Imperial College London

Grantham Institute
Briefing paper No 40

May 2023

IMPERIAL ZERO POLLUTION

Systems thinking for the transition to zero pollution

LIAM KIRKPATRICK, PROFESSOR CLAIRE S. ADJIMAN, PROFESSOR HELEN APSIMON, DR ALEX BERRY, DR AUDREY DE NAZELLE, DR ANA MIJIC, DR RUPERT J. MYERS, PROFESSOR GUY WOODWARD, DR MARK WORKMAN

Headlines

- The complexity of pollution means that we need systemic transformation to tackle it. Systems approaches can help uncover ways for people and sectors to work together to achieve this change, identify new solutions and improve existing ones, reveal co-benefits, and avoid negative unintended consequences.
- The multiple scales of pollution challenges can be better appreciated using a systems approach, which provides a deeper understanding of the links between global, national, regional, local and individual pollution impacts.
- An interdisciplinary approach is essential, considering perspectives from different disciplines and stakeholders to understand the system boundaries, identify leverage points and potential technical, behavioural and policy solutions.

Key recommendations

- Understand the problem from a systems perspective: engage systems experts from across disciplines to help frame the problem and develop solutions.
- Understand the system boundaries: bring in perspectives from a range of academics and industry, policy and societal stakeholders.
- Develop systems tools: use data and systems models to make collaborative decisions and understand trade-offs.

Contents

Grantham Briefings analyse climate change and environmental research linked to work at Imperial, setting it in the context of national and international policy and the future research agenda. This paper and other publications are available from www.imperial.ac.uk/grantham/publications

Introduction

Recent reports on the state of our environment, combined with the direction of travel of organisations like the United Nations Environment Programme, European Commission, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC), have reiterated the urgent need for us to reduce our impact on the environment as quickly as possible and to tackle pollution (UNEP, 2021; European Commission, 2021; Pörtner et al., 2021). This is a multi-faceted demand that requires many considerations: encompassing water, air, and land, with impacts that range from individual species through to ecosystems, water catchments, the climate, human health, socioeconomic development, and economic prosperity.

Pollution affects people and environment from local to global levels. Systems approaches are vital for coordinating decision-making in the face of such complex issues because they provide the whole picture view needed to avoid negative unintended consequences and to generate genuine benefits. This paper explains how systems thinking can be used to capture the problems involved in addressing environmental pollution and support decision-makers in finding solutions.

Defining zero pollution

Whilst there is no universally accepted definition for environmental pollution, dangerous 'contamination' is a recurring theme, comprising adverse impacts on the normal functioning of earth processes that are harmful to people and nature (Halliday, 2007; Rai, 2016; Muralikrishna and Manickam, 2017). We consider direct pollution as the change in quantity of any substance (solid, liquid, or gas) or any form of energy (such as heat, light, sound, or radioactivity) to the environment at a rate faster than it can be dispersed, diluted, decomposed, recycled, used or stored in some harmless form (Whyte et al., 2020). This definition of pollution includes impacts from resource extraction, which also place pressure on the environment.

Pollution operates across spatial and temporal scales and causes diseases such as cancer, heart and lung disease, and diabetes, leading to millions of deaths each year (European Commision, 2021; Vohra et al., 2021; Landrigan et al., 2018). Pollution is also one of the five main causes of biodiversity loss (IBPES, 2019). Contaminants resulting from human activity can be found everywhere, from the peaks of the Himalayas to the bottom of the Mariana Trench (Guzzella et al., 2016; Dasgupta et al., 2018; Jamieson et al., 2019; Gabrielli et al., 2020; Jiao, 2021), highlighting the multi-scale impact of pollution, the recurring failures in responsibility, and the 'business-as-usual' approaches to the environment that have enabled pollution to become so widespread.

A transition to zero pollution, by preventing pollution from being released or by capturing or mitigating it after release, requires a systemic management approach. This means dealing with a wide range of pollutants in air, water, soil, and the biosphere, including but not limited to greenhouse gases. It also means identification and avoidance of unintended pollution consequences and embracing opportunities for co-benefits of solutions and for regeneration.

What do we mean by systems thinking?

Systems are combinations of interacting elements that together form a complex whole: the system often behaves in ways that cannot be predicted from traditional reductionist piecemeal approaches. Systems thinking focuses on the relationships among the system elements and their interactions, rather than simply the elements themselves (Monat and Gannon, 2015). Thus, a systems approach often involves complex interactions and trade-offs, allowing previously unknown or undervalued aspects to be revealed as key leverage points where interventions (such as technological or policy interventions) can generate significant system-level changes (Meadows, 2008). Importantly, systems thinking is needed for tackling complex or 'wicked' problems – like pollution (Campbell and Zellner, 2020), where there are no simple answers – by enabling otherwise uncertain situations to be understood and managed and providing new solutions that are more likely to succeed.

> 'Systems thinking in practice encourages us to explore **inter-relationships** (context and connections), **perspectives** (each actor has their own unique perception of the situation) and **boundaries** (agreeing on scope, scale and what might constitute an improvement)... Systems thinking is oriented towards **organizational and social learning** – and **adaptive management**' (Allen, 2020).

The key systems elements highlighted above operate across disciplines and industries, with the wider system incorporating material, technical and infrastructure systems as well as systems of society, behaviour and economics (Mitchell et al., 2020). Employing systems approaches can lead to more effective policymaking and decision-making in addressing pollution by accounting for different perspectives and can help uncover new solutions where the 'business-as-usual' approach has struggled to cope.

The global scale and complexity of pollution means that systemic transformation is necessary to tackle it. Systems approaches can help to uncover ways for people and sectors to work together to achieve this change. For example, recent modelling has demonstrated that unless immediate and sustained action is taken globally, the growing problem of ocean plastic pollution will lead to the dumping of more than 1.3 billion tonnes of plastic on land and in the oceans between 2016 and 2040 (Lau et al., 2020). However, by investigating scenarios of interventions to tackle plastic pollution, and characterising the different elements and interactions in the global plastic system, researchers have revealed that annual flows of plastic into the ocean could be reduced by ~80% in the next 20 years, by applying existing solutions and technologies more effectively (Lau et al., 2020).

Systems thinking is also a useful tool to interpret specific pollution problems, such as vehicle tailpipe emissions, not as standalone issues, but as components of the wider system. Box 1 discusses considerations around the introduction of electric vehicles (EVs) and urban health. The boundary of system analysis depends on the problem we want to address, and systems approaches are scalable in this sense, allowing prioritisation of the level of complexity that is needed.

Box 1: Systems, cars and urban health

The ongoing surge in the production of electric and hybrid cars, combined with tighter urban emissions restrictions has provided hope for cleaner air in urban environments, but systems thinking demonstrates there is still much to be done.

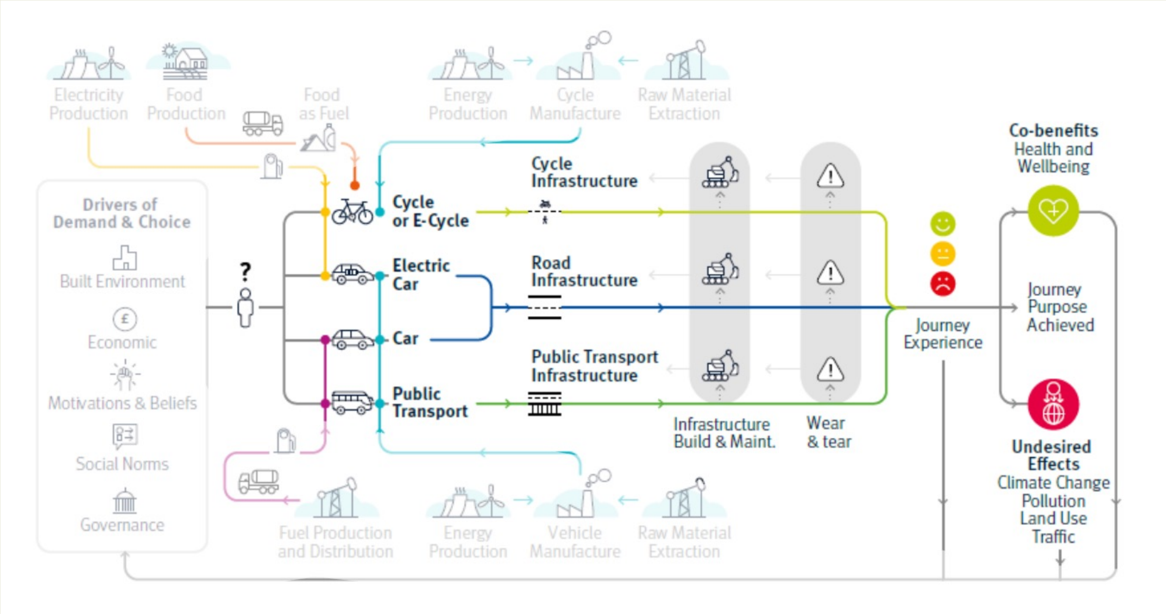
EVs, including hybrid and full electric, have a lower climate impact than petrol or diesel vehicles due to their lower lifetime carbon dioxide emissions (Wolfram and Wiedmann, 2017) and from a pollution context, are often considered superior due to their lack of exhaust emissions, which in urban areas have become an extreme health risk (Sendek-Matysiak, 2019). Nonetheless they are not pollution-free – the process of building EVs, including the mining of rare metals, electricity production to power these vehicles, and emissions from tyre and brake wear are still sources of pollution (Ji et al., 2012; Banza Lubaba Nkulu et al., 2018; Liu et al., 2021, Mehlig et al., 2021).

Traditional approaches to pollution mitigation for cars have focused on technical solutions to make engines and car production more efficient with fewer emissions. Here, a good example of unintended consequences is the relatively recent UK government encouragement of efficient diesel vehicles through lower taxes. The encouragement rewarded diesel vehicles' lower carbon emissions, focussing less on the health problems caused by particle emissions from the combustion of diesel, meaning a limited perspective was prioritised over consideration of the wider pollution system. The scale of the subsequent uptake of diesel vehicles resulted in degraded air quality in cities with serious impacts for human health (Carslaw et al., 2011; Jonson et al., 2017; O'Driscoll et al., 2018). A focus on ever more technically advanced EVs to meet regulatory requirements, such as the UK government's phase out of non-EVs by 2030, will bring some progress towards lower emissions driven by capital investment. Expanding the scope of the problem to include issues like emissions from tyre and brake wear would likely demonstrate that replacing all internal combustion engine vehicles with EVs would represent an improvement but ultimately be an insufficient solution from a systems perspective, since significant health issues would remain unaddressed. The wider transport system and moving to alternative modes of transport are thus important considerations here.

Opportunities are emerging to build on recent trends towards increased levels of cycling through a variety of incentives that encourage active travel. In the UK, expansion of city bike lanes has accelerated and the government has made pledges to make cycling and walking more attractive ways to travel. Among other benefits, the increased physical activity that can be derived from more widespread cycling in the population will promote health far beyond the air pollution benefits (Woodcock et al., 2009; Rojas-Rueda et al., 2012, Mueller et al., 2018) and could lead to potential savings of 1% of the health care budget in England and Wales by decreasing the prevalence of many diseases associated with physical inactivity (Jarrett et al., 2012). Increased cycling may create positive reinforcing feedbacks in a psychological and social sense. The more people are seen cycling, the greater the appeal of cycling since an appreciation of the sense of community and health benefits can lead to further uptake (Götschi et al., 2017). From a behavioural perspective, the advantage of positive feedbacks in bike use is particularly important, as cycling brings many co-benefits apart from physical activity, from social interaction to more space for green spaces, to climate change mitigation (De Nazelle et al., 2011; Gascon et al., 2016; Avila-Palencia et al., 2018; Brand et al., 2021).

From a systems perspective, however, there are many other considerations that need to be balanced to create inclusive transport systems that are accessible to all in an urban environment. For example, there could be a tension between new cycle lanes and provision of bus lanes which needs to be accounted for. This demonstrates the need to appreciate wider systems, and both the challenges and opportunities that presents for human health and wellbeing in a pollution and urban health context.

Box 1: Systems, Cars and Urban Health (continued)



An illustration of a system within a wider system for transport systems modelling, showing how complex interactions between agents and systems combine to produce emissions. The figure is edited from the Grantham Institute and Energy Futures Lab briefing paper on 'Research pathways for net zero transport' (Pearce et al., 2021) to highlight one part of the system governing choice of transport mode.

Understanding our environment as a system

To better understand the issue of pollution, it is useful to consider environmental impacts of human activities on the Earth system. Two notable systems approaches to this are Meadows et al.'s 'Limits to Growth' model (1972), and the concept of 'Planetary Boundaries' by Rockström et al. (2009).

The seminal 'Limits to Growth' model centred on an 'essential problem, which is exponential growth in a finite and complex system' – 'a finite world'. The model professed that the exponential growth of five variables: population, food production, industrialisation, consumption of non-renewables and pollution, would eventually meet a limit that demarked a total 'overshoot and collapse' of the Earth system. The model pioneered the concept of planet-determined limits. It also provides an early example of the role that pollution has in marking thresholds, and the dangers of overstepping these. More recent research has produced models that are much more detailed and robust than the 'Limits to Growth' model, for example, to include renewable resources such as water, land and air, and to more fully identify the challenges posed by climate change (IPCC, 2021).

Rockström et al.'s (2009) 'Planetary Boundaries' concept builds on the Limits to Growth premise by attempting to designate a 'safe operating space' for humanity. Nine earth system processes are identified, with their respective environmental boundaries based on conditions that typify the Holocene epoch that have supported human civilisation over the past 11,650 years or so. These boundaries are presented as uncertainty ranges within which potential environmental tipping points for each process exist.
The 'Planetary Boundaries' concept works well, at least as a heuristic framework, for some aspects of the natural environment. For example, the issue of carbon dioxide emissions within the climate change planetary boundary is now a well-recognised global problem, and a reduction in these emissions is beneficial to all. However, there are also some limitations to this approach. Firstly, many pollution issues are local, with their impact propagating more widely through embodied resources and supply chains. Furthermore, certain pollution processes such as 'chemical pollution' and 'atmospheric aerosol loading' are very difficult to quantify and the former was essentially left undefined in the original scheme. Importantly, if the use of boundaries in this manner provides a quantifiable target for policymakers, it also has the potential to encourage complacency if it is assumed that below the threshold there is no cause for concern; we know for example there are no safe threshold levels for airborne particulate matter (Brauer et al., 2019; Brunekreef et al., 2021; Dominici et al., 2019; Hoffmann et al., 2021). Translating these boundaries into practical action presents a challenge but this is nevertheless happening for individual boundaries such as water (e.g., Zipper et al., 2020) and through holistic approaches such as Doughnut Economics (Raworth, 2017), an approach which also advocates systems thinking.

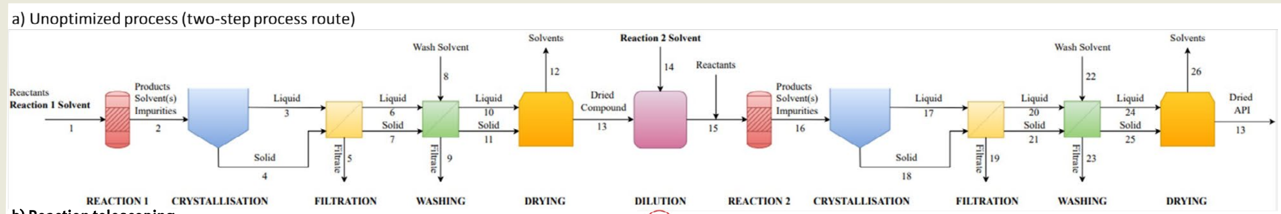
Using a systems approach to understand and tackle pollution

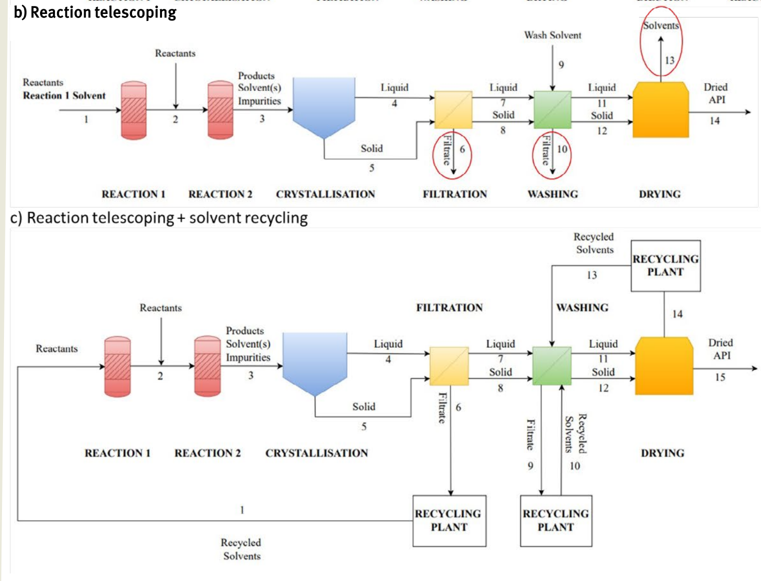
A systems approach is not necessarily the same as a holistic approach *per se*, but rather it strives for reliable interpretation of a real context or problem (Cabrera and Cabrera, 2015), and can apply to both man-made (such as a manufacturing process systems, Box 2) and natural systems. By providing tools to deal with complexity in pollution flows (a flow is the rate at which material or energy passes through a given boundary, such as the amount of water flowing into a lake per minute (Monat and Gannon, 2015)) and contexts, a systems approach can help to identify effective interventions or leverage points for key stressors in the system, such as unregulated or illegal pollution, that can then be more appropriately targeted and tackled.

Box 2: Pharmaceuticals and solvent pollution

A systems approach can be applied to minimise the pollution that arises from the use of solvents in the manufacturing of chemical products, such as medicines within the pharmaceutical industry. Over 50% of the greenhouse gas emissions attributed to pharmaceutical manufacturing stem directly from the use of solvents (Jiménez-González et al., 2004). Excluding water, the amount of solvent used in manufacturing is commonly about four times that of the final product. Furthermore, to minimise the amount of impurities in the final product, solvents are usually incinerated, rather than recycled, after use. This requires additional energy use and generates carbon dioxide emissions.

In a manufacturing process, a series of reactions is typically needed, and considerable time is spent attempting to optimise individual steps, tailoring the solvent to each step. This often means that a significant amount of energy is expended to separate products and reagents from the solvent from one step, to replace it with the solvent for the next step. This focused approach, while ensuring a high proportion of reagents are converted to products, often generates significant amounts of waste. Employing a systems approach to consider solvent use across the entire manufacturing process can reduce waste and energy consumption. Further benefits can also be derived by accounting for the life cycle impacts of producing any solvent that is used in medicines manufacturing. A systems approach can highlight the benefits of recycling solvents or of designing them to be used over multiple steps in the production process (Perez-Vega et al., 2013), known as stage telescoping. Even when focusing on a single step, expanding the range of decision levers from choosing a solvent to choosing a processing technology (e.g., type of crystallisation unit) and operating temperatures lead to reduced pollution by decreasing solvent consumption and increasing product yield, i.e., the proportion of product that is recovered from the reaction mixture. A systems approach is often multi-scale by nature, as interactions between the scales of molecules, manufacturing processes, and wider supply chains need to be considered. These considerations are illustrated below.





Example systems for designing pharmaceutical manufacturing processes to minimise solvent waste pollution. *a) Unoptimized process:* An example two-step process with two reaction steps; each reaction step is followed by a workup train (crystallisation, filtration, washing and drying). This process topology involves several process units and uses different solvents for each reaction step (reaction 1 solvent and reaction 2 solvent). *b) Reaction telescoping:* Identifying a solvent that can be used across both reaction steps eliminates the need for the first workup train, improving process resource efficiency. A remaining problem is that solvent waste from the filtration, washing and drying units is incinerated, rather than recycled, which decreases process efficiency and sustainability. *c) Reaction telescoping + solvent recycling:* In this configuration, solvents are recycled and re-used, minimising solvent use and the associated emissions. Solvent recycling is commonly used in the chemical industry, but not in medicines manufacturing. The development of novel processes with solvent recycling could help to reduce pollution and resource use in this sector.

Systems within systems

One of the most significant advantages of systems approaches is an appreciation of scales and organisational levels, making it possible to differentiate local, national, and global impacts (e.g., Bouman, 2007, Letourneau, Verburg, and Stehfest, 2012, Villarrubia-Gómez et al., 2018, Zipper et al. 2020). A systems approach can improve our ability to investigate and interpret flows and interactions across different scales, using the concept of modularity or 'systems within systems'. For instance, the global-local interactivity of plastic pollution is complex and wide-ranging but shifting our boundary perception to focus on one aspect of the system, such as single-use plastic carrier bags in the UK, can help to break down this complexity into more tractable modules. In this simplified way, focussing on the problem (plastic pollution), and what can be done to help fix it at a more local scale (discouraging the use of plastic bags through the introduction of a plastic carrier bag charge) can be a very effective way to provide a local solution to a more global problem. Systems thinking can help us understand how system interactivity is shaped by intricacies at local and individual levels (e.g., communities volunteering for beach clean-ups) just as much as by global forces (e.g., wind patterns that direct pollutant flows). See Box 1 for an illustration of a system within a system.

Defining the scope of the investigation

The scope of a system should be chosen to focus on aspects that can identify points for intervention through closer and more effective investigation, whilst keeping sight of the wider whole (Nguyen and Bosch, 2013). The choice of boundaries is both important and challenging: there are always alternative perceptions of a system boundary, and these can also change as we shift across scales. For instance, the act of looking through a microscope provides us with an enhanced view of an area within a circular boundary, but if we adjust the lens or shift the focal area, our perceived boundary changes. Whenever a boundary is drawn, there is a risk of losing sight of the bigger picture. Therefore, demarcating a boundary should be done by attempting to appreciate a holistic overview from the starting point. A sound understanding of the system under investigation is essential to define the scope of a new study. Techniques such as HAZOP (hazard and operability) can be used to identify factors that may have been left out of the original scope of the investigation.

The following questions are examples of important considerations in scope-setting when undertaking a systemic analysis of pollution problems:

- What is the threshold for pollution in the context of achieving sustainability and minimising health and environmental impacts?
- Who decides these? Are they stakeholders, and how does their position in the system influence their perception?
- How do boundary perceptions outlined by direct pollution (e.g., emissions/discharges) change when indirect pollution (e.g., extraction of resources) is considered and how might this influence our understanding of the boundaries for zero and net zero pollution?

A lack of understanding of the natural environment's capacity for absorbing many pollutants further compounds the problems these questions present, as do considerations such as human health. Although pollution is far more than just a quantity problem, if levels of pollution are increasing, there is also a need to understand environmental capacity to act as a pollution buffer and understand threshold levels for adverse health impacts.

Key concepts in systems thinking

Some concepts that are central to systems thinking and the analysis of pollution include burden shifting, flows, feedback loops, and system dynamics.

Burden shifting

'Burden shifting' can occur where aspects of a wider system that are considered unhelpful (in this case pollution in the earth system) become distant from their site of production (Algunaibet and Guillén-Gosálbez, 2019), as in the case study on acid rain in Box 3. Often, contaminants are shipped elsewhere, out of mind. For example, in 2018 the UK exported 611,000 tonnes of its recovered plastic packaging to other countries (Harrabin and Edgington, 2019). Alternatively, at the point of local environmental saturation the site of production might simply relocate, as has often occurred at the mercury-poisoned mines in the Amazon rainforest (Asner and Tupayachi, 2017). These processes are unfortunately synonymous with traditional siloed approaches in that they fail to address the wider issue of pollution and distance themselves from a complex problem, which has the potential to lead to a range of known and unknown unintended consequences, such as plastic packaging entering the oceans through mismanagement of plastic waste (Lau et al., 2020) in the case of plastic waste shipped abroad.

Using a systems approach, in contrast, can highlight that even if the problem has not been solved in its entirety, but rather shifted to another part of the wider system, there are still ways to improve the situation via an understanding of system interconnectedness or modularity. Acknowledging this can help policymakers by providing a more realistic assessment of both the problem and proposed solution(s). Effective policy must appropriately reflect complexity, and systems approaches grant novel insights into the uncertainty and interrelations that are at play in the real world.

Flows and feedback loops

In a pollution context, flows include not only material but also information and other (often intangible) inter-relationships, such as those between waste manager and worker, or worker and machine, which can be equally important. For example, in a worker-manager relationship, if the former is underpaid or treated unfairly by the latter, then they may feel less obliged to undertake waste management as effectively, resulting in increased levels of pollution. Prior identification of the possibility of a fractured relationship in this case would provide a leverage point for an intervention to address the issue. The relevance of relationships and social interactions can be pivotal. In this case, the renewed work ethic of the original worker could incentivise colleagues to rise to the same level, and a positive feedback loop emerges that serves to further mitigate pollution. Understanding and recognising where the system reacts and responds to 'balancing' and 'reinforcing' feedback loops such as this is important and can allow for further identification of previously unnoticed leverage points (Sterman, 2001; 2002).

System dynamics

Systems approaches add new insights into the evolution of key metrics and quantities over time. Using a time-based perspective focuses attention on uncertainties, and, particularly regarding feedback loops, allows quantification of lag times (Sterman, 2002). This can be captured in models that represent the system as a whole and its behaviour over time. The resulting predictive capacity can be reflected in environmental design, planning and pre-emptive interventions. For example, systems approaches can be used to inform future planning of water systems, and simulations of these have shown that neglecting interdependences of supply and wastewater systems, which abstract water and discharge into connected rivers, significantly underestimates impacts of sewer effluent on river water quality (Dobson and Mijic, 2020).

Box 3: How systems thinking was used to address the problem of acid rain

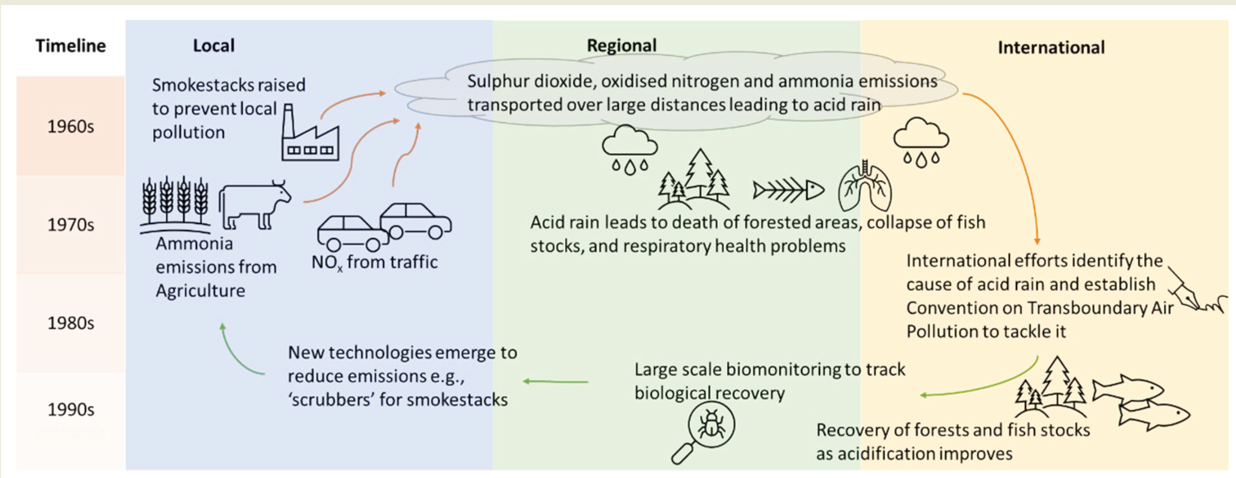
Acid rain provides a good example of how systems-based thinking was ultimately brought to bear on a large-scale pollution problem, to identify its causes and consequences and to develop the solutions that led to continental scale improvements in emissions and ecological recovery over several decades.

From the 1960s onwards in particular, ecologists in North America and Western Europe became increasingly concerned with the death of large swathes of forested areas and collapsing fish stocks in adjacent freshwaters, with many remote regions affected, often at high latitudes far from any obvious sources of pollution (Menz and Seip, 2004). Through correlative, experimental and modelling studies, scientists from a range of disciplines on both sides of the Atlantic eventually identified the 'smoking gun' to be sulphur dioxide emissions. These findings were subsequently extended to include oxidised nitrogen and ammonia, and were derived primarily from internal combustion engines and the large smokestacks of power plants in heavily industrialised areas but with ammonia emissions dominated by agriculture. These emissions entered the atmosphere and were transported at high altitude over large distances, often crossing international borders, before being deposited as 'acid rain'. In addition to ecosystem impacts, acid rain damaged building materials in many urban areas and the particulates associated with the acidifying emissions were linked to increased levels of asthma and bronchitis, revealing the clear association between environmental and human health.

These realisations triggered considerable political activity and societal engagement – the citizen science movement was effectively born in the 1980s from the first large scale mobilisation of volunteers by the Audubon Society to track acid rain in the United States. Sweeping environmental legislation was brought in to control air pollution and new technologies engineered specifically to reduce emissions – including 'scrubbers' for smokestacks and catalytic converters for internal combustion engines. The Convention on Transboundary Air Pollution under the UNECE (United Nations Economic Commission for Europe) was established in 1979 in response to acid rain and extended in subsequent years by eight protocols to tackle air pollution across the region. The Convention has been an effective way of linking science and policy to tackle an international problem using multidisciplinary systems tools such as integrated assessment modelling, which is used to explore cost-effective strategies to tackle emissions of greenhouse gases and air pollutants at the same time whilst also minimising their effects on human and environmental health (Reis et al., 2012).

Long-term, large-scale and holistic biomonitoring schemes were set up in Europe from the 1980s onwards to track biological recovery, which was manifested increasingly from the 1990s onwards, with many waters seeing the return of fish populations after decades of local extinctions (Murphy et al 2014). More recently, a further layer of systems-based approaches has resolved some of the apparent paradoxes around ecological recovery that traditional reductionist approaches could not explain – for instance, complex food-web interactions explained why invertebrate abundance declined as acidity ameliorated, via cascading effects of the returning fish driving down their prey (Friberg et al 2011).

A salutary lesson is that much of the initial problem arose from early decisions to build higher smokestacks to minimise local pollution in the adjacent area, without considering the consequences of moving the pollution to another part of the system. With the benefit of hindsight, a wider perspective could have been employed sooner by accounting for these trade-offs to avert many of the long-term damaging effects and costs of acid rain. We can learn from these lessons for building the next generation of systems-based thinking to mitigate acid rain impacts in other areas around the world that are now undergoing their own rapid industrialisation.



An illustration of the different scales and timeline for addressing acid rain as described in the case study.

Linking systems, pollution and policy

It is vital that people working to tackle pollution take an interdisciplinary approach and (re)engage with wider society at the personal scale. Social science has a strong history in systems thinking and can provide the tools to integrate people effectively into decision-making as key stakeholders, to investigate the social influences on flows of pollution, and to provide the understanding and information needed to evolve human behaviour towards more sustainable choices. Examples of this include those seen from increases in cycling, as described in the case study in Box 1. In a world that must undergo rapid transformation, it is essential to develop communication across different disciplines, organisations, departments and industries (see the case study in Box 4). For such a widespread and varied problem like pollution, the wealth of various perspectives across society holds potential for innovation that has previously been untapped.

There is a growing realisation that systems thinking has the potential to support policymaking. In the UK, for instance, HM Treasury has published guidance for evaluation of complexity in policy using systems thinking (2020), the Department for Environment Food and Rural Affairs (Defra) has developed a systems research programme for the natural environment (GOV.UK, 2019), and the Government Office for Science has published an introductory systems thinking toolkit for civil servants (Government Office for Science, 2022). At the international level, the United Nations Office for Project Services (UNOPS) has developed guidance on systems approaches for strengthening infrastructure (2016) and the Institute for Applied Systems Analysis (IIASA) conducts policy-oriented research into complex, multidisciplinary issues such as pollution and climate change that cannot be dealt with by a single country alone.

Conclusions

- Pollution is a complex problem comprising many different interlinked elements. A systems approach can help to tackle and manage this challenge, propose solutions, and identify co-benefits, while also avoiding unintended consequences. Systems thinking can also help us to understand why existing solutions are not working, which in turn can guide us in developing better ones.
- The multiple scales of pollution challenges can be better appreciated using a systems approach, which provides a deeper understanding of the links between global, national, regional, local and individual pollution impacts.
- An interdisciplinary approach is essential, considering perspectives from different disciplines and stakeholders to understand the system boundaries, identify leverage points and potential technical, behavioural, social and policy solutions.

What next: from theory to practice

To take practical action to tackle pollution problems using systems thinking, we propose three key next steps:

1. *Understand the problem: engage systems experts from the outset to help frame the problem and develop solutions.*

Systems research can help conceptualise the complex nature of interlinked (sub)systems: defining a system and its components allows us to break down problems encapsulated within it without losing sight of their interdependence and define the system management targets such as ‘acceptable’ levels of pollution. From this, key stakeholders can be identified, and their ‘role’ clarified within the pollution system.

Engaging systems experts can help frame the problem and identify solutions that could not be seen from tackling individual aspects in isolation. For example, recent work by an international team into how to tackle the growing problem of plastic pollution showed that no single policy intervention will be enough. It did, however, demonstrate that existing solutions coupled with systems change could cut most of the plastic flowing into the global ocean (Lau et al., 2020). Furthermore, research for the Environment Agency has shown that a systems approach can increase understanding of the interactions between different elements of the water system and be used to develop different ways to manage it (Mijic, 2021).

Box 4: Why tackling nitrogen pollution needs an interdisciplinary systems approach

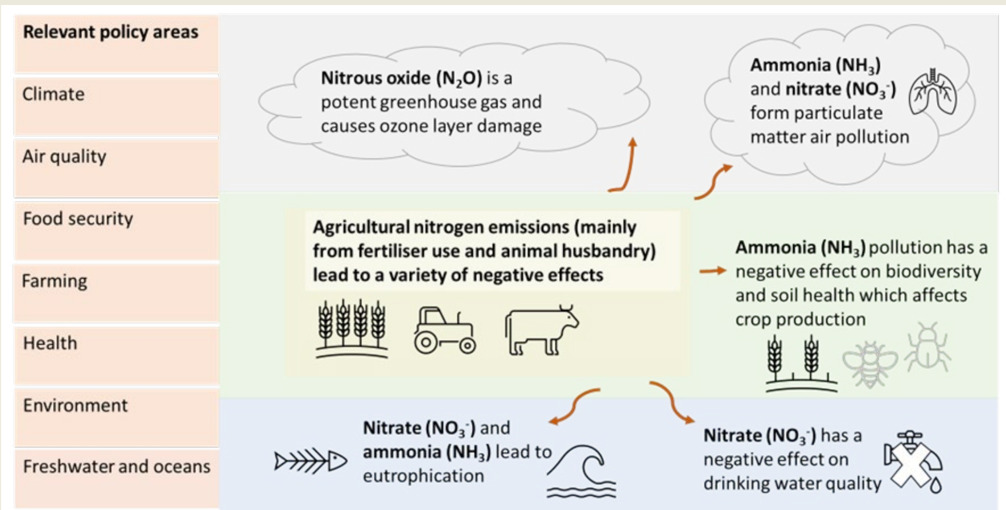
Human-caused disruption to the nitrogen cycle, for example through using ammonia as a fertiliser and burning of fossil fuels, has dispersed nitrogen in various forms through the environment, leading to pollution, greenhouse gas emissions, and widespread environmental impacts on the biosphere and human health.

In its molecular form, nitrogen (N2) is unreactive and forms 78% of the air we breathe, whilst in more chemically reactive forms it is an essential element to life that appears in amino acids, proteins and enzymes. The conversion of atmospheric nitrogen to reactive forms by anthropogenic activities now significantly exceeds natural processes such as biological fixation. The Haber-Bosch process, developed to produce ammonium nitrate for explosives in the First World War, enabled the production of fertilisers to provide food for the expanding world population. However, only a very small proportion of reactive nitrogen ends up as the proteins needed for a healthy diet. The rest cascades through the environment in different chemical forms causing a wide range of problems in the atmosphere, soil processes, freshwater, marine and terrestrial ecosystems and affecting their biodiversity. There is also a link to climate through emissions of nitrous oxide as a potent long-lived greenhouse gas (with a 100-year global warming potential 265 times that of carbon dioxide). Emission of oxidised nitrogen from fossil fuel combustion can be more easily controlled but also contributes to disruption of the nitrogen cycle. These problems are generally less well recognised than those of the carbon cycle with respect to climate change, but are arguably even more complex, with the range of interacting elements and scale of impacts making systems thinking essential for tackling both.

Looking to the future, new developments are likely to affect production of reactive nitrogen, including advances in energy systems such as use of renewable energy to produce ammonia as a fuel, and land use reforms driven by climate measures. Whereas many developed countries are using nitrogen wastefully for agriculture, other areas of the world are deficient in protein, and need either to enhance food production or to import food. The existing problems of anthropogenic influence on the nitrogen cycle are now recognised, and are starting to be addressed internationally, for example with the recent Colombo Declaration setting the ambitious aim of halving nitrogen waste from all sources by 2030. Building on the 2019 UN Environment Assembly Resolution (UNEP/EA.4/Res.14), it is now important to investigate how emerging pressures may change the nitrogen cycle and evaluate and plan towards solutions to mitigate the environmental consequences.

Engaging farmers, the wider agricultural industry and other stakeholders in discussions for effective policymaking on reactive nitrogen use in agriculture is essential to make sure that considerations such as balancing the cost of emission reduction measures with crop yield and meat production are discussed with an appreciation of the wider system (including pollutant impacts on biodiversity, future soil health, human health, the monetary and social costs, and changing dietary behaviour and demands on land-use) to provide valuable context for decision-making. Interdisciplinarity is key here: economists can work on valuation techniques and the socioeconomic effectiveness of measures, and engineers and scientists may focus on agricultural innovation and environmental aspects. Since technical change in such a sector often involves behavioural change, social engagement is also vital to success.

Taking a holistic view of nitrogen pollution is needed to avoid unintended consequences that can be caused when the different forms of reactive nitrogen are considered separately as their impacts fall in different policy areas, such as air pollution, water management, or food security (UNEP, 2019). For example, the process to remove nitrogen pollution from water can lead to nitrous oxide emissions (UNEP, 2021), emphasising the need to tackle nitrogen pollution as a whole system.



An illustration of the effects of agricultural nitrogen emissions (mainly from fertilisers and animal husbandary) and related policy areas.

There is systems expertise in many different fields, whose full multidisciplinary potential can be mobilised by bringing them together to work on a common problem, such as pollution. For example, in the UK, the Centre for the Evaluation of Complexity Across the Nexus is funded by UK Research and Innovation and brings together experts from the social sciences. Meanwhile the National Engineering Policy Centre (NEPC) at the Royal Academy of Engineering is demonstrating the need for a systems approach to reach net-zero and tackle climate change (Mitchell et al., 2020). There is an emerging systems community that engages with issues around pollution and the environment: in government with the systems research programme at Defra (GOV.UK, 2019), in academia with the Transition to Zero Pollution initiative at Imperial College London which is helping to build a cross-institution community of systems researchers, and internationally, as exemplified through the EU Environmental Foresight System (FORENV, 2019).

2. *Understand the system boundaries: bring in perspectives from a range of academics and industry, policy and societal stakeholders.*

Consider perspectives from different disciplines and stakeholders to understand system boundaries, identify leverage points and potential technical, behavioural, economic and policy solutions. Complex problems need to be broken down into manageable chunks to tackle them and bring people together from different disciplines and sectors can facilitate this – such as in the case of tackling nitrogen pollution, which involves multiple actors (Box 4).

As well as involving external stakeholders in discussions, also consider including different people from within an organisation who will be able to bring perspectives from their respective areas of expertise or related activities.

3. *Develop systems tools: use data and systems models to make collaborative decisions and understand trade-offs.*

Modelling and data are important aspects of systems approaches, although mentioned only briefly within the scope of this paper. Systems models and how they are used allows a balance to be achieved between capturing complexity and providing information that can be used for decision-making, to explore the many impacts of new interventions and technologies, support transitions to zero pollution, and provide insights into the impact of uncertainty and interconnections. As such, developing systems tools to use information from data and systems models remains a key next step in tackling systems problems.

Integrated models can be enhanced with data, new simulation tools and digital technologies to improve and (re)design systems in a better way. For example, simulations of water systems can be used to inform future planning of water and other infrastructure (land, housing, etc.), ensuring that interdependencies of supply and wastewater systems are considered to avoid underestimating impacts of sewer effluent on the river water quality (Dobson and Mijic, 2020). Thus, consideration of how to integrate existing data into systems models and identify what new data are needed to improve systems models and their results will also be key to achieving successful outcomes.

In summary, if we are to overcome the multifaceted threats to human and environmental health that will be increasingly posed by pollution in the coming decades, integrated systems thinking will be pivotal for rising to – and meeting – this challenge.

References

Algunaibet, I.M. and Guillén-Gosálbez, G. (2019). Life cycle burden-shifting in energy systems designed to minimize greenhouse gas emissions: Novel analytical method and application to the United States. *Journal of Cleaner Production,* 229, pp.886-901. https://doi.org/10.1016/j.jclepro.2019.04.276.

Allen, W. (2020). Systems Thinking. [online]. *Learning for Sustainability.* Available from: https://learningforsustainability.net/systems-thinking/ [Accessed 03 August 2022].

Asner, G.P. and Tupayachi, R. (2017). Accelerated losses of protected forests from gold mining in the Peruvian Amazon. *Environmental Research Letters,* 12(9), p.094004. https://doi.org/10.1088/1748-9326/aa7dab.

Avila-Palencia, I., Panis, L.I., Dons, E., Gaupp-Berghausen, M., Raser, E., Götschi, T., Gerike, R., Brand, C., De Nazelle, A., Orjuela, J.P., Anaya-Boig, E., Stigell, E., Kahlmeier, S., Iacorossi, F. and Nieuwenhuijsen, M.J. (2018). The effects of transport mode use on self-perceived health, mental health, and social contact measures: a cross-sectional and longitudinal study. *Environment International,* 120, pp.199-206. https://doi.org/10.1016/j.envint.2018.08.002.

Banza Lubaba Nkulu, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N. D., Kayembe-Kitenge, T., Musa Obadia, P., Kyanika Wa Mukoma, D., Lunda Ilunga, J. M., Nawrot, T. S., Luboya Numbi, O., Smolders, E., and Nemery, B. (2018). Sustainability of artisanal mining of cobalt in DR Congo. *Nature sustainability,* 1(9), 495–504. https://doi.org/10.1038/s41893-018-0139-4.

Bouman, B.A.M.(2007). A conceptual framework for the improvement of crop water productivity at different spatial scales. *Agricultural systems,* 93(1-3), pp.43-60. https://doi.org/10.1016/j.agsy.2006.04.004.

Brand, C., Götschi, T., Dons, E., Gerike, R., Anaya-Boig, E., Avila-Palencia, I., de Nazelle, A., Gascon, M., Gaupp-Berghausen, M., Iacorossi, F., Kahlmeier, S., Int Panis, L., Racioppi, F., Rojas-Rueda, D., Standaert, A., Stigell, E., Sulikova, S., Wegener, S. and Nieuwenhuijsen, M.J.(2021). The climate change mitigation impacts of active travel: Evidence from a longitudinal panel study in seven European cities. *Global Environmental Change,* 67, p.102224. https://doi.org/10.1016/j.gloenvcha.2021.102224.

Brauer, M., Brook, J. R., Christidis, T., Chu, Y., Crouse, D. L., Erickson, A., Hystad, P., Li, C., Martin, R. V., Meng, J., Pappin, A. J., Pinault, L. L., Tjepkema, M., van Donkelaar, A., Weichenthal, S., and Burnett, R. T. (2019). Mortality-Air Pollution Associations in Low-Exposure Environments (MAPLE): Phase 1. *Research report (Health Effects Institute),* (203), 1–87.

Brunekreef, B, Strak, M, Chen, J, Andersen, ZJ, Atkinson, R, Bauwelinck, M, Bellander, T, Boutron-Ruault, M-C, Brandt, J, Carey, I, Cesaroni, G, Forastiere, F, Fecht, D, Gulliver, J, Hertel, O, Hoffmann, B, de Hoogh, K, Houthuijs, D, Hvidtfeldt, UA, Janssen, N, Jørgensen, JT, Katsouyanni, K, Ketzel, M, Klompmaker, J, Krog, NH, Liu, S, Ljungman, PLS, Mehta, AJ, Nagel, G, Oftedal, BM, Pershagen, G, Peters, A, Raaschou-Nielsen, O, Renzi, M, Rodopoulou, S, Samoli, E, Schwarze, PE, Sigsgaard, T, Stafoggia, M, Vienneau, D, Weinmayr, G, Wolf, K and Hoek, G (2021), *Mortality and Morbidity Effects of Long-Term Exposure to Low-Level PM2.5, BC, NO2, and O3: An Analysis of European Cohorts in the ELAPSE Project.* HEI Report Series, no. 208, vol. WA 754 R432, Health Effects Institute.

Cabrera, D. and Cabrera, L. (2015). *Systems thinking made simple: new hope for solving wicked problems.* Odyssean Press.

Campbell, S.D. and Zellner, M. (2020). Wicked Problems, Foolish Decisions: Promoting Sustainability Through Urban Governance in a Complex World. *Vand. L. Rev.,* 73, p.1643.

Carslaw, D.C., Beevers, S.D., Tate, J.E., Westmoreland, E.J. and Williams, M.L. (2011). Recent evidence concerning higher NOx emissions from passenger cars and light duty vehicles. *Atmospheric Environment, 45(39)*, pp.7053-7063. https://doi.org/10.1016/j.atmosenv.2011.09.063

Dasgupta, S., Peng, X., Chen, S., Li, J., Du, M., Zhou, Y.H., Zhong, G., Xu, H. and Ta, K. (2018). Toxic anthropogenic pollutants reach the deepest ocean on Earth. *Geochemical Perspectives Letters ,* 7, pp.22-26. https://doi.org/10.7185/geochemlet.1814

De Nazelle, A., Nieuwenhuijsen, M.J., Antó, J.M., Brauer, M., Briggs, D., Braun-Fahrlander, C., Cavill, N., Cooper, A.R., Desqueyroux, H., Fruin, S. and Hoek, G. (2011). Improving health through policies that promote active travel: a review of evidence to support integrated health impact assessment. *Environment international,* 37(4), pp.766-777. https://doi.org/10.1016/j.envint.2011.02.003

Dobson, B. and Mijic, A. (2020). Protecting rivers by integrating supply-wastewater infrastructure planning and coordinating operational decisions. *Environmental Research Letters,* 15(11), pp.1-13. https://doi.org/10.1088/1748-9326/abb050

Dominici, F., Schwartz, J., Di, Q., Braun, D., Choirat, C. and Zanobetti, A. (2019). Assessing adverse health effects of long-term exposure to low levels of ambient air pollution: phase 1. *Research report (Health Effects Institute), (200), 1–51.*

European Commission (2021). COM/2021/400 final: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. *Pathway to a Healthy Planet for All EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil'* [online]. European Commission. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0400&qid=1638450152411 [accessed 03 August 2022]

The EU Environmental Foresight System (FORENV) (2019). *The EU Environmental Foresight System (FORENV) – Final report of 2018-19 annual cycle – Emerging issues at the environment-social interface,* Publications Office of the European Union, Luxembourg, ISBN 978-92-76-09707-5, https://doi.org/10.2779/363227.

Friberg, N., Bonada, N., Bradley, D.C., Dunbar, M.J., Edwards, F.K., Grey, J., Hayes, R.B., Hildrew, A.G., Lamouroux, N., Trimmer, M. and Woodward, G. (2011). Biomonitoring of human impacts in freshwater ecosystems: the good, the bad and the ugly. *Advances in Ecological Research,* 44, 1-68.

Gabrielli, P., Wegner, A., Sierra-Hernández, M.R., Beaudon, E., Davis, M., Barker, J.D. and Thompson, L.G., 2020. Early atmospheric contamination on the top of the Himalayas since the onset of the European Industrial Revolution. Proceedings of the National Academy of Sciences, 117(8), pp.3967-3973.

Gascon, M., Triguero-Mas, M., Martínez, D., Dadvand, P., Rojas-Rueda, D., Plasència, A., and Nieuwenhuijsen, M. J. (2016). Residential green spaces and mortality: A systematic review. *Environment International.* https://doi.org/10.1016/j.envint.2015.10.013

Götschi, T., de Nazelle, A., Brand, C. and Gerike, R. (2017). Towards a comprehensive conceptual framework of active travel behavior: a review and synthesis of published frameworks. *Current environmental health reports,* 4(3), pp.286-295. https://doi.org/10.1007/s40572-017-0149-9

Government office for Science (2022). Systems thinking: an introductory toolkit for civil servants, Government Office for Science. Available at:www.gov.uk/government/publications/systems-thinking-for-civil-servants/toolkit

GOV.UK (2019). Science research programme launched to inform Defra policy making. [online]. Department for Environment, Food and Rural Affairs (Defra). Available at: www.gov.uk/government/news/science-research-programme-launched-to-inform-defra-policy-making [Accessed: 03 August 2022].

Guzzella, L., Salerno, F., Freppaz, M., Roscioli, C., Pisanello, F. and Poma, G. (2016). POP and PAH contamination in the southern slopes of Mt. Everest (Himalaya, Nepal): long-range atmospheric transport, glacier shrinkage, or local impact of tourism?. *Science of the total environment,* 544, pp.382-390. https://doi.org/10.1016/j.scitotenv.2015.11.118

Halliday, T. (2007). Endangered Amphibians. Editor(s): S.A. Levin. *Encyclopedia of Biodiversity.* pp 1-5.

Harrabin, R. and Edgington, T. (2019). Recycling: Where is the plastic waste mountain? [online]. *BBC – Science & Environment.* Available at: www.bbc.co.uk/news/science-environment-46566795 [Accessed 03 August 2022].

Her Majesty's Treasury (2020). The Green Book 2020. *The Green Book: appraisal and evaluation in central government.* HM Treasury. London.

Hoffmann, B., Boogaard, Ha., de Nazelle, A., Andersen, Z. J., Abramson, M., Brauer, M., Brunekreef B., Forastiere, F., Huang, W., Kan, H., Kaufman, J. D., Katsouyanni, K., Krzyzanowski, M., Kuenzli, N., Laden, F., Nieuwenhuijsen, M., Mustapha, Ad., Powell, P., Rice, M., Roca-Barceló, A., Roscoe, C. J., Soares, A., Straif, K., and Thurston, G. (2021). WHO Air Quality Guidelines 2021–Aiming for Healthier Air for all: A Joint Statement by Medical, Public Health, Scientific Societies and Patient Representative Organisations. *International Journal of Public Health,* 66, p. 88. https://doi.org/10.3389/ijph.2021.1604465.

IPCC (2021). Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B. (eds.). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press. In Press.

Jamieson A. J., Brooks L. S. R., Reid W. D. K., Piertney S. B., Narayanaswamy B. E. and Linley T. D. (2019). Microplastics and synthetic particles ingested by deep-sea amphipods in six of the deepest marine ecosystems on Earth. *Royal Society Open Science.* 6180667180667. https://doi.org/10.1098/rsos.180667.

Jarrett, J., Woodcock, J., Griffiths, U.K., Chalabi, Z., Edwards, P., Roberts, I. and Haines, A. (2012). Effect of increasing active travel in urban England and Wales on costs to the National Health Service. *The Lancet, 379*(9832), pp.2198-2205. https://doi.org/10.1016/S0140-6736(12)60766-1.

Ji, S., Cherry, C.R., J. Bechle, M., Wu, Y. and Marshall, J.D. (2012). Electric vehicles in China: emissions and health impacts. *Environmental science & technology,* 46(4), pp.2018-2024. https://doi.org/10.1021/es202347q.

Jiao, X., Dong, Z., Kang, S., Li, Y., Jiang, C. and Rostami, M. (2021). New insights into heavy metal elements deposition in the snowpacks of mountain glaciers in the eastern Tibetan Plateau. *Ecotoxicology and Environmental Safety,* 207, p.111228. https://doi.org/10.1016/j.ecoenv.2020.111228.

Jiménez-González, C., Curzons, A.D., Constable, D.J.C. and Cunningham, V. L. (2004). Cradle-to-gate life cycle inventory and assessment of pharmaceutical compounds. *International Journal of Life Cycle Assessment,* 9, pp.114–121. https://doi.org/10.1007/BF02978570.

Jonson, J.E., Borken-Kleefeld, J., Simpson, D., Nyíri, A., Posch, M. and Heyes, C. (2017). Impact of excess NOx emissions from diesel cars on air quality, public health and eutrophication in Europe. *Environmental Research Letters, 12*(9). 094017. https://doi.org/10.1088/1748-9326/aa8850.

Landrigan, P. J., Fuller, R., Acosta, N., Adeyi, O., Arnold, R., Basu, N. N., Baldé, A. B., Bertollini, R., Bose-O'Reilly, S., Boufford, J. I., Breysse, P. N., Chiles, T., Mahidol, C., Coll-Seck, A. M., Cropper, M. L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., … Zhong, M. (2018). The Lancet Commission on pollution and health. *Lancet (London, England)*, 391(10119), 462–512. https://doi.org/10.1016/S0140-6736(17)32345-0

Lau, W.W., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B. and Thompson, R.C. (2020)., Evaluating scenarios toward zero plastic pollution. *Science*, 369(6510), pp.1455-1461. https://doi.org/10.1126/science.aba9475.

Letourneau, A., Verburg, P.H. and Stehfest, E. (2012)., A land-use systems approach to represent land-use dynamics at continental and global scales. *Environmental Modelling & Software*, 33, pp.61-79. https://doi.org/10.1016/j.envsoft.2012.01.007.

Liu, Y., Chen, H., Gao, J., Li, Y., Dave, K., Chen, J., Federici, M., Perricone, G. (2021). Comparative analysis of non-exhaust airborne particles from electric and internal combustion engine vehicles. *Journal of Hazardous Materials*, 420, 126626. https://doi.org/10.1016/j.jhazmat.2021.126626.

Meadows, D.H., Meadows, D.L., Randers, J. and Behrens III., W.W. (1972). 'The Limits to Growth'. *Potomac.* New York.

Meadows, D., 2008.Thinking in Systems: A Primer. *Chelsea Green Publishing*, White River Junction, Vermont.

Mehlig, D.; Woodward, H.; Oxley, T.; Holland, M.; ApSimon, H. (2021). Electrification of Road Transport and the Impacts on Air Quality and Health in the UK. *Atmosphere, 12*, 1491. https://doi.org/10.3390/atmos12111491.

Menz, F.C. and Seip, H.M. (2004). Acid rain in Europe and the United States: an update. *Environmental Science & Policy*, 7(4), 253-265.

Mijic, A. (2021). Systems water management for catchment scale processes: Development and demonstration of a systems analysis framework. Chief Scientist's Group report. *Environment Agency.* [online]. Available at: https://www.gov.uk/government/publications/a-systems-based-approach-to-catchment-water-management [Accessed 03 August 2022].

Mitchell, D., Shah, N., Apsey, M., Baxter, J., Bulkeley, H., Cook, M., Gardner, I., Harrison, S., Holliday, S., Kemp, R., Lunn, R., McCluskey, I., Owens, S., Parsons, S. and Winser, N. (2020). Net Zero: A systems perspective on the climate challenge. [online] London: *Royal Academy of Engineering*, p.6. Available from: www.raeng.org.uk/publications/reports/net-zero-a-systems-perspective-on-the-climate-chal [Accessed: 03 August 2022].

Monat, J.P. and Gannon, T.F. (2015)., What is systems thinking? A review of selected literature plus recommendations. *American Journal of Systems Science*, 4(1), pp.11-26. https://doi.org/10.5923/j.ajss.20150401.02.

Mueller, N., Rojas-Rueda, D., Salmon, M., Martinez, D., Ambros, A., Brand, C., De Nazelle, A., Dons, E., Gaupp-Berghausen, M., Gerike, R. and Götschi, T. (2018)., Health impact assessment of cycling network expansions in European cities. *Preventive medicine*, 109, pp.62-70. https://doi.org/10.1016/j.ypmed.2017.12.011.

Muralikrishna, I.V. and Manickam, V. (2017). *Environmental management: science and engineering for industry.* Butterworth-Heinemann.

Murphy, J.F., Winterbottom, J.H., Orton, S., Simpson, G.L., Shilland, E.M. and Hildrew, A.G., (2014) Evidence of recovery from acidification in the macroinvertebrate assemblages of UK fresh waters: a 20-year time series. *Ecological Indicators*, 37, 330-340.

Nguyen, N.C. and Bosch, O.J. (2013). A systems thinking approach to identify leverage points for sustainability: a case study in the Cat Ba Biosphere Reserve, Vietnam. *Systems Research and Behavioral Science*, 30(2), pp.104-115. https://doi.org/10.1002/sres.2145.

O'Driscoll, R., M. E. J. Stettler, N. Molden, T. Oxley, and H. M. ApSimon. (2018). Real World CO_2 and NOx Emissions From 149 Euro 5 and 6 Diesel, Gasoline and Hybrid Passenger Cars. *Science of The Total Environment* 621: 282–290. https://doi.org/10.1016/j.scitotenv.2017.11.271 .

Pearce, D., Pearce, A., Gambhir, A., Nelson, J., Gilbert, A., Rhodes, A., and Bhugobaun, R., (2021). *Grantham Institute briefing paper: Research pathways for net-zero transport.* https://doi.org/10.25561/92035

Perez-Vega, S., Ortega-Rivas, E., Salmeron-Ochoa, I. and Sharratt, P.N. (2013). A system view of solvent selection in the pharmaceutical industry: towards a sustainable choice. *Environment, development and sustainability*, 15(1), pp.1-21. https://doi.org/10.1007/s10668-012-9365-5.

Pörtner, H.O., Scholes, R.J., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W.L., Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M. A., Handa, C., Hickler, T., Hoegh-Guldberg, O., Ichii, K., Jacob, U., Insarov, G., Kiessling, W., Leadley, P., Leemans, R., Levin, L., Lim, M., Maharaj, S., Managi, S., Marquet, P. A., McElwee, P., Midgley, G., Oberdorff, T., Obura, D., Osman, E., Pandit, R., Pascual, U., Pires, A. P. F., Popp, A., Reyes-García, V., Sankaran, M., Settele, J., Shin, Y. J., Sintayehu, D. W., Smith, P., Steiner, N., Strassburg, B., Sukumar, R., Trisos, C., Val, A.L., Wu, J., Aldrian, E., Parmesan, C., Pichs-Madruga, R., Roberts, D.C., Rogers, A.D., Díaz, S., Fischer, M., Hashimoto, S., Lavorel, S., Wu, N., and Ngo, H.T. (2021). *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change;* IPBES and IPCC. https://doi.org/10.5281/zenodo.4782538.

Rai, P.K. (2016). *Biomagnetic Monitoring of Particulate Matter: in the Indo-Burma hotspot region.* Elsevier Science. pp 1.

Raworth, K. (2017). *Doughnut Economics: seven ways to think like a 21st century economist.* Random House Business

Reis, S., Grennfelt, P., Klimont, Z., Amann, M., ApSimon, H., Hettelingh, J. P., Holland, M., LeGall, A. C., Maas, R., Posch, M., Spranger, T., Sutton, M. A., & Williams, M. (2012). Atmospheric science. From acid rain to climate change. *Science,* 338(6111), pp.1153–1154. https://doi.org/10.1126/science.1226514

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J. and Nykvist, B. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society,* 14(2), 32. [online]. Available from: www.ecologyandsociety.org/vol14/iss2/art32/.

Rojas-Rueda, D., de Nazelle, A., Teixidó, O. and Nieuwenhuijsen, M.J. (2012). Replacing car trips by increasing bike and public transport in the greater Barcelona metropolitan area: a health impact assessment study. *Environment International,* 49, pp.100-109. https://doi.org/10.1016/j.envint.2012.08.009.

Sendek-Matysiak, E. (2019, March). Electric cars as a new mobility concept complying with sustainable development principles. In *AIP Conference Proceedings* (Vol. 2078, No. 1, p. 020026). AIP Publishing LLC. https://doi.org/10.1063/1.5092029.

Sterman, J. (2002). *System Dynamics: systems thinking and modeling for a complex world.* Massachusetts Institute of Technology. Engineering Systems Division.

Sterman, J.D. (2001). System dynamics modeling: tools for learning in a complex world. *California management review,* 43(4), pp.8-25. https://doi.org/10.2307/41166098.

United Nations Environment Programme (UNEP) (2019). *Frontiers 2018/19 Emerging Issues of Environmental Concern.* United Nations Environment Programme, Nairobi. Available from: www.unep.org/resources/frontiers-201819-emerging-issues-environmental-concern [accessed 03 August 2022]

United Nations Environment Programme (UNEP), (2021). *Making Peace with Nature: A scientific blueprint to tackle the climate, biodiversity and pollution emergencies.* United Nations Environment Programme, Nairobi. Available from: www.unep.org/resources/global-assessments-sythesis-report-path-to-sustainable-future [accessed 03 August 2022]

United Nations Office for Project Services (UNOPS) (2016). *The Systems of Systems Approach to Infrastructure.* [online]. United Nations Office for Project Services. Available from: www.unops.org/news-and-stories/news/the-system-of-systems-approach-to-infrastructure [Accessed: 03 August 2022].

Villarrubia-Gómez, P., Cornell, S.E. and Fabres, J. (2018). Marine plastic pollution as a planetary boundary threat – The drifting piece in the sustainability puzzle. *Marine Policy,* 96, pp.213-220. https://doi.org/10.1016/j.marpol.2017.11.035.

Vohra, K., Vodonos, A., Schwartz, J., Marais, E.A., Sulprizio, M.P. and Mickley, L.J. (2021). Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. *Environmental Research,* 195, p.110754. https://doi.org/10.1016/j.envres.2021.110754.

Whyte, J., Mijic, A., Myers, R.J., Angeloudis, P., Cardin, M.A., Stettler, M.E. and Ochieng, W. (2020). A research agenda on systems approaches to infrastructure. Civil Engineering and Environmental Systems, 37(4), pp.214-233. https://doi.org/10.1080/10286608.2020.1827396.

Wolfram, P. and Wiedmann, T. (2017). Electrifying Australian transport: Hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity. *Applied Energy,* 206, pp. 531-540. Available from: https://doi.org/10.1016/j.apenergy.2017.08.219

Woodcock, J., Edwards, P., Tonne, C., Armstrong, B. G., Ashiru, O., Banister, D., Beevers, S., Chalabi, Z., Chowdhury, Z., Cohen, A., Franco, O. H., Haines, A., Hickman, R., Lindsay, G., Mittal, I., Mohan, D., Tiwari, G., Woodward, A., & Roberts, I. (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *Lancet (London, England),* 374(9705), 1930–1943. Available from: https://doi.org/10.1016/S0140-6736(09)61714-1.

Zipper, S.C., Jaramillo, F., Wang-Erlandsson, L., Cornell, S.E., Gleeson, T., Porkka, M., Häyhä, T., Crépin, A.S., Fetzer, I., Gerten, D., Hoff, H., Matthews, N., Ricaurte-Villota, C., Kummu, M., Wada, Y., and Gordon, L. (2020). Integrating the water planetary boundary with water management from local to global scales. *Earth's future,* 8(2), p.e2019EF001377. https://doi.org/10.1029/2019EF001377.

Acknowledgements

The authors would like to thank Alyssa Gilbert (Grantham Institute – Climate Change and Environment), Professor Tim Green (Energy Futures Lab), Professor Mary Ryan (Vice Provost (Research and Enterprise)), Professor Nilay Shah (Department of Chemical Engineering and Sargent Centre for Process Engineering) and Jane Williams (Faculty of Engineering) for their detailed and helpful comments in the development of this paper, and Mohamad Muhieddine (Department of Chemical Engineering) for producing the illustration for the pharmaceuticals and solvent pollution case study (Box 2).

About the authors

Liam Kirkpatrick is a postgraduate researcher and PhD candidate in the Centre for Environmental Policy and the Grantham Institute at Imperial College London. In partnership with the Environment Agency, his current research focuses on cultural ecosystem services and blue space, investigating methods for alternative valuations of nature in policymaking. He has a background in geography and natural hazards/climate risk, and is interested in interdisciplinary approaches to socio-ecological problems.

Claire Adjiman FREng is a Professor of Chemical Engineering at Imperial College London and Director of the Imperial/UCL Sargent Centre for Process Systems Engineering. Her research group develops computer-aided systems approaches to design more sustainable manufacturing processes and products, e.g., in the pharmaceutical and agrochemical industries, and for carbon dioxide capture and heat recovery.

Helen ApSimon heads the Integrated Assessment Unit in the Centre for Environmental Policy, currently working on modelling future air quality scenarios in the UK, and potential abatement strategies and synergies with climate measures, to support Defra in setting targets for PM2.5 in the Environment Bill. She also has over 25 years' experience working on transboundary air pollution in Europe under the UNECE Air Convention, and development of the Gothenburg protocol and corresponding EU legislation.

Alex Berry manages the Transition to Zero Pollution initiative at Imperial College London. The initiative is bringing together researchers at Imperial College London to work together to realise a sustainable zero pollution future, going beyond thinking about zero carbon to consider pollution in all its forms.

Audrey de Nazelle is a Senior Lecturer at the Centre for Environmental Policy (CEP) at Imperial College London. Her research, at the intersection of public health, environmental science, and urban planning, aims at helping decision making towards healthy and sustainable cities. It includes the development of integrated health impact modelling of urban transport policies; exposure modelling; evaluation of behavioural, health and environmental impacts of real-world urban policies; stakeholder engagement towards transformational transitions in cities.

Ana Mijic is a Reader in Water Systems Integration and a Director of the Centre for Systems Engineering and Innovation (CSEI). She is leading the development of novel systems tools focused on quantifying the interaction between water systems and sustainable development. The work aims to inform regulatory bodies and water industry if and how we can support economic growth whilst ensuring sustainable water use and flood and water quality management under future uncertainties.

Rupert J. Myers is Senior Lecturer in Sustainable Materials Engineering in the Department of Civil and Environmental Engineering at Imperial College London. His research combines systems approaches in industrial ecology with experiments and modelling in materials science, focussing on bulk materials like cement and metals, and the services/products that they provide, e.g., buildings, infrastructure, and cities.

Guy Woodward is an internationally recognised expert in freshwater ecology and Professor of Ecology at Imperial College London and a Director of the Freshwater Biological Association. He studies ecological responses to stressors in fresh waters, with a focus on understanding how these are modulated by the food web. He has investigated how a wide range of chemical and climate-related stressors affect biodiversity, ecosystem functioning and services.

Mark Workman is a specialist in Strategic Foresight. He uses mixed methods to develop insights about risks and opportunities in different possible futures. As an affiliate researcher at Imperial College London, Mark is developing specialisations around: resource systems, energy transitions, environmental and climate change, violent conflict and the processes of decision making under uncertainty.

Please cite this paper as:
Kirkpatrick, L. et al. (2023) Systems thinking for the transition to net zero pollution, Grantham Institute Briefing Paper 40, 18pp, Imperial College London.

doi: https://doi.org/10.25561/104217

About the Grantham Institute, Transition to Zero Pollution initiative and Imperial College London

In 2007, the Grantham Foundation for the Protection of the Environment made the visionary decision to support an Institute at Imperial College London to provide a vital global centre of excellence for research and education on climate change. Fifteen years on, the Grantham Institute is established as an authority on climate and environmental science. The Grantham Institute is Imperial's hub for climate change and the environment, and one of seven Global Institutes established to promote inter-disciplinary working and to meet some of the greatest challenges faced by society. We drive forward discovery, convert innovations into applications, train future leaders and communicate academic knowledge to businesses, industry and policymakers to help shape their decisions.

Transition to Zero Pollution began in 2020 as a flagship initiative of Imperial College London's Academic Strategy, capturing Imperial's vision to transform the way we think about pollution by bringing together ideas around resource management, health and environmental impacts, socio-economic and human behaviour in a 'whole system' approach. This initiative is the research, education and innovation programme of sustainability at Imperial under Imperial Zero Pollution. With a vision to realise a sustainable zero pollution future, at Imperial we embed a consistent and credible commitment to sustainability into all our work – from our world-leading research and education to how we run our campuses and interact with industry.

Imperial College London is a global university with a world-class reputation in science, engineering, business and medicine, and excellence in teaching and research. Consistently rated amongst the world's best universities, Imperial is committed to developing the next generation of researchers, innovators and leaders through collaboration across disciplines. Find out more about the breadth of systems research at Imperial on the systems research at Imperial web page.

www.imperial.ac.uk/grantham

Contact us

For more information about this subject, to discuss how the issues covered affect you and your work, or to contact the authors, please email us at: Transition to Zero Pollution: zeropollution@imperial.ac.uk or the Grantham Institute: grantham@imperial.ac.uk