Carole Bedos · Sophie Génermont
Jean-François Castell · Pierre Cellier
Editors

Agriculture and Air Quality

Investigating, Assessing and Managing

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Foreword

"I honestly think that pollution on our planet is not as serious as people say… It's much worse."

Philippe Geluck,

Le tour du chat en 365 jours (2006)

Breathing is a natural reflex.

Air – a naturally colourless and odourless substance – is essential for all of us. Although air quality has generally improved in France in recent decades, air pollution lowers life expectancy and causes about 48,000 deaths per year in France and 7 million worldwide. It has also been shown to have significant harmful impacts on biodiversity, agricultural yields (with declines of up to 20%) and buildings. The economic impacts of air pollution are considerable: in July 2012, the French Commission for Environmental Accounting and Economics[1] estimated the cost of outdoor air pollution to be €20 to €30 billion per year in mainland France (a more recent report from 2015 by the French Senate even raised this figure to a range of €68 to €97 billion). According to a 2018 survey conducted by OpinionWay for the French Environment and Energy Management Agency (ADEME), air pollution is one of the three most pressing environmental issues for French people, along with global warming and the degradation of fauna and flora.

[1] Commission des comptes et de l'économie de l'environnement.

In May 2018, France was referred to the Court of Justice of the European Union for non-compliance with nitrogen dioxide (NO_2) limit values in ambient air. In addition to this European case, additional litigation has been brought before the French Courts (e.g. decision by the French Council of State[2] of July 2017 and a new case filed against the French government in October 2018 by 78 environmentalist and medical associations for its failure to implement this decision). In total, 15 zones in 6 regions have been affected by these decisions. Many human activities cause pollution, and while some such as industry, transport and household activities (heating, burning, etc.) are well known, others – like farming – are less so. This is why this book has chosen to home in on the relationship between agriculture and air quality.

Agriculture is at a crossroads in terms of pollution, because it not only has an impact on pollution but is also impacted by pollution:

– It has an impact on pollution because it releases emissions into the air (and other environments) through contaminants such as ammonia, volatile organic compounds and plant protection products. It also causes the formation of ozone and secondary particulate matter.
– It is impacted by pollution because the accumulation of ozone weakens plants and leads to yield losses while the deposition of metallic elements can diminish yield quality. Excessive accumulation of ammonia and particles in livestock buildings can also affect the working conditions of farmers as well as animal health and welfare.

In May 2017, France adopted a National Air Pollutant Emission Reduction Plan (PREPA), which established guidelines for reducing emissions for five major air pollutants (sulphur dioxide (SO_2), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), particulate matter with a diameter of less than 2.5 µm (PM2.5), and ammonia (NH_3)). This plan combines various public policy tools: sectoral regulations, taxes, subsidies, awareness-raising and stakeholder mobilization actions, as well as training initiatives. It includes the implementation of mitigation measures in agriculture, with the specific objective of reducing ammonia emissions from mineral fertilizers and livestock manure by 13% by 2030. These measures also include a national guide of best practices, an action plan to ban the highest emissions-producing spreaders, and a study on reducing emissions from nitrogen fertilizers.

ADEME has been involved for several years in actions to improve indoor and outdoor air quality. It lends its expertise and active support to research and knowledge transfer. For nearly 20 years now, the agency has worked in conjunction with other funders to support applied research institutes such as INRAE[3] that study agricultural emissions and how to reduce them. INRAE has been developing scientific

[2] Conseil d'État.

[3] INRAE is the French National Research Institute for Agriculture, Food and the Environment. It was created in January 2020 following the merger of the National Institute for Agricultural Research (INRA) and the National Research Institute of Science and Technology for Environment and Agriculture (IRSTEA).

and technical expertise since the mid-1990s and has conducted numerous research projects on the contribution of agriculture and livestock to air pollution and the impact of air pollution on agriculture. This expertise made INRAE uniquely qualified to coordinate this book, which offers a broad overview of the knowledge researchers have acquired. It takes stock of the historical and societal context of agriculture and outlines how France's regulatory approach to air pollution from agricultural sources has evolved through to today. It provides a detailed summary of the state of knowledge on the relevant polluting compounds, mechanisms and interactions involved at different scales between these elements (emissions from primary pollutants and precursors, atmospheric transport, atmospheric chemistry, etc.) and describes recent methods for observing and modelling interactions between agriculture and atmospheric chemistry. These components underpin an important section of this book dedicated to levers for action and operational strategies to be deployed to reduce the impact of agriculture on air quality.

In short, this book gives readers historical, sociological and technical insights to provide them with an overview of the issues related to agriculture and to inform decisions on necessary actions to effectively mitigate air pollution.

The range of situations decision-makers face means that taking action is a complex process, especially since regulations, technical knowledge of processes and levers for action all evolve rapidly. These various considerations show how the publication of this book fits into an exciting area of research that has thus far been somewhat neglected. In the words of the French Ministry for the Environment, "air quality policy requires ambitious actions, both at the international and local levels, in all activity sectors. The State, local authorities, economic stakeholders, citizens and non-governmental organizations must work together to guarantee everyone the right to breathe air that will not harm their health. This is a pro-active and long-term policy approach that seeks to continually build on its effects."

Executive Director of Expertise and Programmes Marie-Christine Prémartin
ADEME
Paris, France

Preamble

Agriculture is not only directly exposed to different components of global change but also contributes to some of them, including climate change, biodiversity loss and the degradation of soil, water and air quality. Among these challenges, air quality is increasingly garnering greater attention in the media. It is a component of global change that can affect agricultural activities as well as be affected by the pollutants they emit. Like all human activities, agriculture is a source of air pollutants, primarily those related to the use of inputs such as nitrogen fertilizers and plant protection products. However, the effect of agriculture on air quality has only recently come to light and become a concern among agricultural professionals and policymakers – long after the emergence of the acid rain phenomenon, even though agriculture contributes significantly to the problem. These issues only came into focus after springtime peaks of particulate pollution began to occur and local and large-scale contamination from plant protection products were detected. But agriculture differs from many other human activities in that it too is impacted by air pollution from other sources, with the best documented example being ozone. Awareness of this particular issue among professionals is even more recent. Thus, agriculture must not only be concerned with food security, which requires sustained production in terms of quantity and quality, but it must also take environmental conservation into consideration, especially by limiting emissions of atmospheric pollutants from its crop and animal production practices. Accordingly, there is a need to inform both public debate and possible policy actions by summarizing existing knowledge on all relevant scientific fields, processes and scales.

This book aims to give to students, research and agricultural stakeholders, and public policymakers clear information to unravel the complexity of the many processes involved and the possibilities and limits of the means of action available based on the diverse conditions of agricultural activities. Agriculture is a vast field, and as such the complex phenomena must be considered from very different angles, both disciplinary (agronomy, atmospheric and environmental sciences, physiology and ecophysiology, chemistry, metrology, sociology, economic and political sciences, etc.), and on a variety of scales and levels of organization, from agricultural plots and livestock buildings to landscapes, regions, the planet, and even how entire sectors are organized. This book begins with an inventory and analysis of the main sources of agricultural pollutants that impact ambient air quality (indoor air quality is not covered). It highlights their specific characteristics as well as how air pollution impacts crop production. It provides information needed to understand the drivers of the concentration levels to which populations and agroecosystems are exposed. It does not, however, analyse to what extent air quality is degraded. The assessment of exposure, identification and characterization of the different populations and ecosystems concerned are also not addressed as they are part of specific approaches that go beyond the scope of this book.

When considering changes in atmospheric composition, climate change is an obvious factor. While there are many links between air quality degradation and climate change when it comes to emission processes and policy instruments, these two issues differ over time and space. Whereas climate change actions implemented today are meant to have effects over several decades or even centuries on a global scale (with regional variations), air quality issues are characterized by short time scales (from one hour for pollution peaks to a few years for more chronic pollution issues such as acid rain) and by a various spatial scales ranging from around a hundred metres (impact of a point source on the population or its surrounding ecosystems) to the region (ozone) and the continent (cross-border pollution). This duality has major implications in terms of public policies: they must stimulate actions both in the long term (limiting emissions of greenhouse gases and air pollutants) and in the short term (preventing pollution peaks).

This book deals with chemically active compounds, that is compounds which affect chemical and biochemical processes in the atmosphere and/or in the biosphere. Although the issue of the impact of agricultural activities on climate change falls outside the scope of this book, the interactions between air pollution and climate change must be considered. Not only does global warming affect pollutant emissions, but mitigation measures can also have a simultaneous, synergistic, antagonistic, direct or indirect effect on climate change and air pollution.

The different types of air pollutants discussed here are those *from* agriculture, such as ammonia (NH_3), pesticides (plant protection products), nitrogen oxides ($NO + NO_2 = NO_x$), biogenic volatile organic compounds (BVOCs), and primary and secondary particulate matter (PM), along with those *affecting* agriculture, the most significant being ozone (O_3). Some air pollutants – and especially methane (CH_4) – that are better known as greenhouse gases (GHGs) are considered in this book solely for their impacts on air quality. Other pollutants that have no bearing on air quality but which do belong to the same biogeochemical cycle as air pollutants are also mentioned. These compounds are produced by the same reactions or subjected to the same equilibria as the pollutants of interest, or they are consumed in the processes involved in air pollution. This is typically the case for nitrate (NO_3^-) and nitrous oxide (N_2O), which both belong to the nitrogen cycle. Nitrate is a factor in water quality issues, while nitrous oxide is known for its strong greenhouse effect. This shows the complexity of the interactions involved in pollution in terms of shifts between environmental media and types of impacts, and explanations have been provided where necessary for clarity.

This book takes an in-depth look at crop and grassland production, with less attention given to livestock production. Forestry is also only addressed when specifically relevant. The broader context mainly applies to farming systems in France and Western Europe, and as such, many references to production systems, pedoclimatic conditions, societal issues and regulations relate to these areas. However, several of the topics discussed in the book can be generalized to other types of productions and geographical contexts (processes, tools developed, etc.). Biomass combustion in the field is also not covered.

Finally, the approaches that have been developed in this book begin with the underlying processes through to the consideration of means of action, especially at the agricultural plot or livestock building scale. The way in which agricultural activities are organized within the farm or sector is given limited, if any, attention in this book. This reflects how public policies have thus far mostly promoted drivers at the plot and building scales. Similarly, the analysis of atmospheric dynamics and chemistry does not go into considerable detail because it is not specific to agricultural pollutants. Information on this issue is available in books that deal with much more extensive aspects of air pollution.

The book begins with a two-part introduction, and is then divided into three parts, each of which is further subdivided into chapters. The introduction first describes the overall "agriculture and air quality" issue in broad strokes. It then gives a general overview of the rising importance of considering environmental issues within the context of agricultural concerns, while also shedding light on the relationship between agriculture and air pollution.

Part I addresses the theoretical bases concerning air pollutants that are emitted by agricultural activities or that have an impact on agricultural production. Chapter "The Main Pollutants and Their Impacts on Agriculture, Ecosystems and Health" goes into more detail on these pollutants, specifying how agricultural activities contribute to their emissions as well as their impacts on crop production, ecosystems and health, with an emphasis on why these compounds are so relevant. The mechanisms underlying the biological, physical and chemical processes involved in the exchange of these pollutants within agroecosystems and what happens when they enter the atmosphere are detailed in chapter "Mechanisms of Pollutant Exchange at Soil-Vegetation-Atmosphere Interfaces and Atmospheric Fate". An integrative view is provided in chapter "Necessary Integrative Approaches", which outlines these mechanisms' interactions within ecosystems and at higher scales as well as links to climate change, water quality and biodiversity issues. This chapter also presents the processes specific to livestock buildings.

Part II details the tools that have been developed to measure and model the exchanges of air pollutants between the atmosphere and farmland, livestock buildings and agricultural landscapes as well as what happens once they enter the atmosphere. Chapter "Measuring Air Pollutant Concentrations and Fluxes" discusses measurement methods used to study the processes that determine air quality in relation to the biosphere as well as the methods required to measure concentrations. Chapter "Modelling Exchanges: From the Process Scale to the Regional Scale" explains how our current level of knowledge translates into mathematical tools to model the air pollutant exchange processes between different agroecosystems or components of a farming system and the atmosphere (emissions and deposition), as well as what happens to these pollutants in the atmosphere (transport and chemical changes).

Part III analyses the way this knowledge is put into action. Chapter "Establishing a Diagnosis: Inventorying, Monitoring and Assessing" explores the different methodologies used to conduct environmental assessments of agriculture's contribution to air quality and related impacts in terms of policy, air quality monitoring and impact assessment. Finally, chapter "Reducing the Impacts of Agriculture on Air Quality" demonstrates how an understanding of the pollutant emission, transformation, transport and deposition processes, as well as their interactions, makes it possible to identify and implement measures to reduce emissions for each stage concerned (including livestock, which is covered in more detail in this chapter than in previous ones) and at different levels of organization. It also deals with assessing the environmental outcomes once public policies are implemented and how rural and urban populations understand them.

Each part of the book closes with a summary of the main points discussed therein. Finally, to offer readers who are interested in a specific compound or a type of compound a more comprehensive view, summary fact sheets by compound are available at the end of the book. They summarize the information covered throughout the book's different chapters.

Thiverval-Grignon, France

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Carole Bedos After a PhD in atmospheric physico-chemistry focusing on aerosol modelling, Carole Bedos has been working as a Researcher for INRAE since 1999. Her main research interests are pesticide emission to the atmosphere, atmospheric dispersion and deposition, and recently population exposure to pesticides via the atmosphere. Her area of expertise therefore covers the fate of pesticides in the atmosphere as well as the associated experimental methodologies from the lab to field conditions and modelling at the local and regional scale. She also contributes to national working groups for ministries and French Agency for Food, Environmental and Occupational Health and Safety on the mitigation of pesticide emissions to the atmosphere, recommendations for national monitoring of air contamination by pesticides or recommendations for the assessment of resident exposure to pesticides.

Sophie Genermont has been working as a Researcher at INRAE since 1992. She is an agronomist, and for her PhD thesis in atmospheric physico-chemistry, she has been studying ammonia volatilization from cropped fields. Sophie is developing transfer tools and structures for both measurement and modelling at local and regional scales. She is involved as task carrier or coordinator in projects on fertilization and/or air pollution. Her research theme is part of the agronomic and environmental assessment of the agricultural recycling of organic waste products generated by anthropogenic activities and the nitrogen fertilization of crops most specifically in terms of air quality. She contributes to national and international expert groups relative to these subjects. She also leads a nationwide technology network on the issues of recycling, fertilization and environmental impacts involving some 40 research, R&D, development and educational organizations.

Jean-François Castell After completing a master's degree in ecology and plant ecophysiology, Jean-François Castell has been teaching crop physiology and environmental physics at AgroParisTech since 1988. His research at INRAE initially focused plant water functioning and the water balance of vegetation and since the 1990s has been switched to the study of the impacts of atmospheric pollutants on the ecophysiology of plants and on crop yields and ecosystem functioning. More specifically, he is working to quantify the impact of ozone on wheat yields in France and Europe.

Pierre Cellier After completing a master's degree in agronomy in 1979, Pierre Cellier has been working on physics and chemistry of the environment in the context of agricultural research at INRAE. This applied first to spring frost prediction (PhD in 1982), evapotranspiration measurement and soil temperature prediction. Since the 1990s, he moved to analysing and modelling agriculture-air pollution-greenhouse gases relationships with a focus on nitrogen and related compounds (NH_3, N_2O, NO, O_3) and pesticide volatilization. He has also been working on dispersion and deposition of NH_3, pesticides and particles in the vicinity of agricultural sources and on landscape scale modelling of nitrogen transfer and transformations.

Pierre Cellier has been involved in building research programs with French applied research institutes, in European networks and research projects, as well as expert groups. He often participates in French expert groups or scientific committees dealing with nitrogen and air pollution.

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Introduction 1: Agriculture and Air Quality: Background Information

Pierre Cellier, Carole Bedos, Jean-François Castell, and Sophie Génermont

The issue of air pollution emerged in the agricultural world at the turn of the twenty-first century. It is now a major concern for professionals and institutions that help agricultural sector players implement and plan for agricultural and environmental policies. This introductory section offers insight into the relationship between agriculture and air quality in light of recent trends in both air pollution and agricultural activity.

1 Air Quality: A Major Concern

Environmental issues are now at the forefront of the public's concerns in France and Western Europe. Among them, climate change ranks first, followed closely by air quality, while water quality and waste issues have become less pressing issues in France (INSEE 2015[1]) since the 1970s. Air pollution is defined in Article L220-2 of the French Environmental Code (amended by Article 179 of Act 2010-788 of 10 July 2010): "For the present purposes, 'air pollution' means the introduction by man, directly or indirectly, or the presence in the atmosphere and confined spaces of chemical, biological or physical compounds having harmful consequences likely to endanger human health, harm biological resources and ecosystems, influence

[1] https://www.statistiques.developpement-durable.gouv.fr/opinions-et-pratiques-environnementales-des-francais-en-2015 (available in French only).

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climate change, damage material properties and cause excessive odour nuisances." Air quality is not explicitly defined, but rather air pollution and the thresholds[2] above which air quality is considered to be "degraded" with regard to impacts (especially health impacts), with emission ceilings intended to ensure compliance with predefined threshold concentrations.

The deterioration of ambient air quality, which began with the industrial revolution, surged exponentially after the mid-twentieth century. The Great Smog of London in December 1952 was a turning point after it caused the premature death of more than 10,000 people and health problems for more than 100,000 people in just a few days. In the 1970s and 1980s in Europe and North America, media coverage of acid rain, which led to forest dieback, alerted the public to the harmful effects of background pollution. The discovery of the "hole" in the stratospheric ozone layer (even if not directly related to ambient air quality) around the same period and on a global scale heightened awareness among political actors and society of the fragility and finite nature of the atmosphere. More recently, issues related to ground-level ozone, fine particulate matter and compounds such as pesticides have emerged in the public debate. The current consensus is that the consequences on human health (respiratory diseases, cardiovascular diseases, carcinogenic effects, etc.), namely as a result of ozone and PM2.5[3] pollution, are responsible for several million premature deaths every year worldwide, and several tens of thousands in France. These multiple impacts, particularly those affecting human health, mean the costs of air pollution are very high. An official French government report from 2015[4] put the estimated cost for the country at nearly 100 million euros per year, mostly related to health impacts, which are better known and more easily quantified in economic terms than those related to natural and agricultural ecosystems or the climate. However, the impacts of ozone on crops and agricultural production are only starting to be better understood (Mills et al. 2011) and the effects are now more widely reported in the press such as episodes in India in 2014[5]. As part of the European Nitrogen Assessment (Sutton et al. 2011), an assessment of the economic impact of nitrogen in its various reactive forms (reduced nitrogen $NH_x = NH_3 + NH_4^+$; and oxidized nitrogen, which includes NO and NO_2 as well as N_2O and nitrate) was carried out on a European scale. The overall costs associated with all these forms are estimated at between €70 and €320 billion per year, 75% of which are related to the effects of air pollution. With regard to ammonia – which mainly comes from agriculture, as this book will show – the cost is mainly linked to impacts on human health because it is a precursor of fine particles, but impacts on ecosystems (acidification, eutrophication, biodiversity losses) must also be factored in.

[2] https://www.respire-asso.org/comprendre-les-types-de-seuil-des-polluants/ (available in French only).

[3] PM2.5: particle matter (PM) with an aerodynamic diameter of less than 2.5 μm.

[4] http://www.senat.fr/rap/r14-610-1/r14-610-1.html (available in French only).

[5] https://www.theguardian.com/environment/2014/nov/03/india-air-pollution-cutting-crop-yields-by-almost-half

2 Various Frameworks for Understanding Air Pollution and Its Impacts

Attempts to define air pollution and the examples cited above show how complex the issue is: many different compounds, impacts and sources, and therefore anthropogenic activities, are involved. Various approaches, each with specific goals, can be used to better understand this diversity.

2.1 A Framework to Visualize the Processes Involved in Identifying Pollution Sources and Sinks and Predicting Air Quality

Figure 1 is a schematic but straightforward representation of what happens to air pollutants in natural and anthropogenic environments, from their primary emission source or transformation in the atmosphere (leading to secondary pollutants) to their destruction (sinks). This diagram shows the many different air pollutant emission

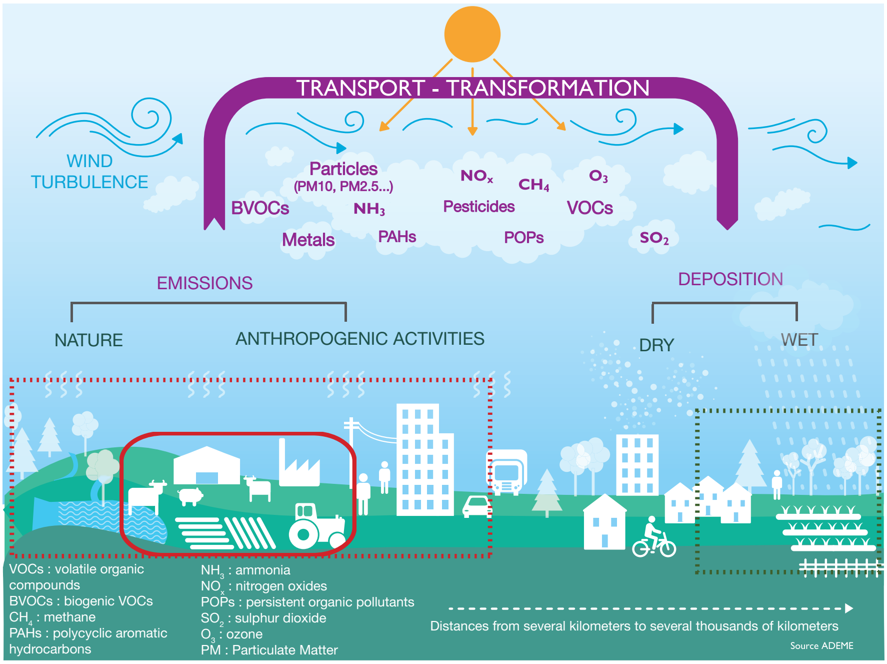

Fig. 1 Dynamics of atmospheric pollutants showing the role of agricultural activities as a source of pollutants (continuous red box), in the context of their close relationship with the rural or urban environment (dotted red box) and as an area affected by atmospheric deposition of pollutants (dotted green box) (Source: ADEME)

sources; the processes of pollutant dispersion, transport and degradation (chemical reactions in the atmosphere), as well as deposition pathways. It also provides the conceptual framework for air quality prediction models and quantitative impact assessment. This framework can be applied on a range of scales from local to continental in order to assess phenomena such as the impact of a pollution source on its surrounding environment or transboundary transfers of pollutants. This diagram also shows the variety of relevant compounds involved: many short-lived intermediate compounds should also be taken into account, as they play an essential role in atmospheric chemistry. Furthermore, it shows that one compound can act as a precursor to another polluting compound.

The aim of this integrative framework is to assess the exposure to pollution these organisms (whether ecosystems or humans) face and ultimately the impacts of that pollution on them. This assessment requires estimating two measurements:

- Pollutant concentrations to which organisms (humans or ecosystems) are exposed: these concentrations are one component of exposure and result from a local sum of emissions, transfers, transformations and deposition. The concentration of pollutants in the atmosphere is an essential intermediate variable, particularly near the land surface where exposed living organisms are found and especially human populations. It is a key explanatory variable for estimating exposure to air pollution and its impacts. The other variables refer to the description of organisms (location, characteristics) and the different routes of exposure. These concentrations are one of the main variables used to calculate ecosystem deposition.
- Depositions on natural or agricultural surfaces: these depositions are the root cause of the impacts of air pollution on natural or agricultural ecosystems. Moreover, they are an essential process in the dynamics of pollutants since they generally represent a final phase because the pollutant leaves the atmospheric compartment and is degraded after deposition.

For both of these measurements, estimates of concentrations or depositions must quantify a chain of processes: physical (microclimate, dispersion, transport), chemical (chemical and photochemical transformations, interface reactivity) and biological (metabolism of living organisms towards pollutants). To forecast air pollution, these processes must be integrated into a common modelling framework. Modelling is imperative due to the complexity of the system and the range of situations to be considered.

Figure 1 also underscores the fact that agricultural activities take place at the surface-atmosphere interface, with plants, animals and soil all being major components. The processes are similar to those in non-agricultural ecosystems, but with a key difference in the type and amounts of inputs (i.e. the main source of emitted pollutants) and in management practices (e.g. tillage, harvesting, residue and animal waste management, grazing). This book follows this framework, while also examining the levers that can be applied to mitigate emissions and impacts.

2.2 A Framework for Public Policy Development

Another approach, more focused on the development of public policies on air pollution, is shown in Fig. 2. Public policies begin with the impacts and move up the chain to the sectors responsible for emissions. Note that the dominant contribution of agricultural activities in atmospheric contamination from pesticides specifically used to protect crops and the resulting consequences on human health and non-agricultural ecosystems could also be added. Public policies on air quality have achieved positive outcomes using this impact-to-source approach. For example, various physical, chemical and economic modelling tools use impact reduction objectives as the starting point to assess which priority activities and geographical areas should be targeted.

The compounds circled in green come from agriculture, with the thickness of the line increasing in step with agricultural emissions for that compound. Pesticides are not shown in this figure because they are not currently regulated for the atmospheric compartment. CH_4 is included as a VOC here.

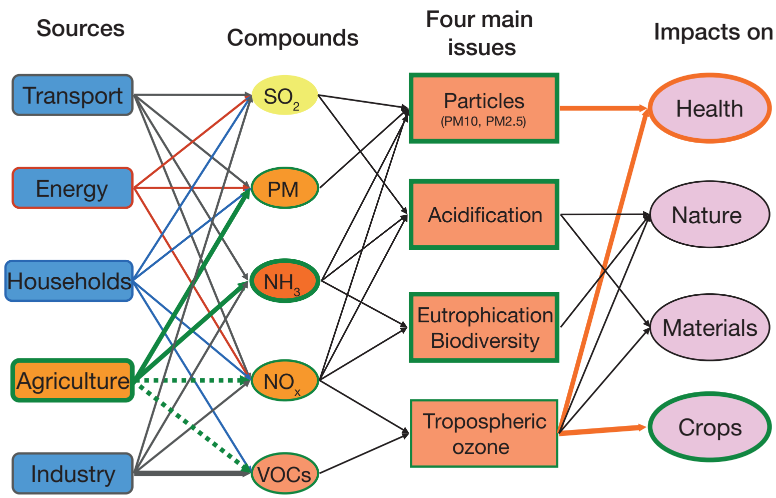

Fig. 2 Air pollution: source of compounds and related impacts. (According to EEA 2012)

2.3 A Framework Linking Drivers, Impacts and Public Regulation

Another way to analyse this complex framework of relationships between agriculture and air quality is to consider them conceptually, as is the case for the DPSIR scheme,[6] which is often recommended for decision-makers by the European Environment Agency.

Figure 3, which has been adapted for the agriculture and air quality issue, highlights:

- The numerous drivers, from land use to farming system characteristics, interactions with other sectors of activity or historical trends.
- The variety of pressures that agricultural activities exert on the environment through emissions of various pollutants, not only in the atmosphere but also in water and soil.
- The need to consider the status of many environments (air, city, neighbouring or remote ecosystems, etc.).
- The diverse impacts resulting from the emissions and deposition of air pollutants.
- A political and regulatory context that involves multiple directives dealing directly or indirectly with air quality and various panels of stakeholders and experts. Decisions taken in these areas may impact all the points mentioned above (dotted arrows from the "Responses" box to the other boxes).

3 Agriculture and Air Quality: Relative Positioning

As Fig. 3 clearly shows, various anthropogenic activities are involved in air quality degradation. Agriculture, an economic activity whose main goal is to feed large numbers of people with nutritious and sanitary food, has a large ecological footprint, affecting all environmental compartments: soil, water, biodiversity and, of course, the atmosphere (Guyomard et al. 2017).

[6] DPSIR: Drivers, pressures, states, impacts, responses.

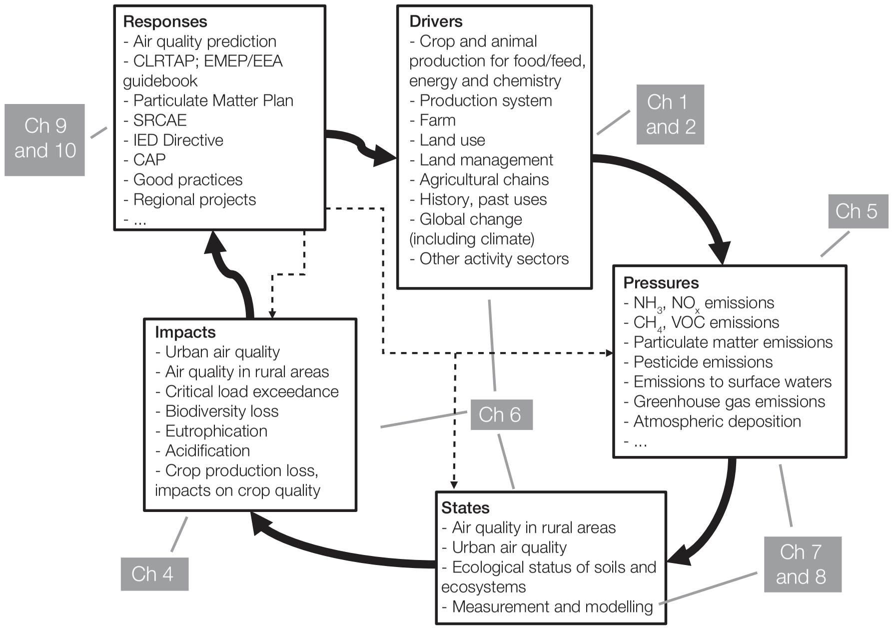

Fig. 3 Applying the DPSIR scheme (generally used to describe the interactions between the environment and society; EEA 1999) to visualize the issue of agriculture and air quality

3.1 Agriculture: An Activity Characterized by Recent Changes

3.1.1 An Important Activity in All Our Societies that is Undergoing Considerable Change

The world's landscapes have been extensively shaped by agricultural activities. This is true in Western Europe and especially in France, which was largely covered with forests until the Middle Ages before agricultural and pastoral activities led to massive deforestation. Agriculture structures humans' living environments to a very significant degree in rural areas as well as in peri-urban areas, where agricultural activities and all other human activities (e.g. residential and industrial areas, economic and commercial activity areas, transport routes).

Although agriculture is still a major economic activity in France – the country is a leading exporter of raw and agri-food products – the sector has seen a sharp drop since the second half of the twentieth century in the number of workers (from 27% of the working population in 1955 to 3.5% in 2010) and farms (a tenfold drop between the end of the nineteenth and the beginning of the twenty-first century). Along with this shift, there has been an increase in the average surface area of each farm, as well as land consolidation operations leading to the expansion of plots and a smaller proportion of semi-natural ecosystems and ecological structures such as hedgerows or ditches. In *Les clés des champs. L'agriculture en question*[7] (Réchauchère et al. 2008), Jacques Diouf notes that agriculture faces three major challenges: producing enough nutritious and sanitary food, striking a balance between sufficient production and ecosystem survival, and being part of a world "that is moving very quickly on all fronts: changes in natural conditions such as climate change, or in the economic and social conditions of production, such as the increasing internationalization of trade." Agriculture and air quality are connected in this context of an agricultural world under pressure, where production factors become pollution factors, where regulations and action plans multiply and cover ever more human activities in order to meet the various needs for environmental protection. In order to ramp up production to meet needs during the second half of the twentieth century, agriculture adopted an intensive approach and increased the use of inputs, fertilizers and plant protection products. In the early twentieth century, the Haber-Bosch process made it possible to use atmospheric nitrogen as a source of reactive nitrogen (Nr) by combining it with hydrogen from natural gas at industrial scale. The massive production of synthetic nitrogen fertilizers was a major step forward in meeting human protein needs and contributed to sustaining population growth, as well as ensuring the necessary food security at the end of the Second World War (Erisman et al. 2008). This widespread use of synthetic nitrogen fertilizers, which greatly contributed to the intensification of crop and animal production, has, nevertheless, led to drastic changes in the nitrogen cycle, resulting in a disruption of pre-existing equilibria and significant losses of Nr into the

[7] The Keys to the Fields. The agriculture in questions.

environment. This has had various impacts on biodiversity, water, air and soil quality, ecosystem productivity and climate (Sutton et al. 2011).

Unlike nitrogen, whose various forms are naturally present in the environment, pesticides are not naturally occurring substances. They have been introduced into the environment through activities such as crop protection. There are strong indications that pesticides affect human health (INSERM 2013) and ecosystem health.

The observation of the environmental and health impacts linked to the use of these inputs and the regulations implemented to limit them have resulted in a shift from conventional practices towards a more rational use of inputs and even organic farming practices, thus anchoring agricultural activity in an agro-ecological transition approach.

3.1.2 An Activity Intertwined with Other Activities and Confronted with New Stakeholders

After a long period of rural exodus following the Second World War, corresponding to the mechanization and intensification of agriculture, the movement reversed from the 1980s due to urban sprawl towards the countryside. The activities of these newcomers are often not related to agriculture. The interfaces between agriculture and other anthropogenic sectors, particularly the residential sector, have changed considerably in recent decades. This is partly due to the movement of urban populations towards rural areas, and partly to the increase in areas occupied by other human activities and their interconnectedness with agricultural activities in rural areas (roads, urban extension, industrial or business areas). Increasing numbers of people are now experiencing the positive and negative externalities of nearby agricultural activities, without being a party to them: examples include applications of pesticides, livestock manure, compost and mineral fertilizers or proximity to livestock buildings or animals in the field. Tensions can run high as a result of inconveniences (Amiet 2018). But agricultural activities are also subject to a whole series of constraints (transport, protection distance, etc.) and contamination associated with the proximity of inhabited areas and activity zones, as well as roads.

Finally, because of its main purpose – producing food for the population – agriculture is an essential activity that all people rely on. Thus, actors who are either directly connected to agricultural activity (farmers, agro-industrial players, consumers, political decision-makers, etc.) or in a more distant way (non-agricultural actors and local residents) are partners who must be considered at one level or another when analysing agriculture-air quality relations.

3.2 Recent Evidence of Connections Between Agriculture and Air Quality

3.2.1 When Air Pollution Became a Problem for Agriculture

The issue of agriculture's impact on water quality began to emerge as early as the 1970s and 1980s. However, the extent of the link between agriculture and air pollution, discussed briefly in the previous section, came to light much more recently, starting in the 1990s in Europe and in the early 2000s in France. Figure 2 shows that agriculture plays a large role in all major environmental issues, mainly through NH_3 and NO_x emissions, as well as those from pesticides. Agriculture's contribution is now a much more prominent concern among regulatory bodies and the general public. The most significant regulatory example is the significant attention given to agricultural emissions in the Convention on Long-Range Transboundary Air Pollution (CLRTAP 1979), which aims to solve the acid rain problem by reducing transboundary pollution transfer. After a sharp decline in emissions of the industrial gas sulphur dioxide (SO_2), reactive atmospheric nitrogen (reduced NH_x nitrogen and oxidized NO_x) has become the main agent of ecosystem acidification in Europe. The environmental impacts of NH_3, previously masked by industrial acid pollution, have become more apparent as a result of the latter's emission reductions. However, national emission ceilings were not imposed until the "multi-pollutant" (SO_x, NO_x, NH_x, and VOC) and "multi-effect" (acidification, eutrophication and ozone) Gothenburg Protocol (1999)[8] came into effect (Sliggers et al. 2004). The 1990s also saw an upturn in photochemical pollution from ozone (O_3). In France, the Air and Rational Use of Energy Act (LAURE, Act No. 96-1236 of 30 December 1996) marked an important step by requiring government authorities to monitor the concentrations of major pollutants and establish plans to improve air quality at local (generally urban areas) and regional levels. Many of these plans include a component related to agriculture. Various European working groups, particularly in the context of the Geneva Convention, supported by technical groups and involving stakeholders in research, agricultural development and air pollution, have developed numerous recommendations to reduce emissions. However, these are of a very different nature and level of detail depending on the pollutants in question: they are quite detailed for ammonia but much less so for compounds such as pesticides or VOC.

These directives and laws, and the resulting actions, have helped to mobilize agricultural stakeholders on air quality issues. More directly, the general public became more aware of agriculture's connection to an "air pollution" problem after it was tied to spring particulate matter pollution episodes, identified since the mid-2000s, as well as the possible impacts of pesticide application near schools. These two examples were reported in the media in the 2010s. A special issue of the French scientific journal *Pollution atmosphérique* in 2016 was devoted to the

[8] http://www.unece.org/env/lrtap/multi_h1.html

subject of the links between agriculture and air quality in cities and the countryside (Roussel 2016). In France, Research programmes such as PRIMEQUAL have launched specific calls for research proposals, such as the 2016 national call "Agriculture and Air Quality," which followed a national seminar on this issue in 2014. The monitoring and reduction of airborne contamination attributed to agriculture is now part of public policy in France. Several measures on agriculture have been implemented, including the 2010 French plan on particulate matter, pilot operations from the 2015 roadmap resulting from the 2014 French Environmental Conference, recommendations from the official government Potier report (2014) relating to the Ecophyto Plan and those issued by the French Court of Auditors in 2015 on the organization of mandatory monitoring of pesticides in the air, the immediate actions taken by the ministers for ecology and health under the third National Health and Environment Plan, the ANSES submission on the methodology for monitoring pesticides in the atmosphere (2017), the strengthening of national ammonia emission reduction targets under the EU National Emission Ceilings (NEC) Directive (2016/2284/EU) and the actions of the latest French National Air Pollutant Emission Reduction Plan (PREPA, May 2017, for the five major pollutants SO_2, NO_x, NMVOC, PM2.5 and NH_3).

However, agricultural stakeholders only became fully aware of the significant impact of air pollution in the early 2010s. Crop yields may indeed be significantly affected by ozone, and in certain agricultural areas near polluting sources (e.g. high-traffic roads), food crops could even be banned as a consequence of local contaminant deposition. An alternative use of these lands could be to plant energy crops.

3.2.2 Agriculture and Air Quality: A Complex and Specific Network

The previous analysis of the context around agriculture and air pollution highlights their complex relationship, the many issues at hand and the actors involved, whether agricultural players or not. Moreover, this context is part of a changing environment and has specific characteristics that must be taken into account.

First, agriculture faces various types of changes:

- Climate change: agricultural activities can aggravate (GHG emissions) or mitigate (carbon sequestration) climate change, which can strongly impact agriculture itself (changes in crop cycles, pest pressure, etc.)
- Land-use changes: which can lead to changes in crops (legumes, energy crops, etc.) or be caused by competition with urban sprawl
- The agro-ecological transition: with incentives to reduce the use of pesticides or to contribute more substantially to the circular economy, in particular through its capacity to recycle organic waste products (or manure); the latter leads to an increase of both the amount and variety of manure recycled (slurry, farm yard manure, composts, sludge, digestate, etc.)
- Consumption pattern changes (less meat in Europe, more meat in Asia; product quality)