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Harnessing science, policy, and law to deliver clean air

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Trends in epidemiological and toxicological science point to health harms arising from air pollution at ever-lower concentrations, making the provision of clean air increasingly urgent yet ever more difficult to achieve. Compelling scientific evidence on causes, effects, and technical fixes is not sufficient to deliver global clean air ambitions; the law must play a central role in shaping actions. Yet despite an increase in the number of national laws and regulations that seek to address the problem, many countries still have weak air quality regimes. We identify six key future looking issues at the interface of science, the law, and policy, each of which shows why air quality governance is a complex, interdependent, and dynamic regulatory space, which needs interdisciplinary attention in diagnosing how air quality regimes might be improved.

We make three caveats at the outset. First, although exposure to harmful air pollution occurs both indoors and outside, we focus on outdoor air where some degree of state control and responsibility has historically existed. Second, we focus at the level of national government and national legal jurisdictions as the primary sites of air quality law and policy globally. Third, national and international legal regimes can import a wide range of doctrines, rights, and norms that affect the implementation and influence of air quality regimes (1). In this piece, we focus on regulatory aspects of air quality law, noting that there are wider legal changes occurring in many jurisdictions around norms, such as the expansion of specific human rights, that may affect the interpretation and implementation of air quality regimes.

THE VALUE OF ROBUST STANDARDS

Science-based air quality standards that are embedded in a robust national legal regime provide the regulatory keystone around which social and technical policies can be built (1). Such standards are "apex," or outcome-based, and thus set the direction for policies that will support their attainment. In this context, a "policy" is the mandated, government-sponsored means by which a particular objective, legally binding or not, can be achieved. Embedding air quality standards legally grounds them in administrative and institutional reality. It creates an obligation, rather than a policy aspiration. Improved public health, labor productivity, and ecosystems might be seen as the "carrot," which economic analysis strongly supports. The combined external mortality costs of industrial pollution in the European Union (EU) in 2021 due to ammonia, nitrogen oxides (NO_x), particulate matter 10 μm or less in diameter, sulfur dioxide, and nonmethane volatile organic compounds were estimated at >190 billion euros (2). Scientifically informed and legally enforceable ambient standards then form a part of “the stick” to make it happen. Recent ambient air quality lawsuits show that legal enforceability is not always straightforward, and protection regimes only work if they contain certain jurisdiction-appropriate features relating to institutional responsibility, empowerment of the public, enforceable drafting, meaningful timescales, monitoring, sanctions, review, and transparency.

The First Global Assessment of Air Pollution Legislation 2021 [(3); authored by E.S. and D.M.] explored why so many countries still have weak air quality regimes. We found that 64% of 194 countries (plus the EU) had legally mandated or embedded ambient air quality standards, but that these were heterogeneous. In at least 34% of countries, air quality was not legally protected. Among those countries without legally framed standards (many in Africa), 86% had no informal national air quality objectives, and 14% had standards that were declaratory only, with no explicit relation to a legal basis or broader framework for environmental policy. Twenty-one percent of countries were reviewing or revising their air quality laws at the time of the assessment, consistent with an upswing in political prioritization and emerging scientific evidence.

The enforceability and legal implications of breaching air quality standards determine the ambition and nature of any policy response—only 33% of national regimes that have adopted standards imposed any formal obligations to meet them (3). Where standards are enforceable and supported by clear legal obligations, they have been used in some jurisdictions as a benchmark of performance in lawsuits, where the adequacy of policy measures taken by public authorities has been challenged (4). In these cases, legal questions turn on the interpretation and implementation of obligations relating to air quality management, measurement, procedural requirements for the review of standards, or what governments are ultimately responsible for achieving and by when. The prospect of legal accountability through courts also turns on viable routes of access to justice through a legal system.

In addition to ambient air quality standards, national air quality regimes usually implicate a constellation of regulations in specific sectors, from controlling emissions to including air quality as a factor in the governance of development and planning. Some soft law instruments and regional treaties, such as the 1979 Convention on Long- Range Transboundary Air Pollution, directed by the United Nations (UN) Economic Commission for Europe, also exist to reduce transboundary pollution and to standardize sectoral emissions from certain products and processes. This wider regulatory landscape provides a mutually reinforcing set of legal levers to control emissions in service of public health and the environment and, more specifically, ambient air quality standards. However, sectoral regulations have lower public visibility, and their contribution to ensuring that apex standards are achieved is not always clearly articulated. The “dieselgate” automotive emissions testing scandal across many jurisdictions highlighted that egregious failures in product regulation can cut through and create points of weakness in the holistic implementation of air quality law.

KEY EMERGING ISSUES

Against this background, we identify six key issues at the interface of science (the “why,” and what is technically possible), the law (which sets out what must be achieved, for which beneficiaries, and by when, as well as providing sanctions and accountability), and policy (how the requirements set in law will be delivered).

1. Setting standards—designing informed air quality ambitions over time

Ambient air quality standards are a health relevant health relevant end point against which the cumulative performance of multiple policy and technical actions can be assessed. Their definition is not standardized across the world, although they are frequently expressed as a maximum acceptable time-averaged amount of pollutant in ambient outdoor air, as a concentration or mole fraction. There are few standards for indoor air despite substantial evidence for harm in these environments (5).

Much debate globally around improving air quality regimes focuses on increasing the ambition of air quality standards. In 2021, the World Health Organization (WHO) issued updated Air Quality Guideline levels (AQGs), indicating that even low concentrations of particulate matter 2.5 μg m^{-3} or less in diameter ($PM_{2.5}$), nitrogen dioxide (NO_2), and ozone cause some harm to health (6). The guidelines suggest institutional and legal structures for implementation; however, they are not intended as a blueprint for immediate, comprehensive legislation, despite some national and global campaigns calling for their regulatory adoption. The use of interim targets prescribes a direction of travel heading to the final destination for public health. Only a modest fraction of countries (25% for $PM_{2.5}$, 30% for NO_2) had aligned their standards with the previous WHO (2005) recommendations, and in 2020, none were aligned with the 2021 revision for $PM_{2.5}$.

The science of pollution is continually evolving. However, this ever-growing scientific evidence cannot, in isolation, dictate ideal legal rules. For air quality limit value standards to be technically enforceable, further elements must be specified including measurement techniques and strategy, data handling procedures (including quality assurance and quality control), and statistical methods (including treatment of uncertainties) (6). Each of these requires norm consensus and scientific accountability. And beyond limit values lies a lexicon of other air quality metrics with differing levels of legal enforceability—target values, average exposure reduction obligations, average exposure concentration objectives, critical levels, alert thresholds, information thresholds, and long-term objectives.

Depending upon the applicable legal framework and how it has evolved, standard setting might also require a tensioning of health evidence with physical science, technical opportunities, and scientific feasibility, and a need to demonstrate cost-effectiveness, and social and political acceptability. Setting standards toward a scientifically informed destination for public health is often a process of revision and increasing ambition over time. As technology and health-related knowledge develop, policy success is tested, evidence changes, and public views evolve.

Increasing social concern around the importance of air quality to health has implications for standard setting. Robust environmental governance implies the inclusion of publics in the review processes that may lead to the adoption of new standards, or the revision of existing standards and policies. Historically, air quality standards have been treated as a largely expert, technical, and governmental domain; however, environmental procedural rights mold new dynamics, where public knowledge about air quality increases as a consequence of legal requirements, such as air quality disclosure rules. This public engagement may be reinforced by technological developments in simple, lower-cost (but also lower-accuracy) sensors of air pollution, as well as public education in social behaviors related to health risks. Sensors can empower individuals and communities to measure in their own neighborhoods and provide a level of agency. Air quality regimes thus need to be sufficiently flexible to accommodate challenge from an increasingly diverse range of data sources.

Finally, there are major normative shifts occurring in many jurisdictions and globally, creating an ever-stronger case for the legal protection of public health from harmful air pollutants, bolstering the legal case for ambitious air quality standard setting. Harmful pollution of air prima facie interferes with the enjoyment of a clean, healthy, and sustainable environment (a human right newly recognized by the UN General Assembly) and such damage also has negative implications, both direct and indirect, for the effective enjoyment of all human rights (7).

2. Setting standards—separating scientific and policy feasibility

Related to ambition, there is an associated complexity dealing with the dilemma of feasibility. On one side, in the UNEP Guide on Ambient Air Quality Legislation (1), we identify the need for flexibility in setting ambitious standards that reflect local development, economic, and technological conditions alongside transboundary and natural effects. On the other side, it is unhelpful to legislate that only readily “achievable” objectives should be adopted, because this could be a route for watering down ambitions (8). Unjustified flexibility can entrench health injustices, license “sacrifice zones,” complicate access to justice on ambient air, and lead to inaction. A way through this dilemma is to recognize that feasibility of achieving standards has two distinct dimensions—scientific and policy-based. A policy-based argument for noncompliance may not be readily justifiable; a scientific case is potentially more compelling.

By way of example of a scientific feasibility argument, the WHO recommends a 5 $\mu g\ m^{-3}$ annual mean concentration for $PM_{2.5}$. Recent revisions of annual limits for $PM_{2.5}$ in the UK, USA, and proposed in the EU are 10, 9, and 10 $\mu g\ m^{-3}$. Natural sources of $PM_{2.5}$ from sea-spray, biosphere, windblown soils, and wildfires might in some places account for 2 to 4 $\mu g\ m^{-3}$. Add 1 to 3 $\mu g\ m^{-3}$ of transboundary anthropogenic $PM_{2.5}$ (and precursors) and a national policy-maker’s room for maneuver is limited. With no accommodation, the WHO AQG may be exceeded solely on account of natural or extraneous conditions, leading to three possible implications: (i) A government will be in perpetual breach of its own laws; (ii) any standard needs to be set high enough to account for these realities; or (iii) natural factors should be discounted in determining legal compliance. How (iii) might be enabled varies by jurisdiction, but there are challenges in reaching agreement over what is “natural” or “exceptional,” and broader governance risks in granting powers of executive discretion.

A policy-based argument around infeasibility might identify that an ambient limit value was not feasible owing to economic and social conditions. Preexisting transport systems, supply chains, industrial policy, and urban planning may set structures for air pollution that are difficult to shift, going beyond what might be possible with technological abatement. Structural arguments are less compelling in maintaining a position of feasibility. The “policy-forcing” role of ambitious standards should take priority because they provide a powerful mechanism for aligning incentives and investment toward structural transformation.

The distinction between scientific and policy reasoning becomes more complex for transboundary effects where the achievability of a national standard may be affected by pollution emanating elsewhere. Pollution might arise from natural causes (e.g., wildfires) or social or economic causes (e.g., higher levels of industrial emissions in a neighboring country). In the latter case, the policy and public health ambitions of one country should not be undermined by choices made in another. There is a case for parity of limit values between countries (9), but perhaps more important are robust systems of air quality governance across borders, including requirements for information sharing and joint working to effectively reduce unhealthy levels of air accumulating through transboundary pollution.

There is also some geographical and political luck in governing transboundary air pollution. Superior legal and policy levers exist for the control of longer-lived and secondary pollutants, such as ozone and $PM_{2.5}$, for which there is a single system of air quality management across large geographical areas, and correspondingly limits on what can be achieved with national regulation at a smaller geographical scale. Higher $PM_{2.5}$ on average in Poland or Slovenia, compared with Ireland, UK, or Norway, arises in part from an accumulation of emissions and secondary pollutants as large-scale flows of air traverse the continent (10).

Improving air quality in Poland depends on coordinated action that starts on the European western coast as well as local actions to reduce domestic sources. Similar effects occur across the USA, China, and India. For a “continental-scale” country like the USA, sufficient policy control levers for ozone (an accumulating secondary pollutant) lie within federal control, with legal limits on ozone in place. In fragmented continents such as Europe, there is reluctance to place binding limits on ozone into individual national laws, because those countries may have almost no policy control over the air quality outcome.

3. Which pollutants to legislate for?

There is a scientific, legal, and policy interdependency in deciding which pollutants require an ambient air quality standard, because air contains many thousands of different chemical and biological components that are plausibly harmful to health. In deciding which components should be subject To regulation, there is a problem of evidential circularity. Legally embedded standards are generally only created when the scientific evidence of harms is considered compelling by lawmakers. Such evidence has historically emerged from longitudinal population epidemiological studies that combined long-term ambient measurement data with health outcomes, leading to the “criteria pollutants” that are commonly regulated today. However, long-term air quality data are generally only collected for those pollutants for which there is a preexisting legal obligation to do so (because data collection can be expensive). As the dominant current example of this, $PM_{2.5}$ is relatively cheap and easy to measure and thus has become a de facto variable in health studies.

It is difficult for a “new pollutant” to break into the incumbent epidemiological and legal framework. EU law proposals require regular scientific review of new evidence on air quality and health. However, without the underlying long-term measurement datasets, the necessary studies may not emerge. There is likely merit in limit values for black carbon, ultrafine particles, formaldehyde, or subcomponents of PM such as secondary organic aerosol; however, each has yet to accumulate weight of evidence to become legal obligations. Reaching scientific consensus on the differential toxicological impact of the chemical subcomponents of PM remains outstanding despite decades of research and debate (11). As analytical capability continues to advance, new areas of possible targeted abatement present themselves to policymakers, such as microplastics and nonexhaust emissions from road transport. Balancing the state of the science within ambient air quality laws, while also providing certainty and stability in legal regimes, is a major challenge.

We would argue for a statutory requirement for “exploratory” air pollution observations, following the precautionary principle, ideally coupled with research funding to incentivize them. There is a risk that regulations remain locked to only those pollutants for which an association with negative health outcomes has already been proven, ossifying the legal position despite scientific advance. This matters for current policy-makers because it may be easier and more cost-effective to deliver health-beneficial changes through more targeted interventions on certain chemicals within particulates, rather than reducing the mass of $PM_{2.5}$ overall.

4. The limitations of limit values—expanding the toolbox of standards?

Air quality standards expressed as limit values alone are not the ultimate destination for a mature system of air quality governance. The most recent evidence on harms from exposure to pollution shows that effects do not have a defined “cutoff,” but rather occur as a continuum and can be nonlinear and still substantial at concentrations below limit values. This creates inconsistency between the latest science and the primary legal tool. In air quality regimes, there is often acceptance of “polluting up to the limit.” This can lead to gaming practices that move sources around to achieve technical compliance with limit values, rather than see them abated. By contrast, the need to prevent deterioration of acceptable environmental quality is a key aspect of water and nature protection laws in Europe.

The precarious legal comfort in prescribing fixed limit values also undermines the robustness of policy responses, because legal obligations to achieve limit values directly influence policy responses. The policy process first identifies which locations exceed limits, then which sources are responsible, and finally what interventions might be staged such that concentrations would no longer exceed the maximum permitted amount. Historically, this approach has served societies well as a starting framework for pollution management. However, as an air quality regime takes effect and air quality improves, policy attention can become intensely focused on a few locations that are out of legal compliance (for example, roadside NO_2 in cities) with sometimes no requirement to deliver further population-wide improvements. This may lead to poor allocation of resources and “tunnel vision” policymaking. By contrast, a small improvement delivered population-wide might realize larger economic benefits than bringing a small number of nonattainment locations into compliance.

Some other regulatory protections can better reflect the scientific evidence that there is no lower concentration threshold for harm. In the UK, for example, legislation in 2023 created a $PM_{2.5}$ population exposure reduction target to sit alongside a limit value. This requires that not only are all limit values achieved, but also that there must be a population-wide reduction in concentration over time, even if below the limit value. Ever-lowering limit values create measurement challenges, particularly for $PM_{2.5}$ for which large relative uncertainties exist at low concentrations. Too large an uncertainty might undermine enforceability of laws in court or shift the burden of evidence onto computer models of air quality. Models have their own uncertainties, would inevitably be state-run or statesponsored, and lack transparency because they are not easily reproduced. Attainment of air quality standards must ideally be verifiable through measurements that are open to public scrutiny, and not give rise to uncertainties that make compliance a marginal question.

5. The limitations of air quality standards—disparities and injustice

Even if a location’s air quality demonstrably falls within acceptable legal standards, that is not a guarantee of environmental justice. There is a burgeoning body of evidence demonstrating that higher concentrations, and greater emissions, are often found in locations populated by deprived communities and minoritized ethnicity groups (12). This is a substantial challenge for policy that may need to reflect social priorities when enacting interventions or abatement. Differences in air pollution driven by geophysical factors are important for public health and may lead to policies that account for them, but they are not structurally unfair. In most societies, however, the disparity in the distribution of pollution is due to myriad sources that have arisen through a complex historical combination of planned and unplanned decisions. Sometimes pollution is deliberately located, sometimes populations gravitate toward or away from a place because it has a pollution source. Deprived communities can shift toward busy roads because of cheaper housing; new industrial sources are often sited where deprived communities are established.

Regulatory systems that exclusively use ambient limits and emission totals (such as “national emissions ceilings”) may not be effective at addressing inequalities and may lack specific actions for disadvantaged groups, instead creating policies that privilege geography over people. Population exposure reduction targets have a role to play but may not necessarily deliver for communities with higher preexisting burdens. Several legal systems are moving toward acknowledging “vulnerable” or “sensitive” populations for enhanced protection in their air quality regimes, but wider regulatory attention in urban planning is also needed. Decisions should consider not only whether development might lead to a new exceedance of air quality limits (already undertaken in many countries), but whether it would exacerbate or reduce the disparities in local pollution exposure, irrespective of limits, and whether it uses best available low-emission techniques.

6. Multilevel coordination and the fundamental challenge of accountability

Coordination of air quality policies is not simple. Polluting emissions arise from almost all human activities, and government structures do not always accommodate collective ownership of “cross-economy” goals. Multiple departments, agencies, and levels of government (regions, states, cities) are implicated. Without clear accountability, there is a risk of no accountability, or delegation to lower levels of government that lack the technical levers, institutional capacity, or legal oversight to deliver on air quality objectives.

Coordinated policy-making must be matched by coordination between different spheres of law and regulation. Air quality officers in cities need resources and influence over local planning and transport policymaking; national decision-making needs to consider and align air quality obligations in the delivery of other government priorities; supranational action needs to promote policy and regulatory coherence in achieving standards through all levels of government.

As one crucial site of coordination, the potential or delivering win-win benefits at the intersection of air pollution abatement and climate emissions mitigation has long been articulated by the scientific community (13), but there is an under-recognized need for legal and regulatory coordination as well. For example, climate commitments for the adoption of low-carbon fuels for aviation can only deliver air quality benefits if there are parallel, internationally agreed, regulatory requirements for reduced engine emissions of NO_x and PM. Carbon regulation alone does not guarantee better air quality. New transboundary challenges may emerge as climate change alters weather patterns, and possibly new emissions and impacts will arise should climate geoengineering become a reality (14). Once-in-a-generation transitions, if not accompanied by a consideration of the air quality impacts, and a coordinated regulatory refresh, could lead to a squandering of opportunity.

More generally, national governments have a key role in coordinating both policy and legal responses for air quality across sectoral and regulatory domains, and in being held accountable. Like climate change, air quality needs to be recognized as an interconnected, multilevel social and economic policy issue at the national level, not merely a discrete, localized environmental problem. A global treaty on ambient air quality that supports universal public health goals and evolving human rights protection might have the effect of enabling greater supranational coordination and harmonization, while also improving visibility at the national level. Prospects of such a treaty, however, currently appear remote (15).

CONCLUSION

Practical policies that improve air quality and public health are frequently shaped and prioritized as a response to meeting legal obligations. However, those legal obligations cannot be static to deliver clean air outcomes. National air quality regimes are increasingly dynamic, with a growing, intersecting influence for civil society, scientists, and the judiciary in molding policy trends. For many national regimes, elevating the ambition of air quality policies and outcomes is not just a matter of increasing legal standards to the level of WHO AQGs. To move the debate forward, we argue that growing the space for dynamic regulatory development at the science-law-policy interface is an important avenue for accelerating the delivery of global clean air goals.

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