national or sub-national level. DOI: https://doi.org/10.1525/elementa.126.f3

as those at NGOs and consultancies. These participants represented 67% of respondents. Twenty-five percent were employed by research institutions, with the remaining percentage in 'other'.

Figure 4 shows responses regarding the participants' main area of responsibility, which are dominated by air pollution and climate change, but also include professionals from environment, energy and natural resources, sustainability, and traffic and transport planning – all areas highly relevant to air quality and climate change. Nine respondents originally classified their area of responsibility as 'other', not fitting within the categories provided. Of these nine, we reclassified four: three to the 'climate change' category, as in all three cases the respondents indicated their area to be 'Klimaschutz' (English: climate protection); and one respondent's answer (environmental health) to 'health'. An additional two of the respondents who chose 'other' indicated that their area was 'noise/noise protection'. Selecting more than one area was possible as an answer. Of those who selected more than one area, environment and air pollution were selected together, as were energy and natural resources and climate change by the largest number of participants (six for each combination). In order of decreasing popularity, the following categories were selected together: climate change and air pollution; climate change, energy, natural resources and environment were often grouped together, sometimes in combination with air pollution, sustainability, or both; air pollution, climate change, traffic and transport; air pollution, traffic and transport; climate change, energy and natural resources, sustainability. Any combinations selected by two participants or fewer are not listed.

3.1. Air quality and climate change knowledge and coordination

The recognition that air pollution has an effect on climate change was higher (85%) than the opposite statement, that climate change has an effect on air pollution (66%). Five percent and 16% 'didn't know', and 5% and 7% didn't answer, respectively. These results indicate that most survey respondents already had a high understanding of the influence of air pollution on climate change and vice versa. They exhibited greater recognition that air pollutants and greenhouse gases are emitted from the same sources (88%), with 3% of respondents who answered 'don't know' and 7% who did not answer. The recognition that air pollutants and greenhouse gases are often emitted from the same sources is a crucial point, because it suggests that mitigation measures can focus on these sources together. Thus, an integrated decision-support tool could quantify synergies among measures to manage air pollution and greenhouse gases.

3.2. Coordinated approach to air quality and climate change measures

When asked if 'plans either exist or are in development to select measures by considering the effects on both climate change and air pollution,' 66% of participants either agreed or strongly agreed. Following on from this,

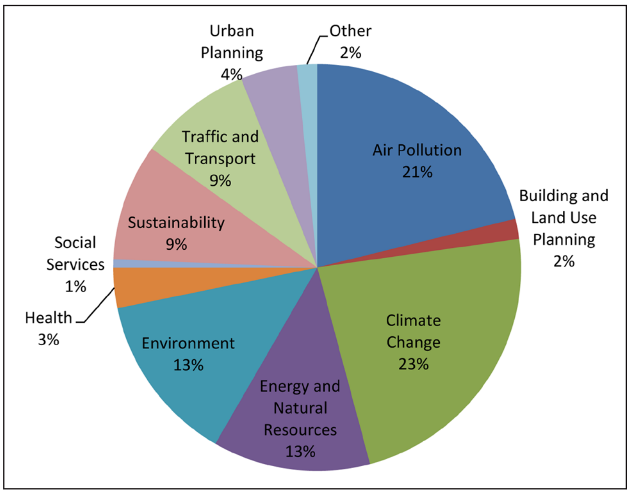


Figure 4: The main area of responsibility that respondents reported. The primary area of responsibility reported by the survey participants were climate change, air pollution, and environment. As more than one area was possible as an answer, the total number of answers was greater than the number of participants. Typical combinations are included in the text. DOI: https://doi.org/10.1525/elementa.126.f4

Figure 5 shows the results and plausibility chain of the answers assessing if such a coordinated or integrated approach specifically links air pollution with climate change mitigation measures. For statements one and two (see **Figure 5**), 42% (strongly) agreed with statement one. Of those that (strongly) agreed, 67% then answered the reverse for statement two when they (strongly) disagreed, which would be the expected answer (15% neither agreed nor disagreed). Therefore, 15% of the respondents that answered (strongly) agree to statement one, also (strongly) agreed with statement two, which indicates an inconsistency in the answers. For the reverse, 42% of respondents (strongly) disagreed with statement one that climate change measures are only evaluated for climate change impacts, of those only 57% (strongly) agreed that climate change mitigation measures were evaluated for their impact on air pollution. Another 11% of those that initially disagreed, neither disagreed nor agreed with statement three.

Overall, around half of the participants (strongly) agreed that either climate change or air pollution mitigation measures were evaluated only for impacts in that area, while about 40% (strongly) disagreed that this was the case. This would indicate that some evaluation of broader impacts is already carried out, however it is not universal. And the inconsistency in some of the answers indicates some lack of clarity around either the science and/or coordinated approach. It is possible that participants did not clearly distinguish between air pollutants and greenhouse gases which could have led to the observed inconsistency. However, given the European, especially the German, regulatory context, we assume that this was generally not the case because CO_2, for example, is not classified as an air pollutant but only as a greenhouse gas. Mistaking air pollutants for greenhouse gases is highly unlikely as well.

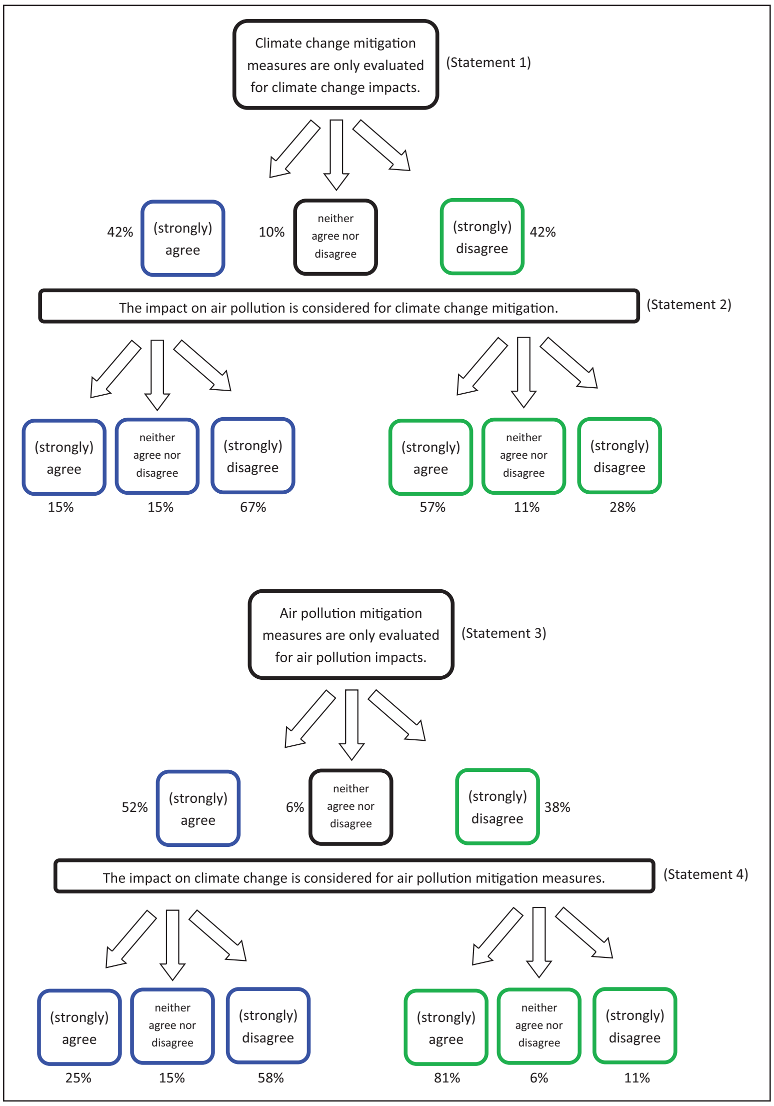


Figure 5: Responses indicating the amount of coordination in the approach to air quality and climate change measures. Participants were asked to indicate their institutional approach to air quality and climate change measures, once from the perspective of air pollution measures as the main focus, and once from the perspective of climate change measures as the main focus, as indicated by the two flow charts. Colors indicate linked responses. For example, of those participants who (strongly) agree to the first statement in the plausibility chain of (a) or (b), colored in blue, their responses to the second statement are also colored in blue. Percentages do not add up to 100% because a small number of respondents answered *'don't know'* and this answer option is not included in the options presented, but is included in the number of total responses for the percentages calculated. DOI: https://doi.org/10.1525/elementa.126.f5

We also assessed the level of priority given to various environmental issues, as well as the importance of working across different departments within the institution. When asked to assign a level of priority to environmental issues, in general, in their institution, 88% of the responses indicated either a *high priority* or *very high priority*. Following this general statement, the survey asked participants to assign a level of priority to specific issues including air quality, climate change, resource use (energy), and waste management. A high priority or very high priority ranking was ascribed to climate change, air pollution, resource use (energy), and waste management by 81%, 65%, 73%, and 45% of the respondents, respectively. Finally, 83% of respondents either *agreed* or *strongly agreed* that working across departments in their institution was very important. These results indicate that institutional structures would or do support coordination across an institution's departments, at least in theory. Such coordination could support an integrated or coordinated approach to recognize and take advantage of synergies, for example, between air quality and climate change or other environmentally relevant areas.

3.3. Decision-making tools

In this section of the paper we explore the survey results pertaining to the utility and usage of decision-support tools. Out of all respondents, 37% indicated that they were at least aware of a decision-support tool similar to the prototype presented in the survey (although not necessarily focused on an integrated approach).

However, of those 37%, less than half had used any of the tools. When asked about their awareness of such an integrated decision-support tool or other form of integrated assessment information already being used in their institution, only 16% of respondents replied positively. Topics covered by tools in use included life cycle assessment; economic and technical assessments; climate change information, air pollutant information, sometimes in combination with resource/energy information; and environmental cost-benefit analyses. Participants, however, provided limited information about these tools beyond the topic. Specifically, they gave little information about specific names, web addresses, or functionality. These results indicate a limited awareness of decision-support tools, and even more limited implementation. This lack of awareness and implementation may result from any number of reasons not covered in the survey, but could range from a simple lack of information to poor usability, to the utility (or lack thereof) of the information included.

Figure 6 presents the responses to the closed questions about qualities that affect usefulness of a decision-support tool, based on respondents exploring the prototype tool. When asked if they generally needed comparable information on the effect of measures on air pollution and climate change, as well as if they needed the information presented in a form such as or similar to that provided by the prototype tool, the majority (≥75%) of respondents *(strongly) agreed* (**Figure 6a**). A series of questions addressed the utility of the tool for supporting or influencing policy decisions (**Figure 6b**). More than 75% of participants indicated that such a tool could provide a useful starting point for policy decisions and over half responded that information provided by such a tool could influence which measures might be pursued or promoted. However, it was similarly clear that such a tool could not be the sole basis for a policy decision. Additional support would be required for policy decisions beyond any qualitative information the tool might provide. When asked about the type of information included in the tool (**Figure 6c**), only 35% of participants thought that the information given would be too general for use. That said, at least 75% of the respondents indicated that the quantitative information added important value, and that pollutant specific information and city specific information would need to be included in such a tool to support decision making. Sixty-six percent indicated that providing the tool in English only would be insufficient, indicating that providing the information in the local language may remove one of the barriers to tools being accepted and used. Finally, when asked to agree or disagree to the statement 'I would not know what to do with this tool' only 21% *(strongly) agreed* with the statement. Assuming that those surveyed understood the content of the tool, this percentage therefore likely found no utility in such tools.

These results indicate that participants see a need for such comparable air pollution and climate change information, and would find such a decision-support tool

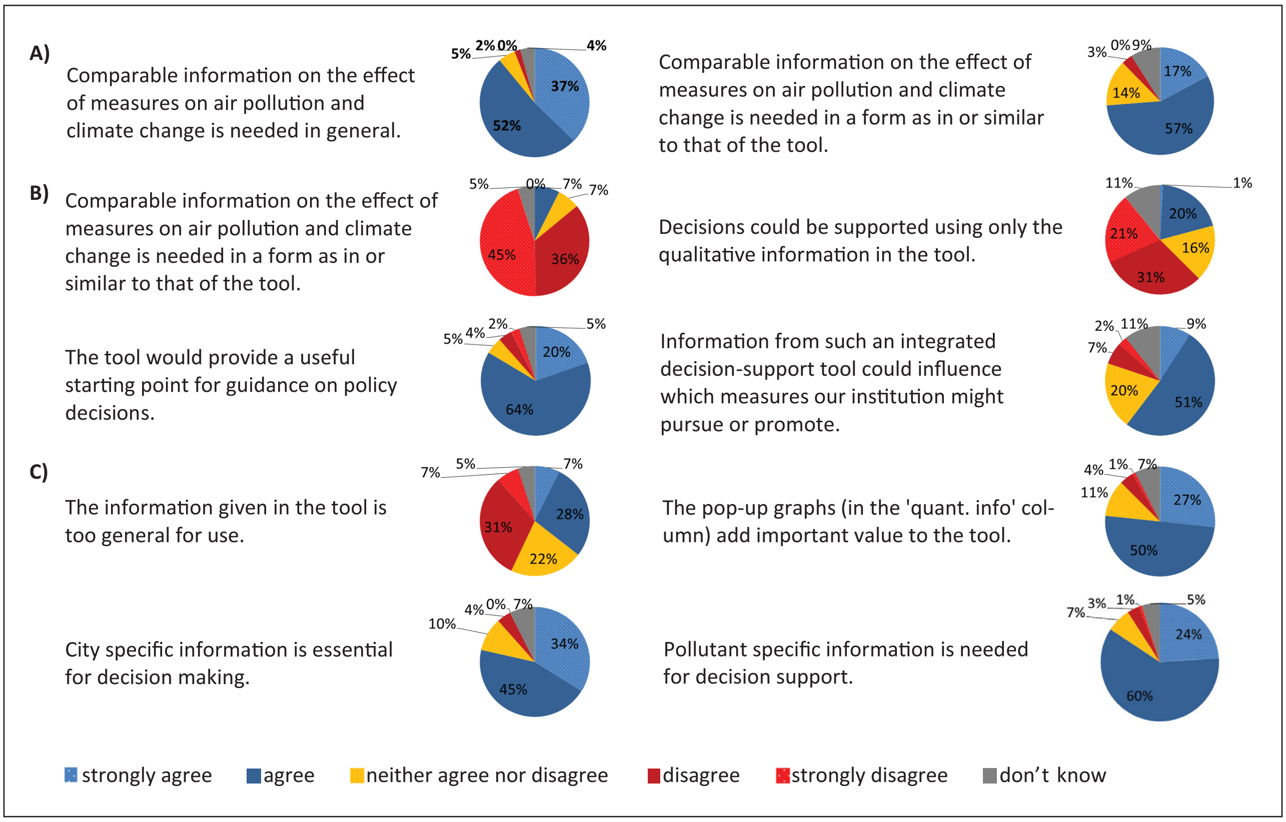


Figure 6: Participants' opinions on qualities of an ideal decision-support tool. Participant responses to closed questions addressing qualities of the prototype decision-support tool that would make such a tool useful. DOI: https://doi.org/10.1525/elementa.126.f6

a useful starting point to inform policy decisions. However, quantitative information would be needed to support decision-making at city level, which is likely much more than such a tool could provide while still being applicable to a wide range of users. The tool would also need to be provided in the local language. Given the initial indication of required features for uptake and use of such tools, it is not clear whether the effort required to create such a tool would match the benefit for the pool of potential users.

Seventy-one percent and 19% of participants provided general feedback about the prototype decision-support tool, in the form of written responses, directly after viewing the tool and again after the closed questions about the tool, respectively. In terms of an initial response, the majority of comments were positive, with 65 participants responding with comments classified as positive (e.g., 'looks useful' or 'very good screening tool'). Fourteen of the participants had negative impressions of the tool (e.g., 'unclear' or 'not understandable straightaway'), while seven participants provided comments that were interpreted to be 'neutral' (e.g., 'no judgement as first impressions have not yet been digested' or 'difficult to assess'). For both questions, a number of participants commented on the amount and detail of the information that should be included, the most common comment was for the tool to include 'more information' (>25 participants between the two questions). This was followed, in smaller numbers, by comments that the tool was 'too general' or useful only as a 'starting point' and that cost information and more measures would be crucial to include in such a tool.

Based on participant's responses to the closed question, the minimum requirements for such a decision-support tool to be useful are, listed here in the order from highest selection to lowest: quantitative information (74%), qualitative information (73%), costs (67%), detailed information (47%), references for the source of information provided in the framework (44%), and general information (36%). Further suggestion about minimum characteristics from the 'other' category included: examples of successful implementation of measures, information on co-benefits, health information, inclusivity of all relevant thematic departments/areas, contacts, error bars, policy instruments for implementation, information as to the application limits, required preconditions for implementation, possible negative consequences, and the flexibility to consider new developments. In summary, participants considered a significant amount of information to be a minimum to have a really useful tool. Furthermore, the diversity in additional minimum characteristics would require substantial tailoring of these tools to each situation, consequently also making them less generally applicable.

We found connections between participants' answers about motivations for and barriers to an integrated evaluation of air pollution and climate change measures (**Table 1**). On the one hand, political regulations and legal obligations would motivate integrated considerations of these measures; on the other hand, the lack of existing regulations requiring a coordinated approach are limiting because it is hard to justify any additional time and resources to support this type of work. Of the 52% of participants who answered the question of motivation, 26% answered that they were already considering an integrated evaluation of air pollution and climate change measures. Other reasons cited that might motivate an integrated approach are listed in **Table 1b**. To contrast

Table 1: Categorized responses to the open questions about barriers and motivations[a]. DOI: https://doi.org/10.1525/elementa.126.t1

(a) Categorized responses (barriers); n = 70	**Number of participants**
Institutional barrier (e.g., lack of coordination, priorities)	14
Lack of resources (incl. time, finances, people)	14
Lack of information	13
Lack of coherent regulations and legal obligations	13
Mental barrier (incl. different interests, willingness, pressure)	9
Conflicts/restriction in measures (incl. definition and implementation)	7
Transparency and trust in outcome	6
None	5
(b) Categorized responses (motivation); n = 79	
Already doing this	18
Synergies/co-benefits	16
Political and legal regulations	14
Resources and priorities (incl. working interdisciplinarily)	11
More information	6
Awareness/public demand	5

[a]Questions were: (a) what are possible barriers to using integrated information to inform decisions about air pollution and climate change measures? and (b) what would motivate you (or from your perception, your institution) to consider an integrated evaluation of air pollution and climate change measures? As the questions were open questions, some participants may have given more than one reason, while others did not provide a response. The number of participants providing a response is listed in the heading (n-value).

this, participants gave a variety of reasons for barriers to an integrated approach. The most common barrier cited was institutional barriers, such as separate departments or priorities that do not reflect or facilitate such an integrated approach. Other barriers cited are listed in **Table 1a**. Only a minority of participants (6%) cited that there were no barriers to an integrated approach. When comparing the responses for motivations and barriers, many response categories were coherent through both, such as (financial) resources, priorities, information, and regulations.

When asked about the sectors in which they saw potential for the implementation of measures that would simultaneously reduce air pollution and mitigate climate change, participants named a wide breadth of sectors, despite the barriers discussed above. The most relevant sector cited by the participants was by far transportation, which was mentioned just over 50 times. This answer showed up twice as many times as the next sector, energy. Transport and energy were followed by industry, city planning/development/infrastructure, residential heating/small boilers, agriculture/forestry, housing, waste, shipping, economy, and consumption (listed as e.g., consumer choices or reducing meat consumption). Finally, we did not categorize a number of other answers that only showed up once.

4. Discussion and conclusions

The survey results indicate, in the German/European context, a general interest in information regarding the effect of pollution mitigation measures on more than one sector, such as air quality and climate change. The majority of participants recognized the linkages between air quality and climate change, with an even greater recognition (88% of participants) that air pollutants and greenhouse gases are emitted from many of the same sources. Unsurprisingly, given the target audience of the survey, participants indicated that their institutions assigned a high priority to environmental issues, with climate change receiving the highest ranking of importance of the options available. Approximately 40% of the participants indicated that their institutions conduct some broader evaluation of impacts of air pollution or climate change mitigation measures, although this is not universal. Participants indicated that, in general, a more coordinated approach in terms of intra-institutional cooperation would be desirable.

Participants' overall awareness of existing decision-support tools was not high (about one-third of participants reported being aware of any), and their use of existing tools was even lower, with only 16% of participants who were aware of such tools reporting use of a decision-support tool either by themselves or others in their institution. Nevertheless, participants responded overwhelmingly positively to the general need for such integrated information as presented in the prototype tool. Their responses also identified a number of barriers which limit the possibility of using such tools, especially limited legal support or lack of time, finances, or manpower. This is in line with previous work that found similar problems applying to such decision-support tools (Carnevale et al., 2014). When asked about the minimum characteristics for a useful decision-support tool, about three-quarters of the participants considered quantitative information to be a necessary minimum. Furthermore, their feedback indicated that situation specific or information regarding the local context would be desirable or a necessity; and they gave similar responses regarding economic and cost information. Participants indicated that the utility of such a tool would likely be to inform policy early in the decision-making process or provide a starting point for the evaluation of a variety of measures. These indications of desirable and required information and of the likelihood that such a tool would be used do not provide a promising picture overall; and especially not for developing decision-support tools aimed at a wider applicability and broader user base. Survey participants saw a wide applicability of integrated information on the effects of air quality and climate change for supporting decision-making on measures from a wide variety of sectors. For these tools to be used, quantitative information that accounts for the local situation is required. To foster use, such tools would likely need to be developed considering local conditions and in cooperation with the end users, which would likely reduce the applicability of the decision-support tool to other cities and user groups.

It remains a challenge to translate scientific knowledge on the importance of tackling air quality and climate change in a coordinated manner into action in sub-national policy. The main barrier identified in this study is the gap between information desired by potential users of decision-support tools and the readily available information that developers can incorporate into such tools. That is, potential users want detailed information from such tools to make them useful at the local scale, whereas tool developers have only higher-level information readily available. Theoretical or global-level information can spur motivation for local transitions towards sustainability, as shown by this study. However, it cannot effectively support local action. Given the gaps in information on sub-national or local-level impacts of air quality and climate change mitigation measures, stronger engagement of national and local research institutions is needed to create a salient knowledge base. This finding supports the general notion on the 'crisis of research effectiveness' for sustainable transitions (e.g., Kueffer et al., 2012). This 'crisis', however, can be overcome by engaging researchers to create locally relevant data to be used in combination with decision-support tools such as the decision-support tool tested in this work, multi-criteria assessments (Schmale et al., 2016) or joint scenario development (Bügl et al., 2012; Stauffacher and Scholz, 2012) amongst others, where success has already been demonstrated. In conclusion, effective on-the-ground sustainability transitions need to go hand in hand with production of knowledge at appropriate scales to inform these transitions.

Data Accessibility Statement

Interested parties may contact the authors to view/receive survey responses, in accordance with proper protection of the human subjects surveyed.

Supplemental File

The supplemental file for this article can be found as follows:

- **Text S1.** A complete version of the survey (English language version only). DOI: https://doi.org/10.1525/elementa.126.s1

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Competing interests

The authors have no competing interests to declare.

Author contributions

All authors contributed to the conception, design, analysis and interpretation of data. EvS drafted the article, RDK and JS revised the article and contributed to the development of tables and figures. EvS approved the submitted version for publication.

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