July 2013

# Urban air quality citizen science

# Phase 1: Review of methods and projects

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This report is part of a programme of work commissioned by the Scottish Environment Protection Agency (SEPA) on behalf of the Scotland's Environment Web Project, supported by the European LIFE+ programme

## Summary

This report will comprise suggestions of links with other work and possible approaches for taking the work forward, providing a map of current and recent air quality related Citizen Science activities in the UK, Europe and beyond.

In this deliverable, we map out the technologies and approaches currently available for air quality monitoring and provide an overview on how they could be applied in a citizen science context. In addition, we provide an overview of existing citizen science activities with relevance to air pollution.

The focus of this report will be on the specific aspects of air pollution monitoring in a citizen science context; we refer to Roy *et al.* (2012) for a more general discourse on citizen science projects. As far as possible, we will closely link to another SEPA funded project with a focus on citizen science for environmental monitoring (by direct personal contact with colleagues at CEH), as well as other ongoing and emerging projects (e.g. EU FP7 project CitiSense, Transport Scotland, etc.). The objective of this report is not to draw final conclusions, but to provide the material and information resources for the following phases 2 and 3 of the pilot project.

# Table of contents

# 1 Acronyms & Abbreviations

| | |
|---|---|
| AOTx | Accumulated Ozone over a Threshold of x |
| APP | Smartphone/mobile device application |
| AQ | Air quality |
| CEH | NERC Centre for Ecology & Hydrology |
| CO | Carbon monoxide |
| COBWEB | Citizens OBservatory WEB European Commission FP7 research project |
| EDINA | Part of the division of Information Services at the University of Edinburgh |
| EU/EC | European Union/Commission |
| FP7 | European Commission 7$^{th}$ Framework Programme |
| GEOSS | Global Earth Observation System of Systems |
| GPS | Global Positioning System |
| ICP | International Cooperative Programme |
| IOM | Institute of Occupational Medicine |
| LIFE+ | European funding scheme |
| mAH | Milliampere hours |
| N/A | Not applicable |
| NASA | National Aeronautics and Space Administration |
| NiMH | Nickel-metal hydride (batteries) |
| $NO_x/NO_2$ | Nitrogen oxides/dioxide |
| $O_3$ | Ozone |
| OPAL | Open Air Laboratories network |
| $PM_x$ | Particulate Matter with an aerodynamic diameter < $x$ µg |
| ppm/ppb | Parts per million/billion |
| S3C | Scottish Sensor Systems Centre |
| SHS | Second-hand smoke |
| TCV | The Conservation Volunteers |
| TWA | Time-weighted average |
| VOC | Volatile organic compounds |
| WHO | World Health Organisation |

# 2 Introduction

## 2.1 Background

Clean air is a basic requirement of life (WHO, 2005a, 2005b, 2010). Yet, particularly in urban areas, air pollution related health impacts affect the well-being of a large number of people and in many European cities, air quality limit values are exceeded on a regular basis. The European Commission has declared 2013 the "Year of Air"[1] and the European Environment Agency identified in its 2012 report on Air Quality in Europe[2] that - while progress has been made with most pollutants - a large share of the European population is still subject to adverse health effects from particulate matter, nitrogen dioxides and ozone. This picture becomes even more compelling if the WHO guidelines for those pollutants are taken into account instead of the less stringent limits implemented by current European legislation.

Scientific research into air pollution monitoring and effects, technological development into sensors and the widespread use of electronic equipment (e.g. smart phones and tablets) are leading to an increase in our ability to gather relevant environmental and positional data. Making use of these developments thus makes it possible, for the first time, to explore how integrating sensors for air quality may enhance the monitoring of the temporal and spatial variability of air pollution, which has so far been difficult to address.

Existing air quality monitoring networks have been primarily established to fulfil regulatory requirements, for instance in response to the EU Air Quality Framework Directive and serve the reporting obligations embedded in national and European law. Monitoring sites have to comply with a set of stringent requirements to attain 'reference' standards and the instruments deployed are thus expensive and require substantial maintenance and operational skills. Due to these aspects, current monitoring networks typically have few sites located in areas that are anticipated to give a sufficiently representative idea of air quality in - mostly urban - areas. As an example, there are only a handful of air quality monitoring sites for particulate matter with an aerodynamic diameter of < 10 $\mu g/m^3$ ($PM_{10}$), in the Edinburgh city area, and only one station monitoring $PM_{2.5}$.

Air quality monitoring networks are making an important contribution in providing data to assess trends and observe the effect of emission control measures. However, their limited extent means that they cannot provide an adequately high resolution (spatio-temporally) picture of air quality, which is subject to local conditions (e.g. hotspots at busy crossroads) and variation over time (e.g. the morning and evening rush hour contributing peak concentrations from traffic emissions). Yet, this information is vital when making the direct links between air pollution and health effects, for instance applying methods to measure personal exposure of individuals to air pollutants (see Steinle *et al.*, 2013).

## 2.2 Overview

In the following sections, we will discuss how existing sensor technologies, and pilot studies applying these, can provide a basis for the design of more methodological and representative citizen science projects than is currently the case. With such projects, the contribution of citizens to the collection of large volumes of data with high spatio-temporal resolution, using low-cost and easy to operate

[1] http://www.eea.europa.eu/highlights/2013-kicking-off-the-2018year
[2] www.eea.europa.eu/publications/air-quality-in-europe-2012/at_download/file

devices, would be one key result (see as well Roy *et al.*, 2012, p50). However, the involvement in and the direct feedback from such activities may have the potential to empower citizens to consider their personal contribution to local air pollution and their individual exposure to it. Thus a citizen science approach not only provides a tool to inform but could ultimately alter behaviour leading to a reduction of air pollution levels beyond those achievable through general regulatory measures.

The *Scottish Air Quality* network website[3] provides a good general overview of monitoring methodologies, dividing them into five main types (with a wide range of costs and performance levels):

For the purpose of this report, only the first two categories of sensor technologies are relevant, as the focus is on citizen science applications and automatic monitoring equipment is typically very expensive and not portable (see AQMesh/Emote description).

**Table 1.1.** Overview over measurement methods relative merits are shown in the table below and discussed in the following section. The use of a particular type of monitoring equipment may need to be justified in review and assessment reports and therefore should be chosen appropriately. Source: Scottish Air Quality[3]

| Method | Advantages | Disadvantages |
|---|---|---|
| **Passive sampling** | **Low cost - simple. Useful for screening and base-line studies and in support of automatic monitoring for Detailed Assessments.** | **Unproven for some pollutants. Laboratory analysis required. In general, only provide weekly or longer averages.** |
| **Photochemical and optical sensor systems** | **Can be used portably.** | **Low sensitivity may only provide spot measurements.** |
| Active (semi-automatic) sampling | Low cost - easy to operate - reliable. Historical data sets available from UK networks. | Provide daily averages. Some methods are labour intensive. Laboratory analysis required. |
| Automatic point monitoring | Provide high resolution data. On-line data collection possible. Provide path or range-resolved data. | Relatively expensive. Trained operator required. Regular service and maintenance costs. |
| Remote optical/long-path monitoring | Useful near sources. Multi-component measurements possible. | Relatively expensive. Trained operator required. Data not readily comparable with point measurements. |

In this report, we will thus both discuss approaches that directly monitor air quality and passive methods such as biomonitoring, which provide a more indirect measure of air quality and its effects (e.g. OPAL). While personal monitoring solutions have the advantage of providing direct feedback to users, technologies are in a relatively early stage of development. Biomonitoring methods have been

[3] http://www.scottishairquality.co.uk/about.php?n_action=monitoring&t=3&item=2

widely applied and could therefore offer a robust near-term opportunity, but are not available for all air pollutants.

We refer as well to the recent report to SEPA by Pocock *et al.* (2013), which addresses several strategic issues for implementing citizen science projects. The conclusions reached and issues discussed are in most cases highly relevant for what we describe in the following sections and the findings will be taken into account for the next phases.

# 3 Existing sensor technologies

## 3.1 Concepts for the evaluation of personal sensors

While a comprehensive and systematic review of all currently available sensors is beyond the scope of this pilot study, there are several ongoing activities which indicate that the development of air quality sensors is a rapidly emerging field. Both sensor developers and those interested in their use appear to be at a stage where widespread deployment of these sensors is imminent (see also section 2.2 on use cases).

The following guiding questions will be applied to review existing sensors and applications. These will be used, in the next phases of the project, to derive a programme for projects based on the recommendations on monitoring approaches or sensor technologies that may be used in phases II and III of this project, which will as well identify and discuss the benefits to participants:

- Scientific/technical quality:
  - Is a sensor fit for purpose?, i.e. can it measure ambient air pollutant concentrations across an adequate range, with sufficient sensitivity?
  - Are cross-sensitivities and other factors influencing the measured concentration levels known? Are sensors calibrated?
  - Can information from the sensors be readily downloaded to a web portal for mapping, accessed in real-time (e.g. on mobile devices) or displayed at central locations for the general public?
- Applicability and usability:
  - Are sensors commercially available or is there a production mechanism to allow their use in sufficient numbers?
  - Are sensors and sensor-packages easy to operate by a lay person?
  - Does operating the sensors or extracting/reporting data require specialist skills?
  - Are sensor-packages cumbersome with the potential to interfere with people's daily activities?
  - How well can sensors be integrated with contextual information gathered (e.g. time stamps, other synchronisation aspects)?
  - Battery lifetime/operating time?
- Costs and form factors:
  - Are sensors sufficiently cheap to allow for a wide-spread use within an appropriate budget?
  - Are sensors (commercially) available in sufficient numbers?
  - Are sensor packages robust and small enough to be easily carried or deployed? Are data communications set up in a way as to incur no additional costs to users?

These guiding questions will be refined in the first phase of the project with input from volunteers and based upon experiences with a deployment in the context of a PhD student's research project conducted by CEH. A final set of criteria for sensor selection will be developed and discussed with SEPA and other stakeholders to aid the selection of both sensors and methods that are likely to yield the best results from a pilot study in phase III. With this in mind, we will review only low-cost sensors and not, for this report, take into account industry-grade products with a unit price that would make them too expensive for a wide-spread deployment. For the purpose of this pilot study, we regard a personal sensor costing < £500 per unit, respectively a fixed site sensor node with a price < £5,000 as viable.

## 3.2 Use cases of air quality sensor application

For the application of air quality sensors in a citizen science context, two main use cases can be identified:

1. small, lightweight portable sensors worn or carried by individuals can provide a good measure of personal exposure and at the same time generate a spatially and temporally resolved picture of urban air quality.
2. network of fixed monitoring sites, for instance a smaller version of an AQ Mesh type network, could be deployed to and operated by citizens across an urban domain, providing a spatially better resolved network than current fixed site reference installations.

It is likely that the latter variant would have limited potential for user engagement and result in a citizen science project with few opportunities for genuine inclusive participation - perhaps similar to the operation of private weather stations - to observing current levels and trends of air pollutant concentrations and other variables. To engage the local residents, access to such sensors could be made via a web interface and this could inform the general public about air quality in their local community.

A key criterion for the application is the degree of data quality that is required. It is clear that none of the sensors currently available is likely to have sufficient precision to achieve equivalence (see EC, 2010) to reference sites in existing monitoring networks. However, a hybrid approach with high quality fixed site sensors and a larger number of small, low-cost sensors which could be calibrated and validated against the nearest fixed site sensor when a mobile sensor unit passes near a fixed reference site (this is, for instance, applied in the city of Zurich with low-cost sensors on trams) could be a good compromise between quality and feasibility or cost.

Another vital (and often underestimated) aspect is that of data generation and management. Even a small network of air quality sensors will quickly generate a large amount of data points (for example, monitoring air quality and location once a minute over a week easily generates several tens of thousands of data points for one person only), which will need to be managed and evaluated. Ongoing work e.g. in the EU FP7 project COBWEB (http://cobwebproject.eu/) and emerging work under the Global Earth Observation System of Systems (GEOSS) will need to be considered for setting up the data infrastructure of such a citizen science network of sensors. The delivery mechanisms of data (from manual retrieval and sending datasets to automatic wireless communication using 3G/4G technologies or WIFI) need to be taken into account as a major cost factor. Existing infrastructure (such as WIFI enabled buses or trams) and crowd-sourcing approaches should be explored for the implementation of a programme.

## 3.3 Examples of air quality sensors

Air quality sensors can be quite varied, from very expensive, high specification reference equipment costing several tens of thousands of pounds, to small commercially available sensors at the size of a pound coin and costing a few pounds. The degree of system integration and form factor, the required precision and visualisation capabilities and the ruggedness of the packages often determines the size and infrastructure needs of sensor solutions. The different technologies have specific advantages and disadvantages depending on the environment in which they are applied, or, for instance, the temporal resolution they can achieve, power consumption or other technological determinants.

The most mature portable sensors have been developed for monitoring compliance with air quality standards in workplace settings, e.g. the TSI Sidepak Personal Aerosol Monitor AM510 (see below). This explains as well, why many electrochemical sensors which can be purchased from sensor companies have sensitivity ranges which are in the ppm rather than the ppb concentration domain. Industrial grade monitors for workplace compliance monitoring and leakage detection are often quite expensive (> 1,000 £/unit) and of high accuracy, while not always being very portable or easy to operate. Units often produce relatively high noise levels (from high volume pumps) that can be obtrusive in normal daily activities.

Current low-cost sensors mainly cover the following air pollutants:

- Particulate matter (in most cases, particle numbers based on laser sensors for $PM_{2.5}$ or $PM_{10}$)
- Carbon monoxide (CO)
- Nitrogen oxides ($NO_x$)
- Ozone ($O_3$)
- Other gases (VOCs, $SO_2$, …)

For urban environments, the particle counters and $NO_x$ and CO sensors are most relevant to determine air quality, with ozone becoming more of an issue in urban environments due to continuing reductions of $NO_x$ emissions especially from road transport affecting urban atmospheric composition. The following sensor packages show the different approaches taken and similarities between them.

### *3.3.1 Dylos Corporation 1700 battery operated air quality monitor*

The Dylos 1700 is a laser particle counter with 2 size ranges (>0.5 & >2.5 µm) distinguishing the output in numbers of small (bacteria, mould, etc) and large (pollen, etc.) particles. It can be deployed with mains power for continuous monitoring and for approx. 6 hours with a fully charged internal battery. Designed for indoor use, it has been intensively used in the UK through a citizen science approach by the University of Aberdeen to monitor exposure to and effects of second-hand tobacco smoke. Chamber and in-home data has been used to provide a conversion factor between the output in terms of particle number concentrations and mass concentration, at least for second-hand tobacco smoke aerosol (Semple *et al.*, 2012). Similar work to generate conversion factors for other combustion and non-combustion type aerosols has recently been reported by Northcross et al (2013).

It is also currently being used in a pilot study in the frame of a PhD student research project at CEH where it is combined with a GPS receiver to track geo-referenced particle concentrations in every day environments to determine if it is feasible to use this package robustly in a personal exposure assessment setting (see Fig. 3.1).

Advantages of the Dylos 1700 are the ease of operation (for up to 6 days of monitoring with current memory capacity, only switching the Dylos on and off and maintaining a charge level is required for mobile use, making it easy to operate without expert knowledge) and the low cost (~ 300£/unit). Disadvantages are the relatively large form factor and the lack of a weatherproof enclosure, making it unusable in wet conditions. In addition, the process of downloading and transmitting monitoring data requires the use of specialist software and moderate computer literacy, as the device does not have a built-in data transmission capability.


**Figure 3.1.** The monitoring pack - the Dylos instrument is strapped onto the backpack with the back exposed to the air. To avoid the interface buttons being pushed accidently, we put a protective plastic cover over it. A hole drilled into the plastic allows reaching the on/off button with a pen for example. The exposed design of the backpack restricts its outdoor use to dry weather conditions.

Field trials with the Dylos 1700 are continuing, including validation experiments against reference particle monitoring devices to exclude effects e.g. of temperature and relative humidity when deploying a device primarily designed for indoor use in an outdoor environment. Semple *et al.* (2012) have evaluated the Dylos' performance against a Sidepak AM510 (which is about 10 times more expensive) and documented satisfactory agreement between the two instruments, despite their substantial price difference; evaluations and validation experiments at reference monitoring sites are currently under way with the Dylos 1700 to test its performance in outdoor environments. There is also likely to be potential for differentiation of particle source type using the ratio of small to large particle numbers. This may be useful in determining if air pollution is derived from vehicle engines or from local incidents such as construction or demolition. This ‘finger-printing’ work is currently ongoing at the University of Aberdeen. While laser-based particle counters do not provide direct particulate matter mass concentrations, but rather numbers of particles, indicative functions to derive approximate mass concentrations are being tested for indoor/SHS, outdoor rural and outdoor urban environments. A publication describing the approach and documenting the results is in preparation.

More information: http://www.dylosproducts.com/dc1700.html

### *3.3.2 Sensaris Senspods*

*Sensaris*, a French company, produces a range of different portable sensors, some with a focus on air pollution. Among these are the ECOSense package, which monitors carbon monoxide (CO), nitrogen oxide ($NO_x$), Noise, Temperature and relative Humidity, and EcO3sense (Ozone, Temperature, relative Humidity) and EcoPM (particulate matter, based on a laser particle counter). All sensors are uncalibrated and use a bluetooth connection and a smartphone application (Android) to send data to a central web portal. Data can be explored, visualised and downloaded (as CSV) from this web portal by the user (login required) and can be made openly available by the user on a basic map application for viewing by the general public.

A first test application of an EcO3 and an EcoPM sensor delivered in April 2013 (see Fig. 3.2) conducted by CEH have so far not yielded satisfactory results, with substantial problems for both sensors to reproduce actual temperature and ozone levels adequately, and a completely failing PM sensor. These may be teething problems and further communication with the manufacturer will be conducted to identify the source for these problems and how to resolve them. EcoO3 can be worn with a flexible strap around an arm or on a belt, whereas the EcoPM prototype is so far not designed for mobile use and wearing.

The form factor of both the ozone and PM sensors are very small and with battery lifetime of approx. 5 hours according to the manufacturer, and would be suitable for deployment for short-term measurements. Recharging is straightforward with a standard micro-USB cable typically used for mobile phone connections. The sensor management with the Android app does not require advanced skills and could be done by a moderately technologically savvy layperson. However, the Android app and the use of both GPS and Bluetooth appears to drain the mobile phone battery of a Samsung Galaxy S3 high end phone at a rate of 20%/hour, which would equally limit the application over longer periods of days or weeks. The packaging of both sensors appears moderately robust, but no information is provided in relation to the devices' weatherproof capability. A first impression would be that they are not suitable for use in wet weather.

Finally, the web interface provides a useful set of tools for visualisation of e.g. daily activities and movements, and both the smartphone app and the web interface provide an easy to interpret "air quality index" value. However, the web portal so far is in an early stage of development and in many ways non-intuitive - requiring better documentation and guidance to be used by the general public.

The cost of the *SensPods* at £420 (EcO3) and £320 (EcoPM) are relatively low, but the requirement of having a Bluetooth-enabled smartphone needs to be taken into account.


**Figure 3.2.** Sensaris EcO3Sense (left) and EcoPM (right) sensors tested in April 2013 (Dimensions EcoO3 - 50 x 80 x 20 mm; EcoPM 75 x 97 x 46 mm (W x L x H))

More information: http://www.sensaris.com/

### 3.3.3 Panstamp RESPIRA sensor

A recent development is the *Panstamp* RESPIRA sensor, which is a community project focusing on the development of a low-cost multi-environmental sensor device for urban spaces. This wireless node measures CO and $NO_2$ levels, temperature and humidity. The envisaged air quality index value assessment of concentrations < 25 ppb of $NO_2$, however, may be difficult to deliver, as the $NO_2$ sensor used has a lowest sensitivity of 0.05 ppm (i.e. 50 ppb). At this time, there is no known application or review available of this sensor in a real world environment. At this stage, the RESPIRA sensor is under development and at a prototype stage, with no costs for the package available.

More information: http://www.panstamp.com/announcements/respirasensor

### 3.3.4 CairPol CairClip sensors

The *CairClip* (USB version) was initially developed for the real-time measurement of pollutants and to survey the effect on people suffering from respiratory conditions. With various health and safety management systems in the workplace now requiring assessment of workers' chronic exposure to risks the *CairClip* has been developed to measure and to follow-up occupational exposure.

Available in a small housing that can be attached to a belt, helmet clip or carried around the neck, the micro-sensor *CairClip* continuously measures the individuals exposure to the particular pollutants, and records the data which can then be downloaded onto a PC. Details on the technology used are not currently available from the company website

*ClairClip* is presently available for the measurement of $O_3$/$NO_2$, $H_2S$ and sulphur compounds, and $NH_3$. Further developments are in progress for other specific pollutants. In the current version, the battery lifetime achieved is 24 to 36 hours. The *CairClip* sensor appears to be in prototype stage and no cost information is provided, with the sensors likely to be custom built on order.

**Figure 3.3.** CairPol CairClip sensor *(images courtesy of CairPol)*

More information: www.cairpol.com

### *3.3.5 RTI MicroPEM*

RTI has developed the v3.2 MicroPEM™ single channel personal exposure sensor/sampler (Build II). The MicroPEM technology provides exposure data at the personal level in a very low-burden package that can be worn by individuals to significantly enhance studies of public and occupational health. The current v3.2 MicroPEM allows for personal exposure characterizations simultaneously defining both the integrated exposure (filter based) as well as the patterns of exposure in real-time in a wearable low-burden package weighing less than 240 grams. Selectable U.S. EPA particle cutpoint definitions of PM2.5 or PM10 relate the collected data to targeted respiratory system deposition zones (deep lung or thoracic, respectively). On board collection of quality control data and accelerometric motion levels allows validation of both wearing compliance for the collected samples and data, as well as enable estimates of ventilation and potential dose following the methodology of Rodes et al. (2012). The microPEM monitors PM2.5 or PM10, with different inlets and has an average operating time of 168 hours on 3 AA batteries. Measurement data is downloaded via a USB connection using a bespoke software. Unit costs of the microPEM are ~ US$ 2,000 (~£1,290), with additional material (spare inlets, filters) as well as the precision filter weight analysis potentially incurring higher operation costs.

More information: http://www.rti.org/page.cfm?objectid=E19BDB1B-A77F-E4A3-F83126CB83065E76.

### *3.3.6 iDust (under development, U Aberdeen)*

The Respiratory Group at the University of Aberdeen are currently in the process of developing a low cost particle monitor using off the shelf components. The device in development (iDust, Fig. 3.4) utilises the *Arduino* open-source electronic prototyping platform and a *Shinyei* PPD42 particle sensor. The Shinyei sensor counts the number of particles > 1 µm and > 2.5 µm passing the measurement area of the sensor. At present the device only monitors the particles greater than 1 µm. No fans or pumps are required for this sensor as the sensor incorporates a heating element to create a thermal draft to pull the particles in to the sensing area. As has been carried out for the Dylos 1700 (Semple *et al.*, 2012), chamber measurements have been carried out with iDust to determine a conversion factor between particle concentration and mass concentration for tobacco smoke aerosol. A combined temperature and humidity sensor has been incorporated into the device with the aim of correcting the mass concentration for changes in humidity.

The iDust instrument runs off a DC supply from 6V to 12Volts and saves the data to a microSD memory card. The iDust is relatively straight forward to use. The user attaches the power cable and then presses the start/stop button and the device will log the 30 second average twice a minute; to stop logging the user presses the start/stop button. Data is downloaded from the iDust by connecting the power cable and then connecting the iDust to a PC with a USB cable, (bespoke download software on the PC is required to download the data) and the data will be downloaded once the download button is pressed on the iDust. The data is then saved in CSV format for further analysis. Other elements to extend the device run time when using batteries are being explored.


**Figure 3.4.** iDust prototype

Initial comparison with the TSI SidePak AM510 Personal Aerosol Monitor gives an $R^2$ value of between 0.85 and 0.9. At lower concentrations of second-hand smoke (SHS) the Shinyei sensor does not appear to perform as well as the Dylos DC1700 with a minimum concentration that can be measured of between 16 and 25 $\mu gm^{-3}$. The upper maximum mass concentration of SHS appears to be about 6,000 $\mu gm^{-3}$.

The component cost of the basic iDust incorporating the particle and temperature and humidity sensors is currently less than £100 including the power supply. Further work is being carried out with the view of making the device smaller (i.e. wearable) and with the ability to run for 24 hours on battery power.

### *3.3.7 TSI SidePak AM510*

TSI Inc. produces precision measurement instruments for measurements relating to aerosol science, air flow, indoor air quality, fluid dynamics and biohazard detection. TSI's headquarter is based in the U.S. and field offices are distributed throughout Europe and Asia.

The SidePak™ Personal Aerosol Monitor AM510 is a rugged, lightweight, belt mounted laser photometer, weighing around 500g. It is compact and minimizes interference and discomfort of the person wearing it. The built-in sampling pump allows the attachment of a wide variety of size-selective inlet conditioners for worker breathing zone, or area measurements with a respirable cyclone, or one of the three integrated impactors. The AM510 operates on long-running NiMH or alkaline battery packs and provides run time information in minutes remaining. The AM510 costs about £2,500, other TSI products, such as the TSI DUSTTRAK DRX Handheld/Portable 8534 Dust/Aerosol Monitor may cost significantly more, between £3,500 to £5,500. The operation of the SidePak for simple monitoring tasks is relatively simple, but for variable logging of data, the menu driven operation is not as straightforward for a lay person.

The core features of the SidePak AM510 are:

- Multiple battery options including 1650 mAH, 2700 mAH NiMH battery packs or a 6-cell, AA-size alkaline battery pack
- Precise run time information in minutes remaining
- Integrated pump allows use of size-selective aerosol inlet conditioners
- 10mm Dorr-Oliver Cyclone for respirable (4 micron) sampling
- Built-in impactors for 1.0, 2.5, 10-micron cut off sampling, i.e. for $PM_1$, $PM_{2.5}$ and $PM_{10}$
- Real-time concentrations ($mg/m^3$) and TWA during sampling
- Statistics functions: max, min. and average readings, elapsed time and 8-hour TWA

### 3.3.8 GeoTech AQMesh

The GeoTech AQ MESH sensors are (relatively) low-cost multi-gas monitors that can be deployed for instance at lamp posts or other fixed locations and provide ppb-level air pollution monitoring through a networked array of monitors. The monitors cover $NO_x$ (NO and $NO_2$), $O_3$, CO, $SO_2$, humidity and atmospheric pressure and are battery-operated with up to 2-year lifetime. The sensors operate autonomously and report measurements to a central web-accessible server from which all data has to be retrieved for further analysis.

**Figure 3.5.** GeoTech AQ Mesh deployed *(images courtesy of GeoTech)*

The AQ Mesh (see Fig. 3.5) units cost between £4,000 and £5,000 (for 3 and 5 gas setups) with additional costs for server access and maintenance in addition to the base unit costs.

### 3.3.9 Envirowatch E-Mote

The Envirowatch E-Mote system is similar in concept to the AQ Mesh discussed above and can monitor 3 different gases in parallel. At this stage, no detailed information has been made available regarding costs and performance of this system. A trial of E-Mote nodes in the Edinburgh Costorphine area is under way, conducted by Edinburgh City Council.

More information: http://envirowatch.ltd.uk/e-mote.html?showall=1

### 3.3.10 Custom sensor developments

As one of the key limitations of standard sensors available from different manufacturers are the low sensitivities to typical ambient concentrations, researchers (e.g. from the University of Cambridge) have been working closely with sensor manufacturers (in this case, AlphaSense) to develop more sensitive electrochemical sensors which are capable of sensing in the low ppb range.

In addition, cross-sensitivities (e.g. between $NO_2$ and ozone) and temperature or relative humidity influence on sensing performance can be effectively compensated for by custom software solutions.

The resulting sensor packages and platforms have been deployed in scientific studies on mobile air quality monitoring e.g. in Cambridge (http://www.escience.cam.ac.uk/mobiledata ) and a current project with a network of >50 fixed site monitor units around Heathrow airport (http://www.snaq.org/) can be regarded as state-of-the-art applications.

### *3.3.11 Other sensor developments and applications*

There are several activities e.g. in the US which feature stationary or mobile sensors and citizen science approaches. These include, but are not limited to the AirQualityEgg (http://airqualityegg.com/) and the CitiSense project (https://sosa.ucsd.edu/confluence/display/CitiSensePublic/CitiSense). The CitiSense project is a good example for a fully integrated sensor-to-infrastructure approach (see Ziftci et al. (2012) for a more detailed description), but has been a one-off development which is not currently continued.

In the Netherlands, an activity to engage citizens in measuring aerosols in the atmosphere (iSPEX, http://spie.org/x91494.xml) is currently under way. Within this project, a small optical device has been developed and distributed free of charge to interested citizens (currently limited to iPhone users, however) and at a certain day with specific meteorological conditions, all participants will be asked to conduct a measurement of the atmospheric composition at their location.

A recent workshop organised by the US Environmental Protection Agency highlighted a range of activities around environmental sensors with several examples for technologies and applications of relevance for this project. This information is being evaluated in detail and will be added to the next version of this report. Existing communities for air quality sensing such as http://communitysensing.org/ may be in a position to provide vital experiences with both technology and approaches.

A wide range of mobile device APPs are emerging as well, with different application concepts. A small selection can be viewed here:

- ObsAIRve iPhone APP: http://www.obsairve.eu/index.php?lang=en
- AirVisibilityMonitoring http://robotics.usc.edu/~mobilesensing/Projects/AirVisibilityMonitoring
- INTEL http://www.intelfreepress.com/news/smartphone-gives-turn-by-turn-directions-to-cleaner-air/6209
- Breathe Well, San Diego http://www.cbs8.com/story/21884506/free-smartphone-app-delivers-air-quality-information

Most of these developments, however, are in a pilot/project phase and not immediately accessible or transferable for application in a citizen science environment elsewhere. For long-term plans, it will be necessary to evaluate how these projects develop over time.

## 3.4 Evaluation of existing personal sensor technologies

The following Table 3.1 provides a first assessment of the sensor technologies currently available for citizen science approaches. Overall, there is an obvious trade-off between the commercial availability of sensors, their unit cost and the degree of system integration. The *Sensaris* concept, for instance, with small, lightweight sensors using Bluetooth connections with existing smartphones to broadcast personal monitoring data to a central web server is promising, however the technical quality of the existing sensors makes them unsuitable for application at this stage. In contrast, the SidePak AM510 is a mature commercially product air pollution monitor, but designed for industrial/workplace applications and (subjectively) too loud for application in day-to-day activities. In addition, the price tag of the AM510 (~£2,500) does not make it readily accessible in larger numbers for a citizen science project. The *CairClip* approach with a very small form factor looks promising, however there is no information on the sensing quality and operational handling of the sensors. The Dylos 1700 in connection with a GPS receiver, as currently applied in a student project, fulfils the usability requirements in general, albeit data retrieval and analysis requires a certain degree of computer literacy.

The Air Quality Egg presents an interesting approach, both with regard to the funding model for the development of the hardware, and the application. However, there are significant challenges as the sensors used are not calibrated and a quick check of data reported by AQ Eggs deployed highlights this, as no concentrations are reported, but just figures (some of them negative) with no immediate way to determine what this means in terms of concentrations. Secondly, while the carbon monoxide concentrations are featured as indicators for air quality, they are of limited use for human health impact assessment and to draw conclusions from CO measurements is not straightforward. For nitrogen dioxides, there is no information on the AQ Egg website on the type and build of electrochemical sensor used and from our experience, the stock-available sensors are traditionally not sensitive enough for a reliable assessment of ambient $NO_2$ concentrations. While conceptually appealing and definitely an approach to keep in mind for the long term, we do not see the AQ Egg viable for short term use in a citizen science environment due to these shortcomings.

While iSPEX ticks all boxes for a wide engagement with citizens, its usefulness for general air quality assessments is limited, as it is designed to measure aerosols in the atmosphere on a specific time/day rather than providing ambient air quality information at this stage. If a similar approach could be taken to develop a simple particle monitor with a form factor that allows direct connection with a smart phone (thus overcoming power consumption issues analogue to the *Sensaris* Bluetooth power drain), e.g. to monitor particle numbers directly, this could be a viable way forward.

Based on our evaluation, there are several packages and sensors available or in development which fulfil some of the requirements set out in the evaluation criteria, but none currently commercially available that could be regarded as mature enough for a full scale citizen science application at this stage. For trialling approaches and methods in pilot studies, a combination of different sensors for specific environments and requirements is readily available within the project team. However, for the mid- to long-term development of a robust citizen science capability, a viable and cost-effective approach may be to build on existing sensors and establish a collaboration with a technology development unit (e.g. the Scottish Sensor Systems Centre, S3C http://sensorsystems.org.uk/, respectively the Innovation Centre for Sensor and Imaging Systems, which was launched in April 2013) to produce bespoke packages which overcome the limitations of existing setups. The University of Aberdeen iDust may present a potential platform for such work.

**Table 2.1.** Overview of existing sensors mapped with evaluation criteria *(the ranking is based on expert assessment, with ++ = fully suited/applicable, + = partly suited/applicable, o = not fully suited/applicable, - = not suited/applicable, ? = not possible to assess with available information)*

| | Scientific/technical quality | | | Applicability/usability | | | | | Costs/Form Factor | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Is a sensor fit for purpose?, i.e. can it measure ambient air pollutant concentrations across an adequate range, with sufficient sensitivity | Are cross-sensitivities and other factors influencing the measured concentration levels known? Are sensors calibrated? | Can information from the sensors be readily downloaded to a web portal for mapping? | Are sensors commercially available or is there a production mechanism to allow use in sufficient numbers | Are sensors and sensor-packages easy to operate for a lay person? | Does operating the sensors or extracting/reporting data require specialist skills? | Are sensor-packages cumbersome with the potential to interfere with people's daily activities? | How well can sensors be integrated with contextual information gathered (e.g. time stamps, other synchronisation aspects)? | Are sensors sufficiently cheap to allow for a wide-spread use within an appropriate budget? | Are sensor packages robust and small enough to be easily carried or deployed? Are data communications set up in a way as to incur no additional costs to users? |
| Personal sensors | | | | | | | | | | |
| Dylos 1700 | ++ | ++ | + | + | o | o | + | + | ++ | + |
| Sensaris Senspods | - | - | ++ | o | + | + | ++ | + | + | + |
| Panstamp RESPIRA[4] | (++)[1] | ? | ? | ? | ? | ? | ? | ? | ? | ? |
| CairPol CairClip[5] | ? | ? | + | + | + | ? | ++ | ? | ? | ++ |
| MicroPEMS | ++ | ++ | + | + | + | + | ++ | + | o | + |
| iDust | (++)[2] | ++ | ? | o | + | + | N/A[3] | N/A[3] | ++ | + |
| TSI SidePak AM510 | ++ | ++ | + | ++ | + | + | - | + | - | + |

**Notes:**
1) no information on commercial availability
2) prototype development ongoing
3) designated for stationary use indoors
4) no sufficient information on development status available
5) sensors not tested yet, limited information available

# 4 Biomonitoring and other passive monitoring approaches

## 4.1 Biomonitoring and bioindicators

In their article on biomonitoring, Holt & Miller[4] set out general criteria for the selection of suitable bioindicators (see Table 4.1).

**Table 4.1.** Regardless of the geographic region, type of disturbance, environment, or organism, good bioindicators often share several characteristics. Source: Holt & Miller (2011)[4]

| | |
|---|---|
| Good indicator ability | Provide measurable response (sensitive to the disturbance or stress but does not experience mortality or accumulate pollutants directly from their environment) |
| | Response reflects the whole population/community/ecosystem response |
| | Respond in proportion to the degree of contamination or degradation |
| Abundant and common | Adequate local population density (rare species are not optimal) |
| | Common, including distribution within area of question |
| | Relatively stable despite moderate climatic and environmental variability |
| Well-studied | Ecology and life history well understood |
| | Taxonomically well documented and stable |
| | Easy and cheap to survey |
| Economically/commercially important | Species already being harvested for other purposes |
| | Public interest in or awareness of the species |

The advantages for the use of bioindicators identified in this article are, as follows:

- bioindicators add a temporal component corresponding to the life span or residence time of an organism in a particular system, allowing the integration of current, past, or future environmental conditions;
- bioindicators have the ability to indicate indirect biotic effects of pollutants when many physical or chemical measurements cannot.

However, some challenges of bioindicators need to be highlighted as well:

- populations of indicator species may be influenced by factors other than the disturbance or stress (e.g., disease, parasitism, competition, predation), complicating our picture of the causal mechanisms of change;
- bioindicator species invariably have differing habitat requirements than other species in their ecosystem, e.g. responses of selected bioindicators may not allow inferring effects on human health or other species.

In the *European Network for the Assessment of Air Quality by the Use of Bioindicator Plants* (EuroBionet[5], funded by the LIFE+ programme, LIFE99 ENV/D/000453), bioindicator plants have

[4] Holt, E. A. & Miller, S. W. (2011) Bioindicators: Using Organisms to Measure Environmental Impacts. Nature Education Knowledge 3(10):8

been used in twelve cities and regions in eight EU countries for monitoring air quality and promoting environmental awareness. In each of the cities, local bioindicator networks (> 100 monitoring stations) were established and operated over a period of three years. At these stations bioindicator plants (tobacco, poplar, rye grass, spiderwort/*Tradescantia* and curly kale) cultivated according to highly standardised procedures were exposed to ambient air in order to assess and to demonstrate the effects of ozone, sulphurous compounds, metals, hydrocarbons and mutagenic substances. The scientific investigations were accompanied by an intensive programme of public relations work and environmental education. Table 4.2 gives an overview of the plant species used as bioindicators in EuroBionet.

The successful use of bioindicator plants in the EuroBionet has contributed to a Europe-wide standardisation of bioindication, which provides a basis for its establishment as a procedure for effect-related environmental monitoring. EuroBionet showed as well that bioindicators are highly suitable for environmental education and municipal public relations activities and can contribute to a more efficient communication in the environmental sector between municipal authorities and the citizens they serve.

**Table 4.2**. Bioindication methods and effect criteria used in the EuroBionet[5].

| Bioindicator Species | Air Pollutants | Effect Criteria |
|---|---|---|
| Tobacco<br>(*Nicotiana tabacum* cv. Bel-W3) | Ozone (photooxidants) | Visible leaf injuries |
| Poplar<br>(*Populus nigra*) clone 'Brandaris' | Ozone (photooxidants),<br>heavy metals, trace elements | Visible leaf injuries<br>Accumulation |
| Spiderwort<br>(*Tradescantia* sp.) clone #4430 | Genotoxic substances | Chromosome damage<br>(micronuclei) |
| Italian rye grass<br>(*Lolium multi-florum* ‚Lema') | Sulphurous compounds,<br>heavy metals, trace elements | Accumulation |
| Curly kale<br>(*Brassica oleracea*‚Hammer/Grüsa') | Polycyclic aromatic hydro-<br>carbons (PAH) | Accumulation |

There are several publications in scientific literature originating from EuroBionet, describing the use of different plant species as bioindicators in more detail.

Finally, in the Picture Post Project[6] (part of the Digital Earth Watch network) is a NASA sponsored science initiative involving citizens in local environmental monitoring. The Picture Post site allows groups to share digital photos documenting local and regional environments. Using a Picture Post, a wooden or plastic box with an octagonal shaped platform on top, groups take eight photos of their area. Once the photos are uploaded they can be examined using analysis tools on the Picture Post site. After analysis the digital records are shared with all those dedicated to environmental monitoring and use. Groups are expected to return weekly or biweekly to record changes in the area.

[5] EuroBionet (2004) European Network for the Assessment of Air Quality by the Use of Bioindicator Plants (EuroBionet) LIFE99 ENV/D/000453, Final Report, 2004, https://ecology.uni-hohenheim.de/project/european-network-for-the-assessment-of-air-quality-by-the-use-of-bioindicator-plants-eurobionet

[6] http://picturepost.unh.edu/

In related projects, approaches to improve and facilitate participation in projects such as Picture Post have been investigated, e.g. by the *Blue Hill Observatory and Science Center*[7].

In Europe, The International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation, http://icpvegetation.ceh.ac.uk/ ) has conducted a lot of work over the years with biomonitors for ozone, using ozone-sensitive and – resistant clover and bean plants in recent years, for which stock plants and seeds are held by CEH in Bangor. A report[8] was published in 2007 on field evidence of ozone effects in Europe and subsequently a paper[9] has been published in Global Change Biology (Mills et al., 2011) on how the evidence of effects fits better with flux-based than AOT40-based risk maps. The paper also lists all the species of crops and natural vegetation (excluding trees) that have been found to develop ozone injury in the field, and could thus be used as biomonitors for ozone, e.g. in a citizen science approach.

While most of the ICP work had been unfunded, the development of a mobile phone and web-based APP is planned in the context of a Defra funded project (final decision on funding pending). The idea is for both trained scientists and citizen scientists to use the APP to upload photographs of potential ozone injury, their geo-location, the species, the recent weather (as a surrogate for ozone concentrations if they do not have access to ozone data). This incoming data would provide a database for Europe and beyond on locations of and degree of ozone damage. The APP had been intended to be developed as a trial version for the end of summer 2013, but due to contract delays, the development could not progress so far. The plan is now to launch the APP at the next Task Force on Measurement and Modelling (TFMM) meeting in January next year for a full run through spring and summer 2014. It will be very similar in principle to an APP recently launched by CEH on ladybird occurrence in the UK[10].

Such mobile phone/web based APPs have the potential to be widely used (they are free of charge to the user and based on existing personal devices) and may enable scientists to plot/track the impacts of high ozone episodes across Europe. In addition, the development of a database of users that could be informed by sending out notifications when ozone episodes occur so they know when to look for damage. While it is not directly transferable to health risks, it is nevertheless a very visible indicator that episodes are high enough to cause some damage and to engage with citizens in the documentation and analysis of this damage.

## 4.2 Other passive sampling options

In addition to bioindicators, technical solutions for passive sampling exist, for instance diffusion tubes for gaseous pollutants, glass slides and other gravitational samplers for dust/aerosols, which have been described in literature and practical application guidelines[11]. For particulate matter, viable approaches

[7] http://picturepost.unh.edu/resources/BlueHillObservatoryFINALReport.pdf
[8] http://icpvegetation.ceh.ac.uk/publications/thematic.html
[9] http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2010.02217.x/abstract
[10] http://www.ceh.ac.uk/news/news_archive/irecord-ladybirds-phone-app-monitor-uk-ladybirds_2013_31.html
[11] ASTM D6966-08. Standard Practice for Collection of Settled Dust Samples using Wipe Sampling Methods for Subsequent Determination of Metals. American Society of Testing and Materials, Philadelphia, USA.

are described and documented in Hunt (2011)[12] with a particular focus on reviewing existing techniques for an application within a citizen science environment.

In the context of 'nuisance dust' complaints due to nearby coal fired power plant emissions, the needs of the monitoring program were identified and the preferred method was characterized as follows:

1) ease in deployment and recovery of dust collection devices at multiple stations simultaneously,
2) samples represent passive dry dust fall on surfaces (these types of dusts were the basis for the nuisance complaints),
3) inexpensive,
4) citizens/homeowners could participate with minimal training,
5) ability to collect gravimetric data (weight of particulate per unit time and unit surface area),
6) field samples after gravimetry were suitable for further chemical analyses employing non destructive techniques without the need for pretreatment (filter based device).

Aspects 3) and 4) are applicable for the context of this report primarily with regard to rolling out a programme for a wider audience, while the other aspects are relevant for the processing and laboratory analysis of the samples.

Krupa and Legge (2000) provided an excellent overview on Passive sampling of ambient, gaseous air pollutants: an assessment from an ecological perspective, including an evaluation of the advantages and disadvantages of passive vs. active samplers for ozone, $SO_2$, $NO_2$ and VOCs. While passive sampling methods have a range of advantages, their lack of time resolution and inability to detect episodes due to averaging over time, as well as not providing direct feedback may be seen as disadvantages for a citizen science application. For $NO_2$ sampling, Tang et al. (2001) conclude that the open diffusion tube used in the U.K. is affected by wind speed, and care must be exercised in the selection of sampling locations. Positive bias due to chemical reaction is difficult to correct, but may be minimised by using badge- rather than tube-type samplers. Diffusion tube data from urban and curbside locations where chemical interference is most pronounced must therefore be treated with caution.

# 5 Existing examples of air quality citizen science applications

Air quality has been monitored as part of a number of Citizen Science initiatives across the world. Table 5.1 shows representative projects with details of their methods, data collected, participants, engagement and support techniques and aims. It is clear that there is substantial diversity under each heading, but some broad conclusions are drawn below.

[12] Gary T. Hunt (2011). "Nuisance Dusts"- Validation and Application of a Novel Dry Deposition Method for Total Dust Fall, Air Quality Monitoring, Assessment and Management, Dr. Nicolas Mazzeo (Ed.), ISBN: 978-953-307-317-0, InTech, DOI: 10.5772/16271. Available from: http://www.intechopen.com/books/air-quality-monitoring-assessment-and-management/-nuisance-dusts-validation-and-application-of-a-novel-dry-deposition-method-for-total-dust-fall

## 5.1 Summary of existing air quality citizen science projects

### *5.1.1 Method*

A wide variety of methods and tools are being used. Methods of data collection can be very simple, requiring little previous knowledge or requiring a degree of expertise and training. Tools range in cost and complexity from cost-free bioindicators and inexpensive diffusion tubes to complex and costly networked technologies. There is no correlation between simplicity of method and tool, with some simple tools (such as the bioindicators used in the *Ozone Garden* Project) requiring some expertise in participants and some complex tools (such as the FLOAT Beijing project) requiring very little expertise or training.

### *5.1.2 Data*

While it is beyond the scope of this activity to fully map all existing datasets generated by citizen science projects, the data infrastructure requirements for citizen science projects are non-trivial and require careful attention already in the design stage. Constant monitoring of air pollutant concentrations in a network of personal monitors and the transmission of data for evaluation and analysis may easily generate data in large amounts (Gigabytes to Terabytes).

Recognising this challenge, work on the development of methodologies and infrastructure for citizen science projects is being funded e.g. by the European Commission (FP7) in the Citizen Observatory Web (COBWEB, http://cobwebproject.eu/) project, which is coordinated by EDINA (http://edina.ac.uk/). We would recommend linking to such activities and to explore collaborations both to enable knowledge exchange and to ensure that any citizen science project designed is compatible, where data collection and formats are concerned, with ongoing international work. This is of particular importance in order to integrate activities into a wider context, such as Big Data, Smart Cities etc.

Recent work carried out by the University of Aberdeen on measuring second-hand smoke (SHS) concentrations has employed either the TSI Sidepak AM510 or the Dylos DC1700 to measure $PM_{2.5}$ as a marker of SHS within home settings. Although not a citizen-science project per se the work has encouraged study participants to use these measuring devices while completing a simple paper-based activity diary to record smoking and other particle generating actions.

The REFRESH programme of research (Wilson et al., 2012) has used the real-time $PM_{2.5}$-SHS data in these homes to engage with smokers in an attempt to motivate the household to change smoking behaviour and/or house smoking rules. This engagement has provided many insights into how lay people interpret air quality data and how to best communicate this information (Wilson et al., 2013). The REFRESH work initially used a research assistant to deliver, install, uplift and download the equipment/data using the TSI Sidepak instruments but has now moved to a more efficient model involving either postal delivery or provision through a health professional with no technical expertise in air monitoring science. This has proved possible through the use of the Dylos instruments with initial, ongoing feasibility trials in homes in Glasgow, Inverness, Lanarkshire and Aberdeen proving encouraging.

### *5.1.3 Participants*

Across the projects researched, participants fall into three distinct groups which can be defined as follows:

*Group A - 'Already interested'*: These participants are keen to take control of measuring their local air quality and are easy to engage to participate. They are likely already to have concerns about the health impacts of air quality and will readily participate in Citizen Science activities which will empower them to press for change or inform their lifestyle choices.

*Group B - 'Out there anyway'* : These participants are already involved in activities which air quality monitoring either dovetails with (e.g. people engaging in outdoor activities) or complements (e.g. school pupils). This group are not difficult to engage if the benefits of participation are clearly communicated and understood, but participation may be compromised by other priorities.

*Group C - 'Wider public'*: These participants might be members of a particular community or just citizens in the widest sense. This group is the most difficult to engage and requires compelling communication and ongoing support. This group is also likely to have a high turnover and considerable loss to follow-up.

### 5.1.4 Engagement, Training, Support and Feedback

This varies widely between projects and may include one or several of the following processes:

- Community Engagement activity to identify and recruit suitable participant groups
- Awareness raising events
- Community engagement workshops
- Training in data collection and submission method
- Training in air quality regulation and health
- Training in advocacy
- On-site support to collect and submit data
- Follow up events to share data and identify action

### 5.1.5 Project Aims and Outcomes

A range of aims and potential outcomes can be identified for such Air Quality projects. These are summarised as:

1. Providing professional scientists with better and more detailed data
2. Filling in gaps in statutory monitoring networks
3. Development and trial of monitoring technology
4. Empowering citizens to press for change
5. Building community capacity to achieve local change
6. Raising awareness of the health impacts of air quality
7. Raising understanding of impact of pollution on climate and environment
8. Increasing skills and knowledge at a community level
9. Effecting positive societal change
10. Effecting 'pro-environmental' lifestyle choices
11. Increasing outdoor activity
12. Increasing understanding of nature

It is of note that most projects aim to achieve a number of the outcomes identified above and that ***identifying outcomes is considered an essential first step in design of a project,*** from which all decisions regarding process, tools, methodology, target participants and engagement must follow.

**Table 5.1.** Representative Existing Citizen Science Air Quality Projects

| Project & Location | Method | Data collected | Participants | Engagement, training, support and feedback | Project Aim and outcomes |
|---|---|---|---|---|---|
| **Common Sense**<br>San Francisco | Vehicular platform includes commodity mobile phones & custom boards - phones receive the data from the boards and send the data to our servers | GPS, carbon monoxide, ozone, $NO_x$, temperature, and humidity data | Street sweeper vehicles | Not known | 1. provide professional scientists with access to richer, finer-grain data sets for modelling and analysis<br>2. create new experiences and usage models for the mobile phone as a tool for grassroots participation in government and policy making<br>3. by choice of sensors and software create a deeper and more informed understanding and concern for our climate and environment - hopefully effecting positive societal change |
| **West Oakland Environmental Indicators project**<br>California | Dustrak 8350 and AMOD GPS unit. PM levels and the location information are shown on a Google-style map on the world-wide-web | PM | Regular people' collecting data as part of their daily routine | Training program offers twelve hours of training re the health impacts air pollution, how the air quality regulation works and how to advocate successfully for social justice and community health | 1. Fill in the gaps in state monitoring networks<br>2. Use new data sources for environmental scientific research<br>3. Lead to the design of lower costs sensors and instruments<br>4. Empower citizens to press for change |
| **Mapping for Change**<br>London<br>. | Diffusion tubes at 7 locations – data integrated with Mapping for Change platform | $NO_2$ | Interested participants concerned about harmful levels of air pollution | Part of the community engagement process involves events feeding back the results to wider community. | To provide communities with;<br>1. a way to measure air quality<br>2. low-technical methods that can be replicated across the country and can engage all sectors of the community to participate.<br>3. reliable localised data which they can use to lobby local government, raise awareness, generate a better understanding of the issues and with which they can compare with other relevant datasets. |
| **Ozone Garden**<br>Great Smoky Mountains NP | Bio indicators: leaves | Ozone | School pupils | As part of school engagement | The study helps us to understand the relationship between foliar ozone injury and the growth of plants.<br>The results may be used to inform decision makers so adequate protective measures can be developed |

| Project & Location | Method | Data collected | Participants | Engagement, training, support and feedback | Project Aim and outcomes |
|---|---|---|---|---|---|
| | | | | | to improve the quality of the air we breathe. *The project has been replicated in a number of schools across US, for example through Clean Air Carolina* |
| **FLOAT** Beijing | kites equipped with sensors recording air-quality data and also reflecting it visually with multi-colour LED lights. | Carbon Monoxide, VOC, PM | both young and old Beijing residents | Groups from three neighbourhood communities were taught how to build kites for themselves and how to record air quality data to share online. A series of workshops and mass kite-flights was also set up, | FLOAT aims to spark discussion about air pollution in Beijing. FLOAT touches upon a number of issues crucial to contemporary China: pollution, civic engagement, public space, and censorship. Air pollution data recorded by the kites would not otherwise be accessible to Chinese citizens: the kites are able to monitor PM 2.5 particles that present the greatest risk to health. The Chinese authorities do not release data on PM 2.5 particles |
| **Global Community Monitor (GCM) 'Bucket Brigade'** Across US | variety of monitoring techniques ('buckets', wipes PM monitors) adapted to each community in order to get the most accurate data | VOCs and PM | Community activists | Training and kit provided by GCM | The programme aims to puts scientific data back in the hands of citizens in pollution affected communities. |
| **London Sustainability Exchange** Deptford, South London | Diffusion Tubes, wipes, Ozone badges, bioindicators (lichens and leaves). | $NO_2$, $O_3$, $NH_3$, PM | Residents of Pepys Estate | Community members were trained to use the equipment and work with local decision makers to influence change | The programme was designed to empower local community members and result in positive change in the local environment. Maps were produced to influence local decision making process |
| **Citizens for a Healthy Community** US | Backpack sensors | PAHs | Local Residents of Delta County | Not known | The project was developed with input from scientists at The Endocrine Disruption Exchange (TEDX) and is designed to establish an air quality baseline by testing for toxic chemicals associated with natural gas drilling. The project is intended to serve as a model for other communities across the country who are fighting to protect their health and environment from runaway drilling and fracking |

| Project & Location | Method | Data collected | Participants | Engagement, training, support and feedback | Project Aim and outcomes |
|---|---|---|---|---|---|
| **OPAL Air Survey**<br><br>England | Bioindicators: lichens & tar spot fungus | $NH_x$ $NO_x$ and reduced nitrogenous pollutants, such as ammonia ($NH_3$) | Wide range of participants | Provided through Community Scientists based across England | Study designed to help to build up a detailed picture of the impact of air quality in local area and across the country. Wider benefits included the engagement of 'hard to reach' participants with the environment, increased participation in outdoor activities and an increased understanding of nature amongst those who participated |
| **Sefton Council Community Air Quality Project**<br><br>Birmingham | | | Community groups, Respiratory illness support groups, Local councillors | Training and Support provided | Outcomes of the project were identified as:<br>1. Significant benefits for not much effort<br>2. Involve, Engage, Empower, Educate<br>3. Monitoring data both parties can use<br>*4.* Monitoring carried out at relevant location |
| **Citisense**[13]<br><br>http://www.citi-sense.eu/<br><br>EU *(including Edinburgh as a case study)* | Customised personal and static sensors; questionnaires | $PM_{2.5}$, $NO_2$, Temperature, Relative humidity | Wide range including conservation volunteers, general public, cyclists | Initial engagement tools: information leaflets, consent forms, acknowledge of receipt and return of devices.<br><br>Instructions on use of the sensors and where feedback from them can be obtained.<br><br>Feedback engagement tools – the sensors, obtaining the data, data display, usefulness of the data, benefits of being involved in the process. | a) develop and test methods for citizen's empowerment in the field of urban air quality.<br>b) conduct cases to demonstrate the concept of citizens' observatories by providing one or more innovative technological platforms for monitoring the environment (e.g. outdoor air quality), with a view to get improved decision-relevant information, to inform citizens' observatories and decision makers |

[13] Methodology still under development so indicative at the time of writing

## 5.2 Biological monitoring approaches - the example of OPAL

### *5.2.1 Overview*

Biological monitoring is the use of living things to monitor environmental change. These living things are known as biomonitors or bioindicators. Historically, change could only be assessed in this way. Local people were often the first to note the impact of a source of pollution, or a change in soil conditions, through its consequences, such as damage to crop yields or loss of aquatic species. In recent years, we have come to rely more on hi-tech equipment and computer modelling, used by a small number of experts, to monitor the world for us and tell us what is happening. However, biomonitors remain essential natural tools for understanding the environment and are available to everyone.

A number of biomonitoring approaches are already being used in the context of Citizen Science measuring Air Quality, including the Ozone Garden projects in the US, the London Sustainability Exchange project and the OPAL Air Survey: the largest scale biomonitoring project focussing on air quality.

The Open Air Laboratories network, or OPAL, was launched in 2007 to provide an opportunity for all sectors of society to get to know nature and to contribute to its protection. The network is directed by Imperial College London, and consists of 32 projects delivered by 15 partner organisations across England, each bringing their own area of expertise.

OPAL use biomonitoring throughout their range of 5 national surveys and are committed to their use as 'natural tools for understanding the environment' which are available to everyone. Biomonitoring has become a widely used alternative to direct monitoring in many countries and OPAL proposed that the use of bioindicators allows a higher sampling density than is typically achieved using more expensive monitors. The OPAL Air Survey uses the presence of lichens and tar spot fungus, which are sensitive to air pollutants, to indicate patterns in air quality.

By 2012, 3,700 lichen surveys had been submitted to the OPAL website, with data from over 14,000 trees. Analysis of data on Oak trees showed that as nitrogen pollution in the atmosphere increases, the number of different types of lichens decreases but the abundance of the OPAL-selected nitrogen-tolerant lichens increases. This supports findings from several academic papers and suggests that lichen diversity is at risk from the high levels of nitrogen pollution currently present in the air, affecting sensitive lichens.

The OPAL Air Survey also confirmed that the diversity and abundance of the nitrogen-sensitive lichens are lowest where concentrations of ammonia are predicted to be at their highest. Levels of ammonia have greatly increased due to modern farming techniques over the last century so this and results from other research carried out by the scientific community add more weight to the evidence that increasing levels of this pollutant can cause changes in the environment.

OPAL's activity in England was supported by a wide number of partners, including further education establishments, research scientists, lichenologists and a team of Community Scientists. This support framework would appear to have been crucial in securing substantial participation in the surveys and wider benefits from participating in the activity. Wider benefits included the engagement of 'hard to reach' participants with the environment, increased participation in outdoor activities and an increased understanding of nature amongst those who participated.

### 5.2.2 Achieving outcomes

The OPAL air survey has been used across Scotland by volunteer teams supported by the The Conservation Volunteers. An evaluation of this activity (see Table 5.2) was carried out through phone interviews with project leaders of 5 Conservation Volunteer groups supervising a total of 40 volunteers participating in practical environmental projects. The evaluation indicated that:

- If participants are interested and have appropriate literacy and numeracy skills, the survey can be carried out without prior expertise
- Many participants enjoyed completing the survey
- Completing the survey complemented the existing volunteering activity
- It isn't for everyone – it can be difficult to engage all volunteers with the survey
- It is relatively time consuming to complete
- It requires the ability and patience to identify species
- Additional resources and support are very helpful
- It raises awareness of Air Quality issues amongst participants

It should be noted that OPAL's project delivery to date focussed in England. This means that TCV's use of the OPAL Air quality survey in Scotland was not supported by the network of community scientists and academic institutions made available in England. If OPAL are successful in their aspiration to deliver the project in Scotland, the support framework which would be put in place would provide much of the resources, training and support that TCV staff identified as further needs for accessible use of the survey with their volunteer groups.

The evaluation of use of the OPAL survey by TCV teams would indicate that the OPAL Air survey is effective in achieving outcomes around awareness raising, skills development, increased understanding of nature and increased understanding of the impacts of pollution on the environment.

OPAL's recent Community Environment Report indicates that participating in the range of OPAL surveys increases outdoor activity and understanding of nature. Almost half (43%) of people questioned about OPAL said taking part had changed the way they thought about the environment and more than a third (37%) said they will change their behaviour towards it.

This report indicates that 'the OPAL survey found that pollution–tolerant lichens such as species of *Xanthoria* and *Physcia* were more abundant on oak trees growing close to roads or to intensive agriculture. These lichens are tolerant of nitrogen in the form of nitrogen oxides produced from vehicle exhausts and of nitrogen in the form of ammonia produced by intensive agriculture. The OPAL survey also showed that pollution –sensitive lichens such as species of Usnea and Hypogymnia were disappearing from our countryside. The survey showed that the OPAL lichen air quality index reflected modelled air quality data'. Additional, as yet unpublished research by OPAL into the use of lichens as indicators of air quality shows that the six indicator species used in the OPAL Air is large scale public survey have been shown to have robust relationships with modelled nitrogenous pollutants at the national scale. The lichen Presence and Pollution Indices derived from these six widespread species, therefore, appear to have great potential as a tool for evaluating small scale patterns in levels of nitrogenous pollutants.

If additional data on these pollutants is of value to professional scientists and helps fill gaps in statutory monitoring networks, then the OPAL Air survey has the potential to be of use in gathering such data in an urban context.

**Table 5.2.** TCV Volunteer Group OPAL Air Survey Feedback

| | |
|---|---|
| **How easy is the Air Quality Survey to do with groups? Why did you give that answer?** | ➢ Very easy a new younger start volunteer who'd just finished an ecology degree did it<br>➢ Easy enough<br>➢ Not too bad really, quite simple<br>➢ Out of 10, I'd give it a 6. People hadn't done it before and we all had to get our heads around it. It's quite confusing at first<br>➢ If people are interested then it's easy to do |
| **Did you do the lichens or the tarspot survey? Why?** | ➢ Lichens – there were quite a lot of trees with lichens about and a lack of sycamore trees<br>➢ Lichens, there weren't many sycamores at the site<br>➢ The lichens survey, mainly because of what was available on site<br>➢ Lichens because of what was nearby<br>➢ Lichens, there's no leaves about to do the sycamore one |
| **How did you complete the survey?** | ➢ Just one volunteer did the survey on her own<br>➢ I led the group of 6 volunteers, that size was fine because there was a task for all members<br>➢ We did 2 or 3 trees in different wee groups, I took the lead on the activity though<br>➢ I showed everyone who was taking part how to do it and then passed it on to the group to do themselves. It was with a Green Gym<br>➢ A Key Volunteer did the survey and took 2 other volunteers with him |
| **Did the volunteers enjoy it? What feedback did they give you?** | ➢ I think she did, she was pretty happy after. She said the key was quite good but she did need to use the FSC key at times too to make sure<br>➢ Some more so than others, there were lots of questions! They got more into it when they realised that it was about air quality<br>➢ Yeah I think so<br>➢ They seemed to, yes. A few got into it.<br>➢ Yes they did enjoy it. There was 1 girl who's studying at the moment so is on a work placement kind of thing with us and she wanted to take a copy to do in her own time |
| **What benefits does it have for your work?** | ➢ It offers variety for the volunteers and a chance for them to learn new stuff<br>➢ It can fill the gaps in practical activity and take up an hour, it's a good back up activity to have. Surveys are good to add in to a day.<br>➢ It does give reference to what's going on the area that we're working in<br>➢ It gives everyone a bit more knowledge<br>➢ It adds an extra element to on site work for people who are interested |
| **What are the drawbacks for your work?** | ➢ Not everyone is interested in it<br>➢ Trying to enthuse the volunteers<br>➢ It's time consuming when you first start it<br>➢ It's wholly dependent on the time taken to teach the survey<br>➢ Probably that we work at some inappropriate sites for the survey and it's hard to do when the workload is high |

| | |
|---|---|
| **Do you think this is a survey the volunteers could do themselves having done it as part of your group? Why?** | ➢ Yes, no trouble at all<br>➢ No, they'd end up IDing the wrong ones. I could only do it because I had done the training<br>➢ I think so, it depends on the volunteers. Some take to it, some don't<br>➢ Yes<br>➢ It depends, some could yes. It's dependent on the volunteer but I would definitely say some of them are more than capable |
| **Do you think it has improved participants' awareness of air quality issues in urban areas?** | ➢ Yes, it's something that we'd never previously talked about<br>➢ I would think so<br>➢ Yes<br>➢ Yes<br>➢ Not really… Maybe it would've if we'd been a site which had worse air quality so you could see a comparison |
| **What would improve this survey for participants?** | ➢ Having wee samples would be good. I went to a workshop where there were samples which made it really easy to compare things<br>➢ It's fairly straightforward, so nothing really<br>➢ Probably a better guide to the lichens, more details on that<br>➢ Simplification of the species, and a bit more description around the pictures<br>➢ It's a positive thing, I don't think it could be improved really |

# 6 Evaluation

The evaluation of available approaches with the objective to design air quality citizen science programmes for pilot testing heavily depends on the priorities set and ambitions levels of the respective programmes. Based on our evaluation, there is no one-size-fits-all solution or silver bullet that is suitable and readily applicable for a range of citizen science projects. In the following, we briefly discuss the advantages/disadvantages of general and specific approaches.

## 6.1 Objective driven evaluation

If the objective for the citizen science programme is a **direct engagement and information/awareness-raising of citizens**, the monitoring approach needs to provide immediate or near-term feedback related to the observations made. Passive sampling methods requiring laboratory analysis will likely be less useful for this, unless they can be conducted e.g. with small groups at a school or in close collaboration with institutions that are capable of providing fast analysis results or even own analysis capabilities. Personal sensors typically provide direct feedback/results, but may require a degree of technological skills in operating sensors or extracting/submitting data. Solutions such as the MicroPEMS or the Dylos could be deployed with a close engagement with volunteer groups to pilot the use of personal sensors until better integrated, GPS-enabled sensors become commercially available. Mobile phone APPs may be best suited as they build on existing and available technologies that are widely used by the general public. The processing capability of smart phones or tablet PCs enables direct evaluation of monitoring results, or can provide contextual information e.g. on images submitted to a central (web) service. In addition, mapping and visualisation applications are typically available. The level of interactivity could range from basic display of monitoring network concentrations on maps to full-scale submission of data/images and questionnaires on local conditions, providing a contextual evaluation of air quality (e.g. specific for vulnerable groups).

If the objective, however, is on **expanding current fixed site reference monitoring networks with a variety of fixed and mobile sensor nodes**, personal monitoring solutions would need to be explored, with the option to deliver data to a central database. Technologies such as the Air Quality Egg in the low-cost range, respectively AQ Mesh/E-Mote nodes in the high cost range could provide viable options to achieve this. These could be deployed for instance at schools or other institutional settings to provide a basis for engagement with students or similar groups around the monitoring results on the location they spend a substantial amount of time. The challenge of using current personal monitors such as the Air Quality Egg will be in ensuring that observations made are robust and can be related to reference site concentrations observed, otherwise observations made by citizens may give rise to regulatory complaints based on data that may be inaccurate. Specific approaches to for instance improve the spatial resolution of observations could be based on distributing large numbers of passive samplers for a given period of time, requiring central analysis and feeding back to volunteers once the results are available. This would potentially lead to good engagement, but the one-off character of the approach may not trigger a lasting interest in or awareness of air pollution problems in citizens.

### 6.2 Evaluation of time horizons

For the **short term** (i.e. immediate availability), biomonitoring and passive sampling methods may be best suited to deliver robust results. These methods are tested and readily available at comparatively low costs and require little to moderate training and education of citizen scientists. In the **mid term**, emerging mobile APPs are promising avenues to engage with a wider community at low or zero costs (to the user), however they require an investment in the data infrastructure and the development of bespoke services targeted to the audience and locale in which they are to be applied. Personal sensors show the potential to be viable in the **long term**, with technologies becoming readily available and developments being supported by a range of agencies and research groups. Currently, the lack of commercially available highly sensitive sensors for ambient conditions and the learning curve in packaging and software interpretation of raw observation data present barriers for a wide-spread use. However, it is anticipated that economies of scale and a growing demand for smart sensors may change that picture in the next few years.

### 6.3 Conclusions based on the evaluation

For this pilot phase II, we recommend to select a portfolio of 3-5 different groups of citizens to test different approaches, including a trial with personal sensors (Dylos, microPEMS), a programme with biomonitors (for ozone) and – if available – a mobile phone APP (e.g. ObsAIRve). All these individual trial projects will need to be closely monitored and feedback collected during and after the trial phase to identify the key issues and potential uses for rolling out a more comprehensive citizen science project in the near future.

## 7 Literature and other resources

### 7.1 Online resources, incl. SE Web SC Toolkit

The recently launched SEPA Citizen Science Toolkit already covers a range of resources for data collection and infrastructure development for citizen science projects (http://www.environment.scotland.gov.uk/get_involved/toolkit.aspx). Other online resources, such as the community mobile sensing platform (http://www.communitysensing.org/index.php) indicate, that a key requirement for lasting success is to build an active user community, otherwise activities may dissipate (the most recent activity/publication on the community mobile sensing platform is from 2011). Other activities and online resources, such as the Bucket Brigade (http://www.bucketbrigade.net/index.php) have a been active over a long period of time, while the majority of activities seem to have a clear "project" setup with a defined runtime and resources remaining available online, but not being further updated (e.g. http://www.urban-atmospheres.net/CitizenScience/) .

In the current work, we will have a particular focus on the SEWeb resources and, in preparation for the pilot study in Phase III we will investigate how the SEWeb Citizen Science toolkit could be used and tested in practice. This will be integrated into the testing of different approaches to Citizen Science described in Section 6.3 above. A summary of the elements of the toolkit is provided below, further examination and brief evaluation of each of the included IT tools will be carried out in the later stages of this study and will be reported separately.

Scotland's Environment Web (SEWeb) is a website which brings together information on Scotland's environment, from air quality and waste sites to listed buildings and land use. The SEWeb resources include a brief introduction to citizen science together with examples of environmental projects and organisations, and a toolkit comprising a list of freely available resources which can be used as part of a citizen science project. These resources are grouped under three main headings:

- Data collection tools (3) – Two of these tools enable the design of data collection forms, the collection of data via mobile devices (either Android, iPhone or both) and aggregation of the data on a project website. The third tool is web-based and specifically for the recording of wildlife (plants and creatures) data.
- Identification tools (3) – These tools are all designed to aid identification of things in nature. One is specifically for plants, one for trees and the third more wide ranging including plants and creatures.
- Infrastructure tools (5) – These tools are more advanced and IT knowledge is needed to use them. One of these tools specialises in software for collection, visualisation and interactive mapping of data and can be used for crowd sourcing via SMS, email, Twitter and the web. Another tool specialises in the collection and analysis of air pollution data. The other three tools in this category are mapping tools allowing the display of collected data spatially, they do not provide specific tools for the collection of data.

The relevance of each of these tools, and the identification of other tools which can be used will be assessed as part of the subsequent phases of the work. It is likely that mobile data collection and aggregation tools, and some of the mapping tools may be relevant to the work programme but that the nature identification tools are less likely to be.

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